coastalmanagement

Porirua Harbour

Broad Scale Subtidal Habitat Mapping 2013/14

Prepared for

Greater Wellington Regional Council

June 2014

Cover Photo: Mud sample from the central basin of the Pauatahanui Inlet - Jan. 2014.

Porirua Harbour, Pauatahanui Arm

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by

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PORIRUA HARBOUR - EXECUTIVE SUMMARY

This report summarises the results of the 2014 broad scale subtidal habitat mapping of Porirua Harbour, a large (809ha), well flushed "tidal lagoon" type estuary fed by a number of small streams. It comprises two arms, each a relatively simple shape, Onepoto (280ha) and Pauatahanui (529ha). Compared to the majority of NZ's tidal lagoon estuaries which tend to drain almost completely at low tide, the harbour has a large subtidal component (69%). It is one of the key estuaries in Greater Wellington Regional Council's long-term coastal monitoring programme. The following sections summarise broad scale monitoring results, risk indicator ratings, and monitoring and management recommendations.

BROAD SCALE RESULTS

- Very soft mud was the most dominant subtidal feature in the estuary comprising 59% of the substrate (64% of the Pauatahanui Arm and 51% of the Onepoto Arm).
- Very soft muds were located almost exclusively within the relatively shallow (1-2m deep) settling basins in the upper reaches of both arms, and had a very high mud content (mean 62%, median 82%, and often >80%). The sediment risk indicator (percent mud) was consistently "very high" within the subtidal settling basins, indicating a likely low diversity of sediment-dwelling invertebrates.
- A band of soft muddy sands was consistently found in shallower water (0.5-1.0m deep), before a relatively sharp transition into firm muddy sands near the intertidal margin (0-0.5m below MLWS).
- The remaining subtidal area (228ha, 41%) was sand-dominated (mean mud content <10%, sediment risk indicator (percent mud) "low" to "moderate"), with a trend of decreasing mud from the upper estuary to the harbour entrance.
- Channel areas were well flushed and comprised stable consolidated sandy sediment, often armoured with shell. Marine sands created relatively shallow, but firm stable bars and tidal sand flats towards the harbour entrance.
- No subtidal areas were found exhibiting gross eutrophic conditions or nuisance macroalgae growth, and the eutrophication risk indicators TOC and RPD depth were generally "low" to "moderate".
- The only significant submerged aquatic vegetation present was seagrass which covered 18ha, (3.3%) of the subtidal area. Subtidal seagrass was located primarily in the well flushed mid-lower estuary reaches, was only present in sand dominated sediments, and was not found deeper than 0.25m below spring tide low water level.

ESTUARY CONDITION AND ISSUES

In relation to the key issues addressed by the broad scale subtidal monitoring (i.e. excessive muddiness, eutrophication and high value habitat loss), the 2014 broad scale mapping results (extensive soft mud, poor water clarity, restricted seagrass cover, but no significant subtidal eutrophication symptoms) showed that fine muddy sediment was the primary subtidal stressor within the harbour.

Although large sections of the subtidal estuary were sand dominated, the majority was excessively muddy with likely ecological consequences of reduced biodiversity and seagrass loss.

RECOMMENDED MONITORING AND MANAGEMENT

Sediment muddiness and infilling and, to a lesser extent, nutrient enrichment, have been identified as key issues in Porirua Harbour. To monitor these issues it is recommended that broad scale habitat mapping be repeated every 5 years (next due in 2018). Fine scale monitoring is also recommended on a 5 yearly cycle (next due in 2015), following review and optimisation of the programme within a 'whole of estuary' (intertidal and subtidal) approach. It is recommended that sediment (grain size, oxygenation and sedimentation rate) and macroalgal monitoring continue annually, and that specific fine scale seagrass monitoring be established.

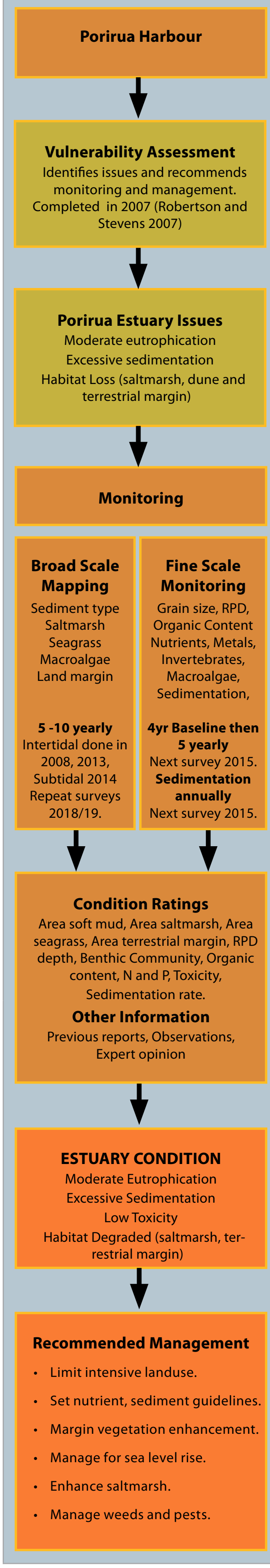
For management, interim and long term sediment targets have been approved by the joint councils (Porirua City Council, Wellington City Council and Greater Wellington Regional Council), Te Runanga Toa Rangatira and other key agencies with interests in Porirua Harbour and catchment, as follows:

- Interim – Reduce sediment inputs from tributary streams by 50% by 2021.
- Long-term – Reduce sediment accumulation rate in the harbour to 1mm per year by 2031 (averaged over whole harbour).

Strategies to determine the best options for managing sediment within the catchment are currently being developed.

Although eutrophication is not a major issue in the harbour, the estuary is currently showing symptoms of moderate enrichment. To ensure a shift to a eutrophic state does not occur it is recommended that upper trigger limits for nutrient loads to the estuary be established, and the current catchment nutrient loads be estimated (note this has already been done for sediment). If catchment loads exceed the estuary's guidelines then it is recommended that sources of elevated loads in the catchment be identified, and measures taken to ensure trigger limits are met.

1. INTRODUCTION



Developing an understanding of the condition and risks to coastal and estuarine habitats is critical to the management of biological resources. In 2007, Greater Wellington Regional Council (GWRC) identified a number of estuaries in its region as immediate priorities for long term monitoring and initiated monitoring of key estuaries in a staged manner. The estuaries currently monitored include; Porirua Harbour, Lake Onoke, and Whareama, Hutt and Waikanae estuaries. Risk assessments have also been undertaken to establish management priorities for a number of other estuaries.

The monitoring and management process used for Porirua Harbour is summarised in the margin flow diagram, and is described below. It consists of three components developed from the National Estuary Monitoring Protocol (NEMP) (Robertson et al. 2002):

1. **Ecological Vulnerability Assessment** (EVA) of the estuary to major issues (see Table 1) and appropriate monitoring design. This component has been completed for Porirua Harbour and is reported on in Robertson and Stevens (2007).

2. **Broad Scale Habitat Mapping** (NEMP approach). This component (see Table 1) documents the key habitats within the estuary, and changes to these habitats over time. Broad scale intertidal mapping of Porirua Harbour was first undertaken in 2008 and repeated in 2013 (Stevens and Robertson 2008, 2013), with annual mapping of intertidal macroalgal cover undertaken since 2008 (see Stevens and Robertson 2014). The current report specifically addresses the large (69%) subtidal component of the harbour through detailed broad scale subtidal habitat mapping and sediment characterisation undertaken in the summer of 2013/14.

3. **Fine Scale Monitoring** (NEMP approach). Monitoring of physical, chemical and biological indicators (see Table 1). This component, comprising an initial 3 year baseline of detailed information on the condition of Porirua Harbour, commenced in 2008 and is reported on in Robertson and Stevens 2008, 2009, 2010. Sedimentation rates in the estuary have been monitored annually in the Harbour since 2008 (see Stevens and Robertson 2014, Figure 1).

The current report describes work undertaken in January 2014 to establish a baseline of dominant habitat types, and broad scale sediment quality in subtidal areas:

- Broad scale mapping of subtidal estuary sediment types.
- Broad scale assessment of sediment condition (e.g. oxygenation, organic content, mud content)
- Broad scale mapping of subtidal macroalgal beds (i.e. *Ulva* (sea lettuce), *Gracilaria*).
- Broad scale mapping of subtidal seagrass (*Zostera muelleri*) beds.

Porirua Harbour (Figure 1), is a large (809ha), well flushed "tidal lagoon" type estuary fed by a number of small streams. It comprises two arms, each a relatively simple shape, Onepoto (280ha) and Pauatahanui (529ha). The arms are connected by a narrow channel at Paremata, and the estuary discharges to the sea via a narrow entrance west of Plimmerton. The estuary is relatively shallow (mean depth ~1m - see Figure 2), and compared to the majority of NZ's tidal lagoon estuaries, which tend to drain almost completely at low tide, the harbour has a large subtidal component (69%). Residence time in the estuary is less than 3 days.

Gibb and Cox (2009) identified sedimentation as a major problem in the estuary, with subtidal basins being primary sediment settling areas and containing very muddy sediments sourced primarily from catchment (as opposed to marine) sources. Gibb and Cox (2009) predict that the estuary is highly likely to infill and change from a tidal estuary to brackish swamp within 145-195 years (Pauatahanui), and 290-390 years (Onepoto). The dominant sources contributing to increasing sedimentation rates in the estuary were identified as discharges of both bedload and suspended load from the various input streams.

The harbour has been extensively modified over the years, particularly the Onepoto Inlet where almost all of the historical shoreline and saltmarsh have been reclaimed and most of the inlet is now lined with steep straight rockwalls flanked by road and rail corridors. The Pauatahanui Inlet is less modified (although most of the inlet's margins are also encircled by roads), with extensive areas of saltmarsh remaining in the north and east, a large percentage of which have been improved through local community efforts.

The remaining saltmarsh areas are ecologically important, as are the relatively extensive areas (59ha) of seagrass growing mostly in sand-dominated intertidal areas. The estuary overall has high ecological values and high human use, and provides a natural focal point for the thousands of people that live near or visit its shores.

Table 1. Summary of the major environmental issues affecting most New Zealand estuaries.

1. Sedimentation

Because estuaries are a sink for sediments, their natural cycle is to slowly infill with fine muds and clays (Black et al. 2013). Prior to European settlement they were dominated by sandy sediments and had low sedimentation rates (<1 mm/year). In the last 150 years, with catchment clearance, wetland drainage, and land development for agriculture and settlements, New Zealand's estuaries have begun to infill rapidly with fine sediments. Today, average sedimentation rates in our estuaries are typically 10 times or more higher than before humans arrived (e.g. see Abrahim 2005, Gibb and Cox 2009, Robertson and Stevens 2007, 2010, and Swales and Hume 1995). Soil erosion and sedimentation can also contribute to turbid conditions and poor water quality, particularly in shallow, wind-exposed estuaries where re-suspension is common. These changes to water and sediment result in negative impacts to estuarine ecology that are difficult to reverse. They include;

- habitat loss such as the infilling of saltmarsh and tidal flats,
- prevention of sunlight from reaching aquatic vegetation such as seagrass meadows,
- increased toxicity and eutrophication by binding toxic contaminants (e.g. heavy metals and hydrocarbons) and nutrients,
- a shift towards mud-tolerant benthic organisms which often means a loss of sensitive shellfish (e.g. pipi) and other filter feeders; and
- making the water unappealing to swimmers.

Recommended Key Indicators:

Issue	Recommended Indicators	Method
Sedimentation	Soft Mud Area	GIS Based Broad scale mapping - estimates the area and change in soft mud habitat over time.
	Seagrass Area/biomass	GIS Based Broad scale mapping - estimates the area and change in seagrass habitat over time.
	Saltmarsh Area	GIS Based Broad scale mapping - estimates the area and change in saltmarsh habitat over time.
	Mud Content	Grain size - estimates the % mud content of sediment.
	Water Clarity/Turbidity	Secchi disc water clarity or turbidity.
	Sediment Toxicants	Sediment heavy metal concentrations (see toxicity section).
	Sedimentation Rate	Fine scale measurement of sediment infilling rate (e.g. using sediment plates).
	Biodiversity of Bottom Dwelling Animals	Type and number of animals living in the upper 15cm of sediments (infauna in 0.0133m^2 replicate cores), and on the sediment surface (epifauna in 0.25m^2 replicate quadrats).

2. Eutrophication

Eutrophication is a process that adversely affects the high value biological components of an estuary, in particular through the increased growth, primary production and biomass of phytoplankton, macroalgae (or both); loss of seagrass, changes in the balance of organisms; and water quality degradation. The consequences of eutrophication are undesirable if they appreciably degrade ecosystem health and/or the sustainable provision of goods and services (Ferriera et al. 2011). Susceptibility of an estuary to eutrophication is controlled by factors related to hydrodynamics, physical conditions and biological processes (National Research Council, 2000) and hence is generally estuary-type specific. However, the general consensus is that, subject to available light, excessive nutrient input causes growth and accumulation of opportunistic fast growing primary producers (i.e. phytoplankton and opportunistic red or green macroalgae and/or epiphytes - Painting et al. 2007). In nutrient-rich estuaries, the relative abundance of each of these primary producer groups is largely dependent on flushing, proximity to the nutrient source, and light availability. Notably, phytoplankton blooms are generally not a major problem in well flushed estuaries (Valiela et al. 1997), and hence are not common in the majority of NZ estuaries. Of greater concern are the mass blooms of green and red macroalgae, mainly of the genera *Cladophora, Ulva,* and *Gracilaria* which are now widespread on intertidal flats and shallow subtidal areas of nutrient-enriched New Zealand estuaries. They present a significant nuisance problem, especially when loose mats accumulate on shorelines and decompose, both within the estuary and adjacent coastal areas. Blooms also have major ecological impacts on water and sediment quality (e.g. reduced clarity, physical smothering, lack of oxygen), affecting or displacing the animals that live there (Anderson et al. 2002, Valiela et al. 1997).

Recommended Key Indicators:

Issue	Recommended Indicators	Method
Eutrophication	Macroalgal Cover	Broad scale mapping - macroalgal cover/biomass over time.
	Phytoplankton (water column)	Chlorophyll a concentration (water column).
	Sediment Organic and Nutrient Enrichment	Chemical analysis of sediment total nitrogen, total phosphorus, and total organic carbon concentrations.
	Water Column Nutrients	Chemical analysis of various forms of N and P (water column).
	Redox Profile	Redox potential discontinuity profile (RPD) using visual method (i.e. apparent Redox Potenial Depth - aRPD) and/or redox probe. Note: Total Sulphur is also currently under trial.
	Biodiversity of Bottom Dwelling Animals	Type and number of animals living in the upper 15cm of sediments (infauna in 0.0133m^2 replicate cores), and on the sediment surface (epifauna in 0.25m^2 replicate quadrats).

Table 1. Summary of major environmental issues affecting New Zealand estuaries (continued).

3. Disease Risk

Runoff from farmland and human wastewater often carries a variety of disease-causing organisms or pathogens (including viruses, bacteria and protozoans) that, once discharged into the estuarine environment, can survive for some time (e.g. Stewart et al. 2008). Every time humans come into contact with seawater that has been contaminated with human and animal faeces, we expose ourselves to these organisms and risk getting sick. Human diseases linked to such organisms include gastroenteritis, salmonellosis and hepatitis A (Wade et al. 2003). Aside from serious health risks posed to humans through recreational contact and shellfish consumption, pathogen contamination can also cause economic losses due to closed commercial shellfish beds.

Recommended Key Indicators:

Issue	Recommended Indicators	Method
Disease Risk	Shellfish and Bathing Water faecal coliforms, viruses, protozoa etc.	Bathing water and shellfish disease risk monitoring (Council or industry driven).

4. Toxic Contamination

In the last 60 years, NZ has seen a huge range of synthetic chemicals introduced to the coastal environment through urban and agricultural stormwater runoff, groundwater contamination, industrial discharges, oil spills, antifouling agents, leaching from boat hulls, and air pollution. Many of them are toxic even in minute concentrations, and of particular concern are polycyclic aromatic hydrocarbons (PAHs), heavy metals, polychlorinated biphenyls (PCBs), and pesticides. When they enter estuaries these chemicals collect in sediments and bio-accumulate in fish and shellfish, causing health risks to marine life and humans. In addition, natural toxins can be released by macroalgae and phytoplankton, often causing mass closures of shellfish beds, potentially hindering the supply of food resources, as well as introducing economic implications for people depending on various shellfish stocks for their income. For example, in 1993, a nationwide closure of shellfish harvesting was instigated in NZ after 180 cases of human illness following the consumption of various shellfish contaminated by a toxic dinoflagellate, which also lead to wide-spread fish and shellfish deaths (de Salas et al. 2005). Decay of organic matter in estuaries (e.g. macroalgal blooms) can also cause the production of sulphides and ammonia at concentrations exceeding ecotoxicity thresholds.

Recommended Key Indicators:

Issue	Recommended Indicators	Method
Toxins	Sediment Contaminants	Chemical analysis of heavy metals (total recoverable cadmium, chromium, copper, nickel, lead and zinc) and any other suspected contaminants in sediment samples.
	Biota Contaminants	Chemical analysis of suspected contaminants in body of at-risk biota (e.g. fish, shellfish).
	Biodiversity of Bottom Dwelling Animals	Type and number of animals living in the upper 15cm of sediments (infauna in 0.0133m^2 replicate cores), and on the sediment surface (epifauna in 0.25m^2 replicate quadrats).

5. Habitat Loss

Estuaries have many different types of high value habitats including shellfish beds, seagrass meadows, saltmarshes (rushlands, herbfields, reedlands etc.), tidal flats, forested wetlands, beaches, river deltas, and rocky shores. The continued health and biodiversity of estuarine systems depends on the maintenance of high-quality habitat. Loss of such habitat negatively affects fisheries, animal populations, filtering of water pollutants, and the ability of shorelines to resist storm-related erosion. Within New Zealand, habitat degradation or loss is common-place with the major causes being sea level rise, population pressures on margins, dredging, drainage, reclamation, pest and weed invasion, reduced flows (damming and irrigation), over-fishing, polluted runoff, and wastewater discharges (IPCC 2007 and 2013, Kennish 2002).

Recommended Key Indicators:

Issue	Recommended Indicators	Method
Habitat Loss	Saltmarsh Area	Broad scale mapping - estimates the area and change in saltmarsh habitat over time.
	Seagrass Area	Broad scale mapping - estimates the area and change in seagrass habitat over time.
	Vegetated Terrestrial Buffer	Broad scale mapping - estimates the area and change in buffer habitat over time.
	Shellfish Area	Broad scale mapping - estimates the area and change in shellfish habitat over time.
	Unvegetated Habitat Area	Broad scale mapping - estimates the area and change in unvegetated habitat over time, broken down into the different substrate types.
	Sea level	Measure sea level change.
	Others e.g. Freshwater Inflows, Fish Surveys, Floodgates, Wastewater Discharges	Various survey types.

1. INTRODUCTION (CONTINUED)

Figure 1. Porirua Harbour showing the boundary of the subtidal area mapped in January 2014.

Pauatahanui Inlet - view south towards Browns Bay at low tide highlighting the extensive subtidal extent of the harbour

1. Introduction (continued)

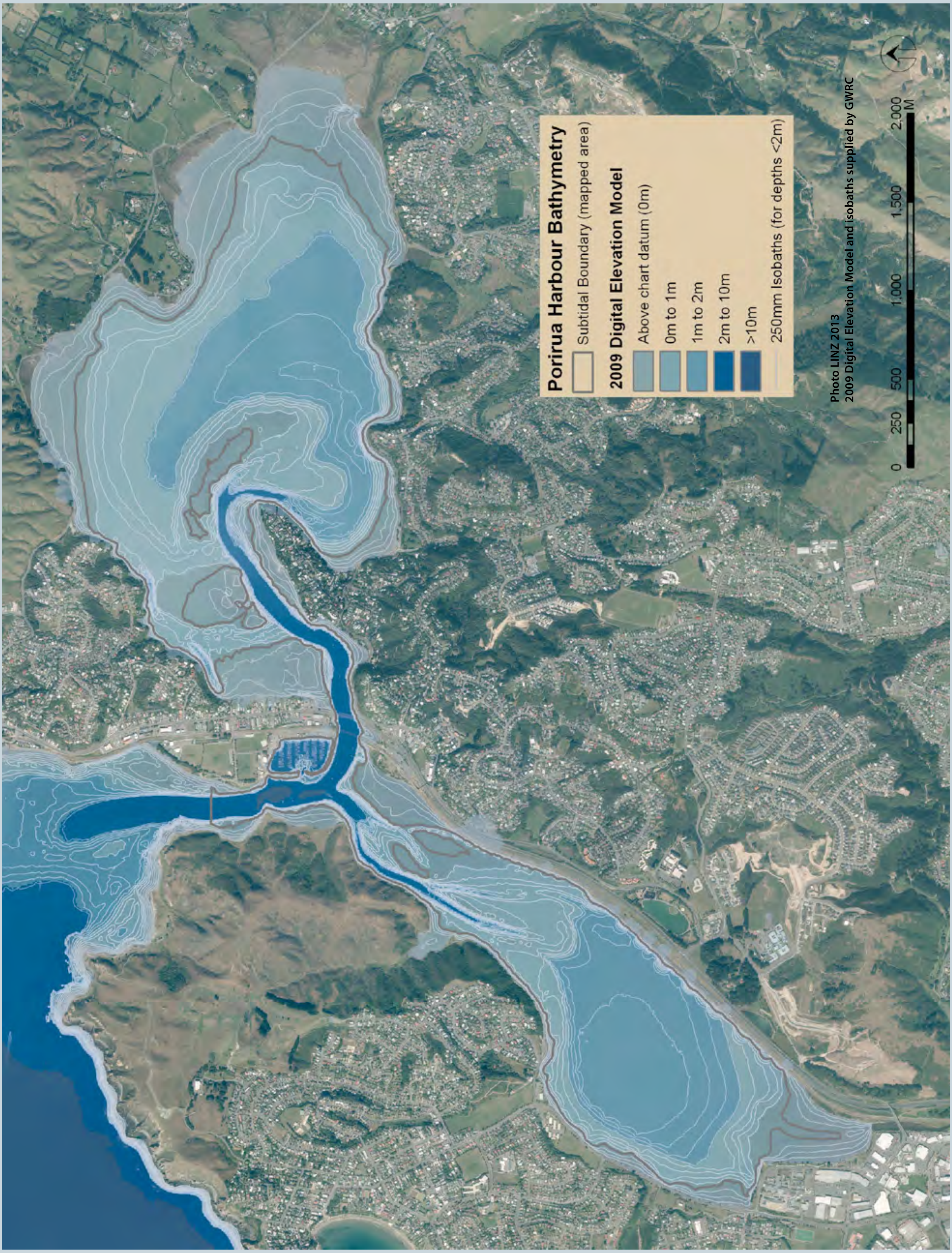
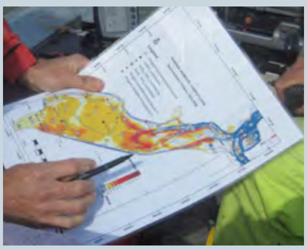


Figure 2. Map of Porirua Harbour bathymetry.

2. METHODS



The primary aims of the subtidal habitat assessment of Porirua Harbour were to:

i. define the type and location of dominant substrate types (e.g. mud, sand, shell, cobble, rock), and submerged aquatic vegetation - SAV (e.g. macrophyte (*Zostera* seagrass), macroalgae (*Ulva, Gracilaria*).

ii. assess the broad scale condition of identified habitats in relation to the key stressors of sediment muddiness and trophic status (eutrophication).

The methods used were based directly on those described in the NEMP (Robertson et al. 2002). Dominant features below Mean Low Water Springs (MLWS)[1] were assessed throughout the estuary by either wading, snorkelling, or sampling from a dinghy or canoe using a range of remote sampling and recording techniques successfully used previously to map underwater features in shallow coastal lakes (e.g. Robertson and Stevens 2013). The techniques used were as follows:

- **Substrate/SAV Sampler.** A purpose built sediment sampler mounted on the end of a telescopic 4-5m pole was the primary method used to sample benthic substrate. The sampler has a 20cm square flat bottom, two 20cm high enclosed sides, and a supported open back. The front section, which digs into the sediments, is pointed to assist in collecting deep samples. The sampler is painted black and white, and the pole graduated, to enable Secchi depth to be determined. A separate rake attachment was used to assess or collect SAV.
- **Bathyscope.** A 48cm high cone-shaped bathyscope with an 11.5cm open-ended viewing hole at the top, and a 31cm diameter clear perspex bottom, was used to quickly view substrate or SAV in shallow water.
- **Underwater Videography.** In deeper water (>4m) a portable lightweight 420TVL CCD underwater camera with attached surface monitor was used to assess sediment type and SAV. The camera has a 30m cable, built-in LED lighting (~5m illumination in pitch black), and adjustable ballast tilt control. It provides clear underwater video images in real time, even under turbid or low light conditions (e.g. Secchi depths <0.5m). The camera, angled slightly downwards, was deployed on a cable (supported by a pole where necessary) until the bed sediments and/or SAV came into focus on the viewer.
- **Depth Sounder.** A Garmin Fishfinder 90 dual-beam transducer, which provides excellent shallow-water performance, was used to track estuary depth and identify changes in subsurface features including the presence of SAV.
- **Ipad/field sheets.** The "iGIS HD" field app. provided live tracking (via an inbuilt GPS accurate to ~5m) to locate designated sampling sites, log positions, and show GIS layers of bathymetry and aerial photos while field sampling. Laminated colour aerial photos (LINZ ~0.3m/pixel resolution photos flown between Dec 2012/Jan 2013), and maps of sedimentation patterns (prepared by Gibb and Cox 2009) were also used to directly record hard copy notes on.
- **Georeferenced field photos.** Field photos were georeferenced using GPS-Photolink software and exported to ARCmap 9.3 to provide a photographic record of sampling data.

[1] For GIS mapping purposes the MLWS subtidal boundary (Figure 2) was defined as the -0.5m isobath (depth contour) of the 2009 bathymetry supplied by GWRC. This isobath provided a consistent depth marker and appeared to best represent field observations of the average MLWS level throughout the Harbour. Based on the chart datum and tidal ranges presented in Gibb and Cox (2009), the mapped boundary is approximately 9cm above MLWS.

An arbitrary seaward boundary ~500m north of the Mana marina entrance was also ascribed, with the transitional waters of the estuary plume seaward of this point addressed elsewhere through broad coastal risk assessments (e.g. Robertson and Stevens 2007). The subtidal boundary closely matched that of the recent broad scale intertidal habitat mapping (Stevens and Robertson 2013), although was adjusted slightly using the detailed bathymetry provided by GWRC.

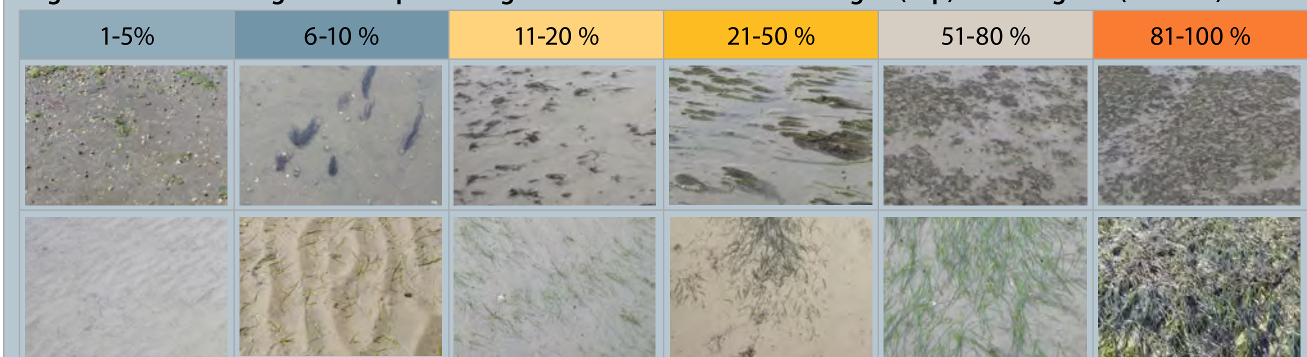
The assessment and mapping approach was to start sampling from the shoreline, checking the substrate at regular intervals while moving steadily out towards deeper central basin areas. Sampling effort was concentrated in areas where existing knowledge was sparse, or sediment accumulation or degradation was predicted to be greatest, with emphasis placed on delineating, characterising, and systematically mapping boundaries between sediment types, and any SAV. This was done primarily by using the substrate sampler to carefully dig and bring to the surface a 10-15cm deep layer of sediment where it could be visually assessed. Representative photographs were taken, and the sediment type, the depth to any blackened sulphide rich layer (apparent Redox Potential Discontinuity layer - aRPD), and any SAV (taxa, height, percentage cover) was recorded as summary information. Appendix 1 lists the definitions used to classify substrate and vegetation, while the density of any macroalgae or seagrass was assessed using a 6 category percent cover rating scale (see Figure 3 below).

Broad scale habitat maps of the dominant subtidal substrate, and the location of any submerged SAV e.g. macroalgae (e.g. *Ulva, Gracilaria*) and seagrass (*Zostera*) beds, were prepared and digitised into ArcMap 9.3 shapefiles using a Wacom Cintiq21UX. These broad scale results are summarised in Section 4

In addition, to assess the broad scale condition of identified habitats, 57 sediment samples were also collected for chemical analysis (Figure 4, Appendix 3). A preliminary stratified sampling plan was developed before commencing fieldwork to ensure sampling captured a range of depths, predicted sediment types, and sediment conditions. The sampling plan was based on bathymetry, maps of sedimentation patterns (prepared by Gibb and Cox 2009), and available mud content data (e.g. Stevens and Robertson 2013, DeLuca 2011, GWRC 2008). The sampling plan was finalised in the field based on the broad scale ground-truthing results. At each selected station (Figure 4), a single composite sample of the top 20mm of sediment was collected for grain size, total organic carbon (TOC), and total sulphur (TS) analyses. Analyses were undertaken by Hill Laboratories using the methods described in Appendix 2. Results of chemical analyses have been overlain onto substrate maps for ease of interpretation in Section 4.

The supporting GIS files are supplied on a CD for easy spatial interrogation to address specific monitoring and management questions.

Figure 3. Visual rating scale for percentage cover estimates of macroalgae (top) and seagrass (bottom).



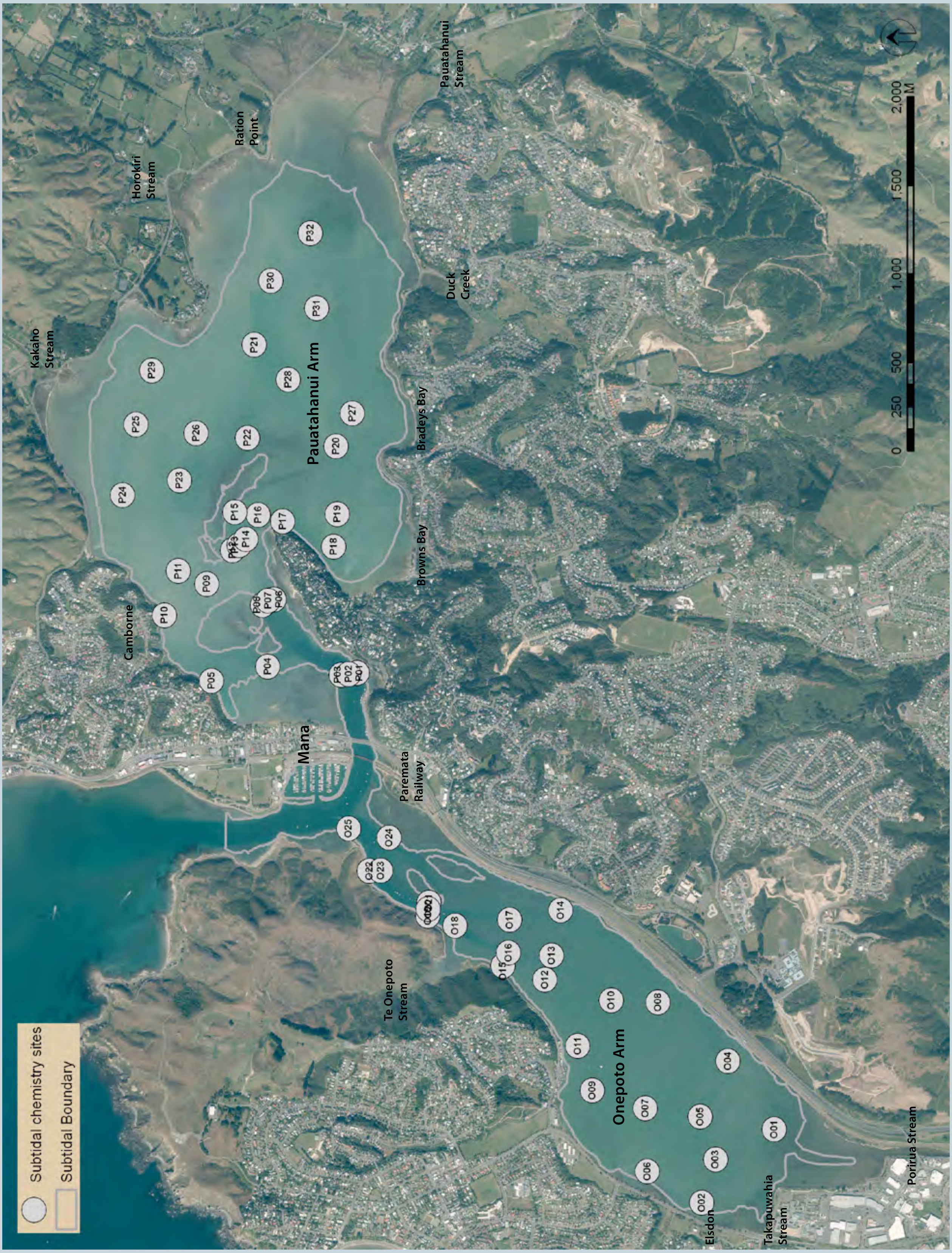


Figure 4. Map of broad scale sediment condition chemistry sampling sites - Porirua Harbour, Jan. 2014.

3. RISK INDICATOR RATINGS

The sampling approach adopted follows that of the National Estuary Monitoring Protocol (NEMP, Robertson et al. 2002), and subsequent additions (e.g. Robertson and Stevens 2006, 2012), which recommend a defensible, cost-effective monitoring design for assessing the long term condition of shallow, tidally-dominated, NZ estuarine systems. The design is based on the use of indicators that have a documented strong relationship with water or sediment quality, and is intended to help quickly identify the likely presence of the predominant issues affecting NZ estuaries (i.e. eutrophication, sedimentation, disease risk, toxicity and habitat change).

In order to facilitate this assessment process, "risk indicator ratings" that assign a relative level of risk (e.g. very low, low, moderate, high, very high) of specific indicators adversely affecting intertidal estuary condition have been proposed (e.g. Robertson and Stevens 2014). Although no broad scale subtidal risk ratings have been developed to date, the risk ratings developed for intertidal fine scale indicators that are also applicable to subtidal areas are summarised in Table 2 below.

Each risk indicator rating is designed to be used in combination with relevant information and other risk indicator ratings, and under expert guidance, to help assess overall estuary condition in relation to key issues. When interpreting risk indicator results we emphasise:

- The importance of taking into account other relevant information and/or indicator results before making management decisions regarding the presence or significance of any estuary issue.
- That rating and ranking systems can easily mask or oversimplify results. For instance, large changes can occur within a risk category, but small changes near the edge of one risk category may shift the rating to the next risk level.
- Most issues will have a mix of primary and secondary ratings, primary ratings being given more weight in assessing the significance of indicator results.
- Ratings for most indicators have not been established using statistical measures, primarily because of the extensive additional work and cost this requires. In the absence of funding, professional judgment, based on our wide experience from monitoring >300 NZ estuaries, has been used in making initial interpretations. Our hope is that where a high level of risk is identified, the following steps are taken:
    1. Statistical measures be used to refine indicators and guide monitoring and management for priority issues.
    2. Issues identified as having a high likelihood of causing a significant change in ecological condition (either positive or negative), trigger intensive, targeted investigations to appropriately characterise the extent of the issue.
    3. The outputs stimulate discussion regarding what an acceptable level of risk is, and how it should best be managed.

The indicators and risk ratings relevant to the Porirua Harbour subtidal monitoring programme are summarised in Table 2 below, and described more fully in Appendix 4:

Table 2. Interim risk indicator ratings for Porirua Harbour.

INDICATOR	RISK RATING				
	Very Low	Low	Moderate	High	Very High
Sediment Mud Content[1]	<2%	2-5%	>5-15%	>15-25%	>25%
Apparent Redox Potential Discontinuity (aRPD)[2]	>10cm depth below surface	3-10cm depth below sediment surface	1-<3cm depth below sediment surface	0-<1cm depth below sediment surface	Anoxic conditions at surface
Total Organic Carbon (TOC)[3]	<0.5%	0.5-<1%	1-<2%	2-<3.5%	>3.5%

NOTES: [1]**Sediment Mud Content:** In their natural state, most NZ estuaries would have been dominated by sandy or shelly substrates. Fine sediment is likely to cause detrimental and difficult to reverse changes in community composition (Robertson 2013), can facilitate the establishment of invasive species, increase turbidity (from re-suspension), and reduce amenity values. High or increasing mud content can indicate where changes in land use management may be needed.

[2]**Redox Potential Discontinuity (RPD):** RPD depth, the transition between oxygenated sediments near the surface and deeper anoxic sediments, is a primary estuary condition indicator as it is a direct measure of whether nutrient and organic enrichment exceeds levels causing nuisance (anoxic) conditions. Knowing if the RPD close to the surface is important for two main reasons:

1. As the RPD layer gets close to the surface, a "tipping point" is reached where the pool of sediment nutrients (which can be large), suddenly becomes available to fuel algal blooms and to worsen sediment conditions.
2. Anoxic sediments contain toxic sulphides and support very little aquatic life.

In sandy porous sediments, the RPD layer is usually relatively deep (>3cm) and is maintained primarily by current or wave action that pumps oxygenated water into the sediments. In finer silt/clay sediments, physical diffusion limits oxygen penetration to <1cm unless bioturbation by infauna oxygenates the sediments. The tendency for sediments to become anoxic is much greater if the sediments are muddy.

[3]**Total Organic Carbon (TOC):** Estuaries with high sediment organic content can result in anoxic sediments and bottom water, release of excessive nutrients, and adverse impacts to biota - all symptoms of eutrophication.

4. RESULTS AND DISCUSSION

SEDIMENT CHARACTER

The results of the January 2014 broad scale subtidal habitat assessment of Porirua Harbour are presented below. Table 3 summarises the total estuary area and highlights the extensive subtidal component of the estuary (556ha, 69%), particularly within the Onepoto Arm which has suffered from extensive losses of historical saltmarsh and intertidal flats through reclamation and drainage.

Table 3. Summary of dominant broad scale features in Porirua Harbour.

Dominant Estuary Feature	Pauatahanui Arm		Onepoto Arm		Entire Estuary	
	Ha	%	Ha	%	Ha	%
Saltmarsh	49.7	9.4%	0.7	0.3%	50.4	6%
Intertidal flats	143.9	27.2%	58.1	20.8%	202.0	25%
Subtidal	335.4	63.4%	221.0	79.0%	556.4	69%
TOTAL	529	100%	280	100%	809	100%

Within the subtidal part of the estuary, no areas were found exhibiting gross eutrophic conditions or nuisance macroalgae growth. The only significant SAV present was seagrass located in the well flushed mid-lower estuary (discussed further on page 16).

The dominant subtidal substrate types present within Porirua Harbour are summarised in Figure 5 and Table 4, with the two arms of the estuary showing a very similar substrate composition. Very soft mud was the most dominant feature in the estuary comprising 59% of the subtidal habitat (64% of the Pauatahanui Arm and 51% of the Onepoto Arm). Very soft muds were located almost exclusively within the relatively shallow (1-2m deep) settling basins in the upper reaches of both arms (Figure 2). Surrounding these muddy basin areas, a narrow band of soft muddy sands was consistently found in shallower water (0.5-1.0m deep), before a relatively sharp transition into firm muddy sands near the intertidal margin (0-0.5m below MLWS).

Further towards the estuary entrance in both arms, deposits of marine derived sands have created relatively shallow, but firm stable bars and tidal sand flats. These areas are well flushed by tidal streams and did not appear to be significant deposition zones for fine muds.

Within the deeper channel areas, and along the steep banks of the intertidal flats, substrate was dominated by firm sands, often armoured with shell. The consolidated sediments in these areas made grab sampling difficult, and the channel bottoms and margins appeared very stable. Substrate became noticeably sandier towards the estuary entrance.

In the upper estuary the rapid transition from soft muds to firm sands closely matched the bathymetry of the harbour and it appeared likely that wave action was a primary influence in sorting sediments in these shallow areas, finer sediments being mobilised through wave action and subsequently settling in deeper basin areas.

Table 4. Summary of dominant subtidal substrate, Porirua Harbour, Jan. 2014.

Estuary Location	Pauatahanui Arm		Onepoto Arm		Entire Estuary	
Dominant substrate Area	Ha	%	Ha	%	Ha	%
firm SAND	2.3	1%	0.0	0%	2.3	0%
firm SAND (shell)	14.2	4%	20.8	9%	35.0	6%
firm muddy SAND	74.7	22%	50.5	23%	125.2	22%
firm muddy SAND (shell)	0.0	0%	4.3	2%	4.3	1%
soft muddy SAND	28.1	8%	32.3	15%	60.4	11%
soft muddy SAND (shell)	0.5	0%	0.0	0%	0.5	0%
very soft MUD	215.5	64%	113.1	51%	328.7	59%
Grand Total	335	100%	221	100%	556	100%

Figure 5. Dominant subtidal substrate types - Porirua Harbour, Jan. 2014.

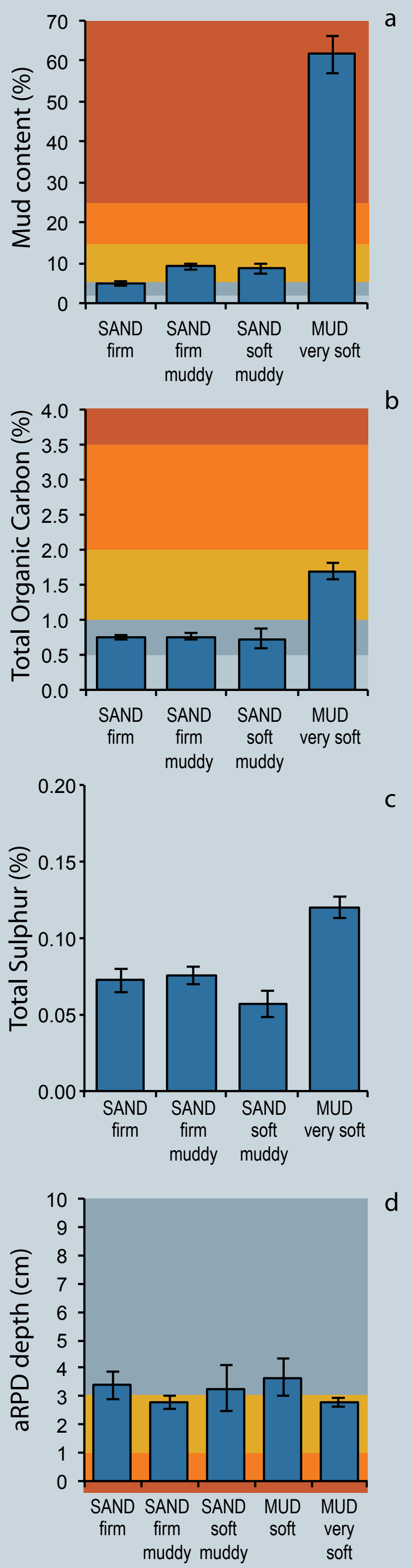


Figure 6. Percent mud, Total Organic Carbon, Total Sulphur, and aRPD depth (mean +-SE) within dominant subtidal substrate types - Porirua Harbour, Jan. 2014.

To characterise the broad scale condition of sediment within the dominant habitat zones, percent mud, percent organic carbon, percent total sulphur, and sediment aRPD depth were measured and assessed using the available "risk indicator ratings" presented in Section 3. Mean results for the dominant habitat types are presented in Figure 6. Figures 7, 8, and 9 show values spatially throughout the estuary for percent mud, percent organic carbon, and sediment aRPD depths. Full results are presented in Appendix 3, and discussed below.

Sediment Mud Content

Sediment mud content (i.e. % grain size <63µm) provides a good indication of the muddiness of a particular site. Estuaries with undeveloped catchments, unless naturally erosion-prone with few wetland filters, are generally sand dominated (i.e. grain size 63µm to 2mm) with very little mud (e.g. ~1% mud at Freshwater Estuary, Stewart Island). In contrast, estuaries draining developed catchments typically have high sediment mud contents (e.g. >25% mud) in the primary sediment settlement areas e.g. where salinity driven flocculation occurs, or in areas that experience low energy tidal currents and waves (i.e. upper estuary intertidal margins and deeper subtidal basins). Well flushed channels or intertidal flats exposed to regular wind-wave disturbance generally have sandy sediments with a relatively low mud content (e.g. 2-10% mud).

This pattern for developed catchments is clearly evident in Porirua Harbour. Figure 7 shows that the muddiest sediments were located within the deeper settling basins, and had an average mud content of 62% (Figure 6a). In the deepest parts of the settling basins the mud content was often >80% (Figure 7). The widespread presence of subtidal soft mud (59% of the subtidal estuary), and the high mud content, indicate a "very high risk" of adverse impacts from the deposition of catchment-derived muds within the settling basin areas.

The types of impacts expected include increased muddiness and turbidity, shallowing, increased nutrients, displacement of seagrass, reduced sediment oxygenation, increased degradation of organic matter by anoxic processes (e.g. sulphide production), and alterations to fish and invertebrate communities (particularly biodiversity). A review of monitoring data from 25 typical NZ estuaries (shallow, short residence time estuaries) (Wriggle database 2009-2014) confirmed a "high" risk of reduced macrobenthic species richness for NZ estuaries when mud values were >25-30% mud and a "very high" risk at >55% (see Appendix 4, Section 1). Also, because contaminants are most commonly associated with finer sediment particles, extensive areas of fine soft muds provide a sink which concentrate catchment contaminants.

Outside of the settlement basins, sand was the dominant component of the sediments with the mud content predominantly <10% (Figures 6a and 7) - "low" to "moderate" risk indicator categories. Figure 6a shows little difference in the mud content of firm and soft muddy sands. Intuitively soft muddy sands would be expected to have a higher mud content than firm muddy sands. The similarity in mud values, but the difference in sediment firmness, is therefore thought to reflect reduced sediment compaction around the shallow (0.5-1.0m deep) edges of the settlement basin margins (where soft muddy sands were primarily located), probably as a consequence of regular wave disturbance in these areas.

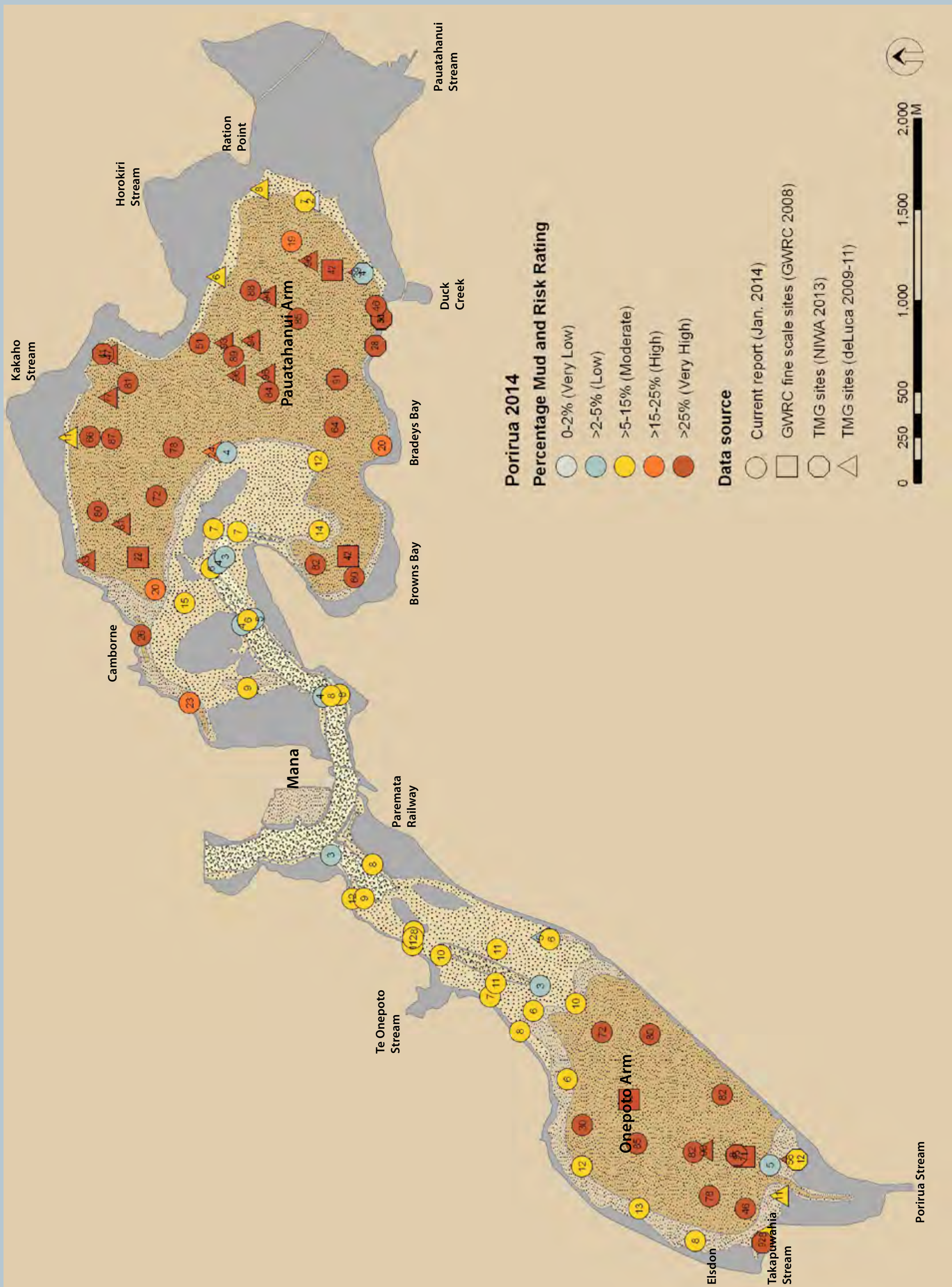


Figure 7. Percentage mud content - Porirua Harbour, Jan. 2014 (and previous studies).

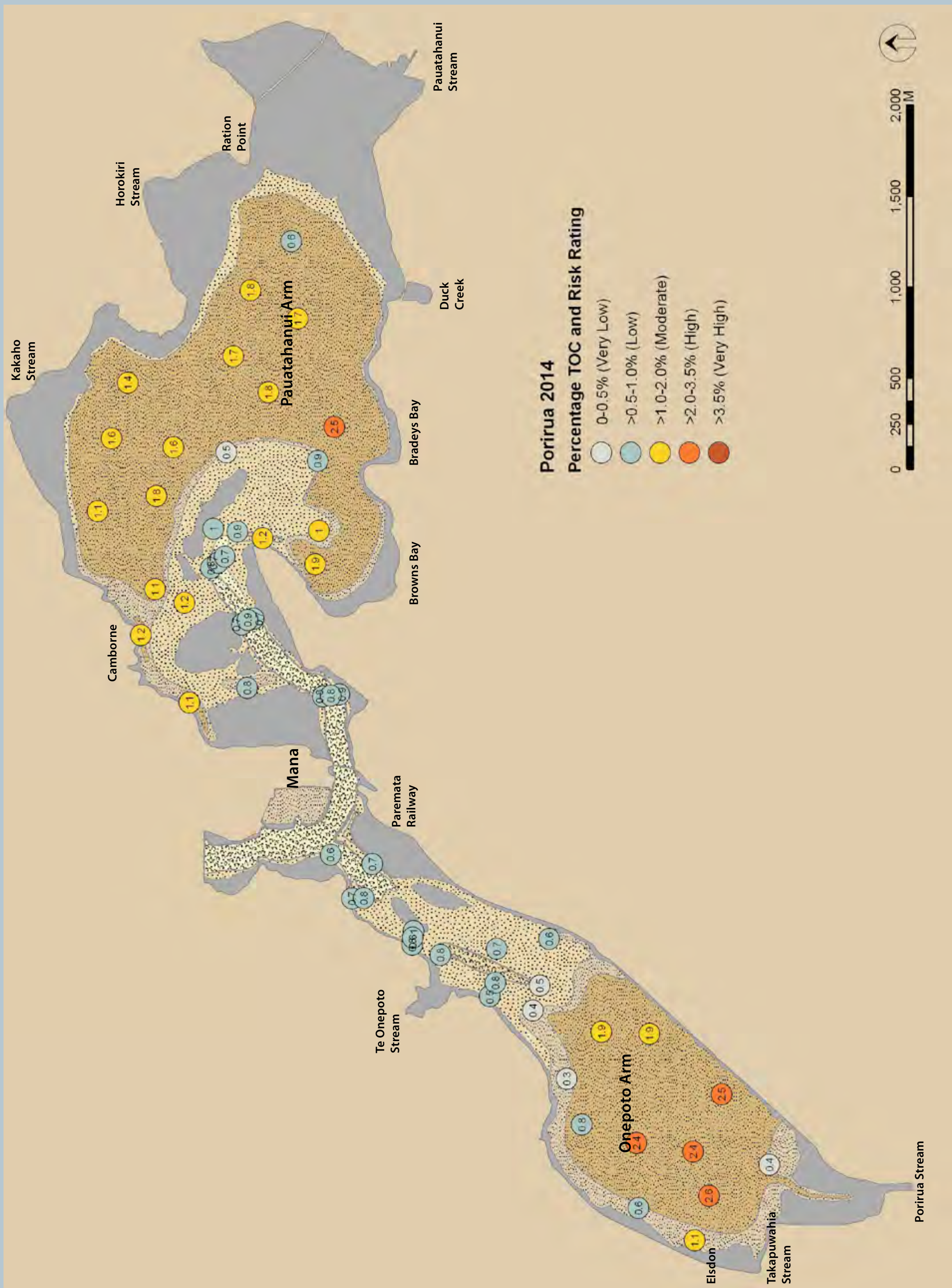


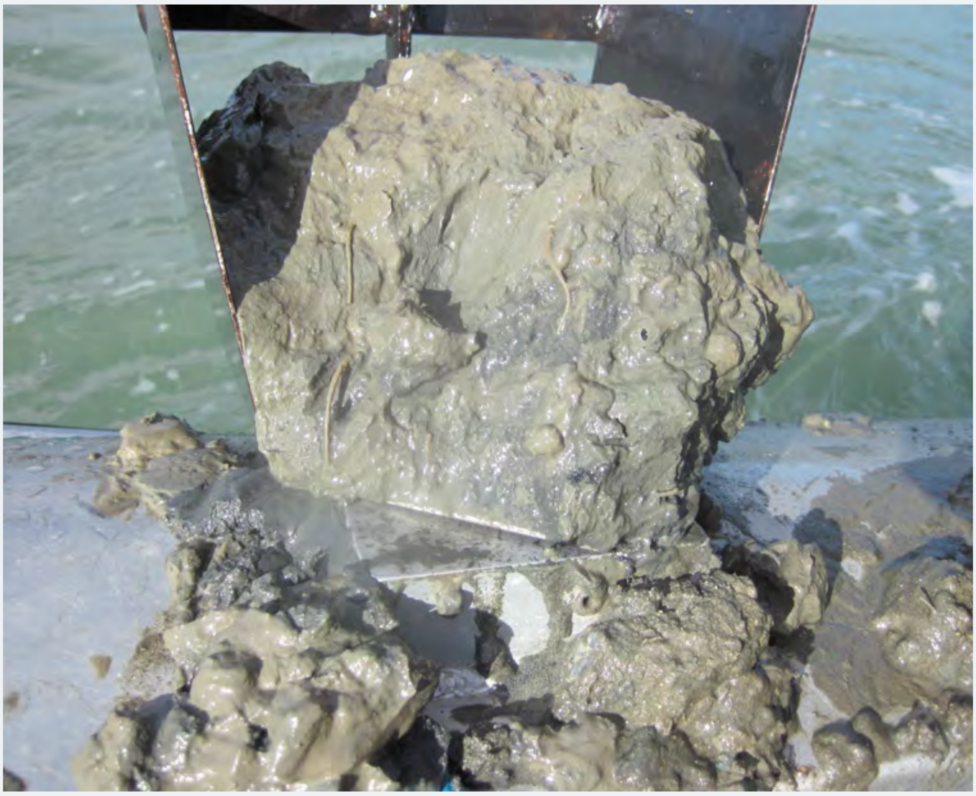
Figure 8. Total Organic Carbon (TOC) percentage - Porirua Harbour, Jan. 2014.

Total Organic Carbon - (TOC)

The concentration of sediment organic matter (commonly measured as TOC) provides valuable broad scale information on trophic state and is therefore a key indicator of symptoms of eutrophication.

High sediment organic content can directly cause adverse bioeffects, primarily by creating sediment and bottom water anoxia, which in turn contributes to the release of excessive nutrients and subsequent impacts on biota though increased nuisance algal growth. TOC can also be an effective screening-level indicator of ecological stress in the benthos caused by other factors such as high levels of ammonia and sulphide, low levels of dissolved oxygen (often associated with the decomposition of organic matter), or the presence of chemical contaminants that co-vary with TOC in relation to a common controlling factor such as sediment particle size. TOC is therefore used alongside other information to determine the extent of its overall influence.

Figure 6b shows that the mean TOC content in the dominant substrate types was lowest in the sand-dominated lower estuary, and highest in the soft muds of the main settling basins, indicating a “low” risk rating for sandy sediments and a “moderate” risk rating for mud dominated sediments. Further, Figure 8 shows that within the mud dominated sediments, the Onepoto Arm had higher TOC values than the Pauatahanui Arm (mean TOC of 2.1% and 1.5% respectively). These values highlight that the most likely subtidal areas to exhibit eutrophication symptoms were the settlement basins. However, their moderate TOC levels, combined with the general absence of other key eutrophication symptoms (e.g. total sulphur concentrations were low (Figure 6c), sediments were well oxygenated (Figure 6d), nuisance macroalgal growth was absent), indicate that the subtidal sediments within Porirua Harbour are currently not exhibiting eutrophic symptoms.



Sediment sample from the central basin of the Onepoto Arm - Jan. 2014 showing soft oxygenated surface muds (3-5cm light brown layer) overlying deeper more enriched and oxygen depleted (grey) muds. Note that the very soft and unconsolidated mud samples generally lost cohesion and collapsed after being removed from the water.

Redox Potential Discontinuity (RPD) and Total Sulphur (TS)

RPD depth and TS content indicate the extent of oxygenation within sediments. RPD depth particularly is a key estuary condition indicator as it is an easily assessed measure of whether sediment enrichment (predominantly nutrient driven) exceeds levels causing nuisance anoxic conditions within surface sediments. The extent of sediment oxygenation is ecologically important as a shallow or rising RPD boundary will force most macrofauna towards the sediment surface to where oxygen is available. In addition, anoxic sediments contain toxic sulphides that support very little aquatic life, and facilitate the release of sediment bound nutrients that can fuel algal blooms and worsen sediment conditions. However, the extent of anoxia (or depression of redox potential, eH) in estuarine sediments varies below the aRPD depth depending on a number of factors. As a consequence, other indicators are required to further assess sediment oxygenation if the aRPD indicates a high/very high risk of ecological impacts. The measurement of redox potential and/or various sulphur fractions are the most common approaches.

In relation to the Porirua Harbour, the aRPD results (Figures 6d and 9) showed that the sediments were generally well to moderately oxygenated (aRPD 1 to >5cm) despite their often muddy nature. The aRPD depths in the muddy basins were generally within “low” to “moderate” risk rating categories in the Onepoto Arm, and “moderate” to “high” in the Pauatahanui Arm. These latter “high” results indicate a need for further investigation of the likely extent of reducing conditions.

Currently, TS is being explored as one of the alternative indicator options. TS provides an integrated measure of sediment oxygenation that is possibly better able to balance out short term and small scale spatial variance in aRPD measures. It achieves this because, in estuarine and marine sediments, TS is mainly composed of reduced forms (Chandran et al. 2012) and reduced sulphur is a proven indicator of redox conditions.

Estuary sediment TS concentrations may therefore be used as a useful sediment oxygenation proxy. Various estuary studies (Chandran et al. 2012, Schartup et al. 2014), have found TS to be <1000 mg/kg in less organically enriched areas (TOC <0.5%) and >5,000mg/kg in more enriched and polluted situations (TOC>2.5%). The validity of these TS thresholds for NZ estuaries is currently being assessed at Otago University. In relation to the Porirua Harbour, the TS results (400-1800 mg/kg) suggest moderate levels of sediment oxygenation (i.e. not strongly reducing conditions) which was supported by the moderate TOC results (0.5-2.5% - Appendix 3). These results provide a preliminary indication that Porirua Harbour sediments were in the “low” to “moderate”, rather than “high” category, for extent of reducing conditions and likely reflect the combined influence of relatively low organic content, and the process of currents or wave action pumping oxygenated water into the sediments. This is greatly facilitated by the shallow water depths and unconsolidated sediments present, particularly in the shallower Onepoto Arm.

Conversely, the low aRPD depths in firm sands in high current areas did not reflect sediment enrichment, but the fact that their consolidated (hard packed) nature limits the physical diffusion of oxygen penetration into the sediments.

Overall, the sand-dominated habitats appeared to be in good (healthy) ecological condition. The muddy habitats had a very high mud content but did not exhibit symptoms of excessive eutrophication. The dominant stressor, and therefore a key management priority, is considered to be excessive fine sediment within the subtidal estuary settling basins.

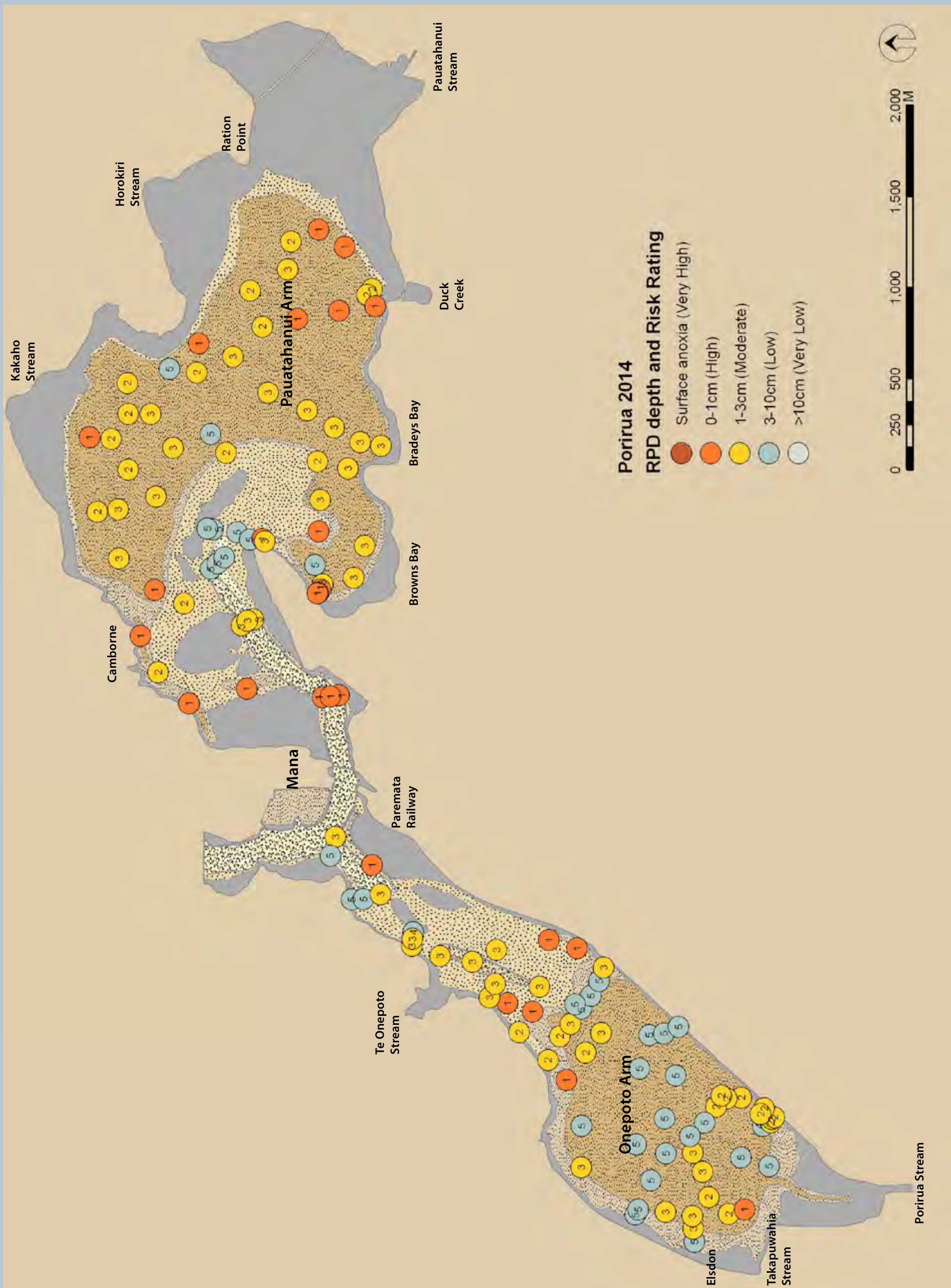


Figure 9. Sediment oxygenation measured as aRPD depth - Porirua Harbour, Jan. 2014.

SEAGRASS

Seagrass (*Zostera muelleri*) was the only significant submerged aquatic vegetation found in the estuary. Seagrass beds are important ecologically because they enhance primary production and nutrient cycling, stabilise and oxygenate sediments, elevate biodiversity, and provide nursery and feeding grounds for a range of invertebrates and fish. Though tolerant of a wide range of conditions, seagrass is vulnerable to excessive nutrients, fine sediments, and sediment quality (particularly if there is a lack of oxygen and the production of toxic sulphide).

Figure 10 shows the location of subtidal seagrass within the harbour (alongside intertidal seagrass beds mapped by Stevens and Robertson 2013), and Table 5 summarises the area of intertidal and subtidal beds. Table 6 summarises subtidal seagrass density, and its extent in relation to the overall subtidal area of the Harbour.

Table 5. Summary of total seagrass cover, Porirua Harbour, Jan. 2014.

TOTAL SEAGRASS	Pauatahanui Arm		Onepoto Arm		Entire Estuary	
	Ha	%	Ha	%	Ha	%
Intertidal	22.2	59.3%5	15.2	83.0%	37.4	67.1%
Subtidal	15.2	40.7%	3.1	17.0%	18.3	32.9%
TOTAL	**37.4**	**100%**	**18.3**	**100%**	**55.7**	**100%**

Key findings were as follows:

- Subtidal seagrass beds covered 4.5% of the Pauatahanui Arm and 1.4% of the Onepoto Arm.
- All subtidal beds were located within 0.25m of MLWS (i.e. less than knee deep at low tide).
- All subtidal beds were adjacent to, and contiguous with, intertidal beds.
- Seagrass was only found in sand dominated sediments (i.e. those with a low mud content).
- The largest and highest density beds were located in well flushed parts of the lower estuary.
- No seagrass was found in the muddy subtidal settling basins.

The presence of seagrass beds only within well flushed, sandy, shallow parts of the estuary, combined with the rapid and easy re-suspension of soft muds, contributing to poor clarity throughout the Harbour, supports mud being the key factor limiting seagrass extent. Natural expansion of seagrass into muddy areas is considered extremely unlikely. Stevens and Robertson (2013) considered documented declines in Porirua Harbour seagrass to be most likely driven by the combined stress of macroalgal smothering (particularly epiphytic growths), the impact of increasing muddiness, contributing to poor water clarity (Secchi disk depth commonly <1m) and, to a lesser extent, associated reductions in sediment oxygenation. The subtidal results emphasise that muddy sediment is currently likely to be the primary stressor to seagrass.

However, Matheson and Wadwha (2012) link seagrass loss primarily to nutrient levels in the harbour that (at times) reach levels known to cause toxicity symptoms in some overseas estuaries. Further investigation is clearly required to determine if elevated nutrient levels (particularly nitrogen species) are contributing to seagrass loss in the harbour.

Table 6. Summary of subtidal seagrass cover, Porirua Harbour, Jan. 2014.

SUBTIDAL SEAGRASS	Pauatahanui Arm		Onepoto Arm		Entire Estuary	
Percentage Cover	Ha	%	Ha	%	Ha	%
No seagrass	320	95.5%	218	98.6%	538	96.7%
>0-10%	0	0.0%	0	0.0%	0	0.0%
11-20%	0.8	0.2%	0.0	0.0%	0.8	0.2%
21-50%	2.0	0.6%	0.4	0.2%	2.4	0.4%
51-80%	0.5	0.1%	2.4	1.1%	2.9	0.5%
>80%	11.9	3.6%	0.3	0.1%	12.2	2.2%
Total	**335**	**100%**	**221**	**100%**	**556**	**100%**

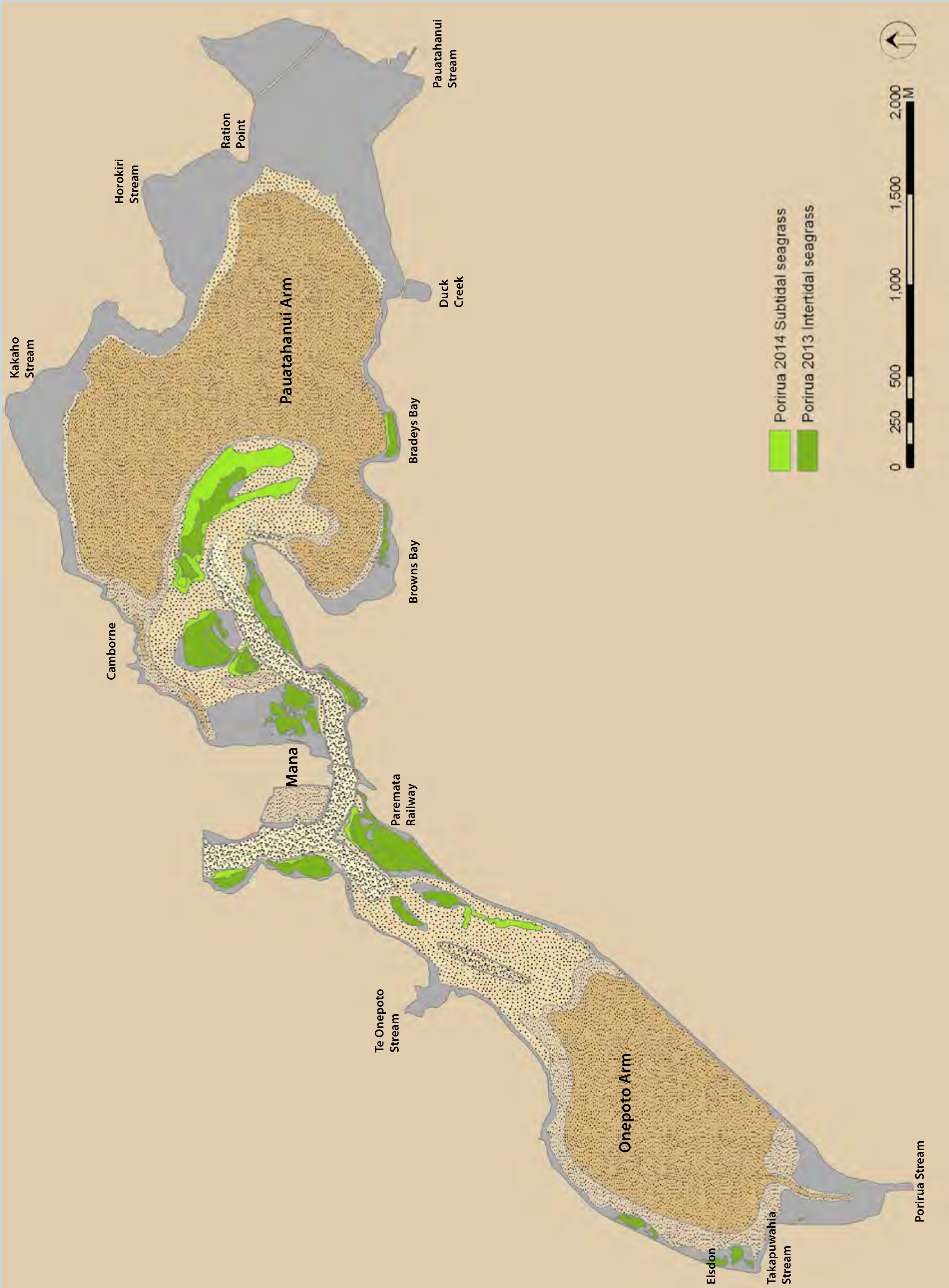


Figure 10. Location of intertidal and subtidal seagrass - Porirua Harbour, Jan. 2014.

5. SUMMARY AND CONCLUSIONS

Porirua Harbour (809ha) is a relatively large, shallow, well flushed, "tidal lagoon" type estuary with an extensive subtidal component (556ha, 69%). Subtidal broad scale mapping showed the dominant subtidal substrate to be very soft muds (329ha, 59%) located primarily in the deeper settlement basins located in the upper parts of both arms. Soft muds within these areas had a very high mud content (mean 62%, and often >80%), and muds were quickly and easily re-suspended, contributing to poor clarity throughout the harbour (e.g. Secchi disk depth <1m).

The remainder of the subtidal area (228ha, 41%) was sand-dominated (mean mud content <10%), with a trend of decreasing mud from the upper estuary to the harbour entrance. Channel areas were well flushed and comprised stable consolidated sediment, often armoured with shell. The sediment risk indicator (percent mud) was consistently "very high" within the subtidal settling basins (indicating a likely low diversity of sediment-dwelling invertebrates and seagrass loss) and "low" to "moderate" elsewhere.

Throughout the estuary, sediment was relatively well oxygenated, had a low total organic carbon and sulphur content, and did not support nuisance macroalgal growths. Eutrophication risk indicators for TOC and RPD depth were generally "low" to "moderate", and overall the harbour exhibited no symptoms of eutrophication.

The only significant submerged aquatic vegetation (SAV) present was seagrass which covered 18ha, 3.3% of the subtidal area. Subtidal seagrass was located primarily in the well flushed mid-lower estuary reaches, was only present in sand dominated sediments, and was not found deeper than 0.25m below the spring tide low water level.

Overall, the absence of eutrophication symptoms, but the large extent of very soft mud combined with poor water clarity, highlight excessive fine sediment as the dominant stressor in the subtidal estuary.

6. MONITORING

Porirua Harbour has been identified by GWRC as a priority for monitoring, and is a key part of GWRC's coastal monitoring programme being undertaken in a staged manner throughout the region. This arises because the estuary is large, has high ecological and human use values, and is vulnerable to excessive sediment muddiness, eutrophication and disease risk. Based on the combined 2013 intertidal and 2014 subtidal monitoring results and risk ratings, it is recommended that monitoring continue as follows:

Broad Scale Habitat Mapping (both intertidal and subtidal).
To assess changes in dominant habitats, particularly saltmarsh, seagrass, and soft mud extent, repeat broad scale habitat mapping on a 5 yearly basis. Next scheduled for January 2018.

Fine Scale Monitoring (both intertidal and subtidal). To assess estuary condition it is recommended that a "complete" fine scale monitoring assessment be undertaken at 5 yearly intervals (next scheduled for Jan-Feb 2015). It is recommended that the subtidal fine scale monitoring programme be reviewed in light of the broad scale subtidal survey results, and optimised within a 'whole of estuary' monitoring approach that includes stratification of monitoring within dominant habitat types.

Annual Sediment Monitoring (both intertidal and subtidal). To assess sediment derived changes in the estuary, annually monitor sedimentation rate, RPD depth and grain size at the existing intertidal and shallow subtidal sites. Next monitoring due in January 2015. In addition, establish transect-based sediment plates between intertidal sites and deeper subtidal basin areas to measure sedimentation rates across a full range of dominant habitat types/depths. To optimise reporting, it is recommended that results be fully reported every 5 years (first 5 year review due in 2018).

6. MONITORING (CONTINUED)

Macroalgal Monitoring
Based on the widespread cover of intertidal macroalgae and the presence of nuisance conditions, undertake annual monitoring of intertidal macroalgal cover (next scheduled for January 2015).

Seagrass Monitoring
Establish fine scale monitoring sites within established seagrass beds to assess non-lethal changes in seagrass condition (e.g. biomass, root density, root depth). Determine whether nutrient toxicity is a limiting factor in the estuary (see below).

Catchment Sediment and Nutrient Inputs
In order to develop sediment and nutrient budgets, monitor nutrient and suspended sediment inputs from major sources during both base-flow and flood conditions and use to validate modelled load estimates produced for the harbour.

Catchment Landuse
Track and map key major changes in catchment landuse, particularly where activities have the potential to release sediments or nutrients to the harbour (5 yearly).

7. MANAGEMENT

The sediment indicators monitored in 2014 reinforce the 2008 to 2010 fine scale monitoring results about the need to manage fine sediment inputs to the estuary.

In particular, limiting catchment sediment inputs to more natural levels that will not cause excessive estuary infilling and will improve harbour water clarity. To achieve this, interim and long term targets have been prepared and approved by the joint councils (Porirua City Council, Wellington City Council and Greater Wellington Regional Council), Te Runanga Toa Rangatira and other key agencies with interests in Porirua Harbour and catchment, as follows:

- Interim – Reduce sediment inputs from tributary streams by 50% by 2021.
- Long-term – Reduce sediment accumulation rate in the harbour to 1mm per year by 2031 (averaged over whole harbour).

Greater Wellington's ongoing catchment and sediment transport modelling will help determine the catchment suspended sediment load inputs and the target reductions required to reduce in-estuary sedimentation rates. GWRC and PCC have also undertaken desktop assessments to determine the likely sediment input loads from different landuses, including the Transmission Gully motorway development, and modelled the zones of deposition within the estuary. Strategies to determine the best options for managing sediment within the catchment are currently being developed.

Although eutrophication is not a major issue in the harbour, it is clear that the estuary is currently showing symptoms of moderate enrichment. To ensure a shift to a eutrophic state does not occur, it is recommended that upper trigger limits for nutrient loads to the estuary be established, and that the current catchment nutrient loads be estimated. If catchment loads exceed the estuary's guidelines then it is recommended that sources of elevated loads in the catchment be identified and measures taken to ensure trigger limits are met.

In addition, because estuary condition has been degraded by extensive past modifications (particularly saltmarsh reclamation and the loss of vegetated terrestrial margin), there is a high potential for the ecological and human use values of the estuary to be improved if restoration was to be undertaken. This is formally recognised through the Porirua Harbour and Catchment Strategy and Action Plan (PCC 2012) which identifies a range of strategies and priorities for improving estuary quality.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Abrahim, G. 2005. Holocene sediments of Tamaki Estuary: characterisation and impact of recent human activity on an urban estuary in Auckland, NZ. PhD Thesis, University of Auckland, Auckland, NZ, p 361.

Anderson, D., Gilbert, P. and Burkholder, J. 2002. Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. Estuaries 25, 704–726.

Black, K., Sloan, J. and Gries, T. 2013. Everything goes somewhere; tracking the movement of contaminated sediments in an industrialised estuary using dual signature sediment tracers (A Haugan, Ed.). EPJ Web of Conferences 50, 1–7.

Chandran, M. S. S., Sudheesh, S., Ramasamy, E. V, & Mohan, M. 2012. Sulphur Fractionation in the Sediments of Cochin Estuary. Journal of Environment, 01(01), 1–6.

de Luca, S. 2011. Transmission Gully Project Technical Report 10 - Marine Habitat & Species: Values & Description. Prepared by Boffa Miskell Ltd for NZ Transport Agency and Porirua City Council. Report No: W09034E. 73 pp + App.

de Salas, M.F., Rhodes, L.L., Mackenzie, L.A., Adamson, J.E. 2005. Gymnodinoid genera Karenia and Takayama (Dinophyceae) in New Zealand coastal waters. New Zealand Journal of Marine and Freshwater Research 39,135–139.

Ferreira, J., Andersen, J., and Borja, A. 2011. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. Estuarine, Coastal and Shelf Science 93, 117–131.

Gibb, J.G. and Cox, G.J. 2009. Patterns and Rates of Sedimentation within Porirua Harbour. Consultancy Report (CR 2009/1) prepared for Porirua City Council. 38p plus appendices.

GWRC, 2008. (Milne, J.R., Sorensen, P.G., Kelly, S.) Porirua Harbour subtidal sediment quality monitoring. Results from the November 2008 survey. GWRC report. 86p.

IPCC. 2007. Intergovernmental Panel on Climate Change web site. https://www.ipcc.ch/publications_and_data/ar4/wg1/ (accessed December 2009).

IPCC. 2013. Intergovernmental Panel on Climate Change web site. https://www.ipcc.ch/report/ar5/wg1/ (accessed March 2014).

Kennish, M.J. 2002. Environmental threats and environmental future of estuaries. Environmental Conservation 29, 78–107.

Matheson, F. and Wadwha, S. 2012. Seagrass in Porirua Harbour - Preliminary assessment of restoration potential. Prepared for Greater Wellington Regional Council. 35p.

Milne, J.R., Sorensen, P.G., Kelly, S. 2008. Porirua Harbour subtidal sediment quality monitoring. Results from the November 2008 survey. GWRC report. 86p.

National Research Council. 2000. Clean coastal waters: understanding and reducing the effects of nutrient pollution. Ocean Studies Board and Water Science and Technology Board, Commission on Geosciences, Environment, and Resources. Washington, DC: National Academy Press. 405p.

Oliver, M., Stevens, L.M., Green, M. 2013 (in press). Foundation report for the CLUES and Source to Sink sediment models used in the Porirua Harbour and catchment science programme (working title).

NIWA 2013. Transmission Gully monitoring data (Excel spreadsheet) provided by GWRC, April 2014.

Painting, S.J., Devlin, M.J., Malcolm, S.J., Parker, E.R., Mills, D.K., Mills, C., and Winpenny, K. 2007. Assessing the impact of nutrient enrichment in estuaries: susceptibility to eutrophication. Marine pollution bulletin 55(1-6), 74–90.

Robertson, B.M. Gillespie, P.A. Asher, R.A. Frisk, S. Keeley, N.B. Hopkins, G.A. Thompson, S.J. Tuckey, B.J. 2002. Estuarine Environmental Assessment and Monitoring: A National Protocol. Part A. Development, Part B. Appendices, and Part C. Application. Prepared for supporting Councils and the Ministry for the Environment, Sustainable Management Fund Contract No. 5096. Part A. 93p. Part B. 159p. Part C. 40p plus field sheets.

Robertson, B.M. and Stevens, L. 2006. Southland Estuaries State of Environment Report 2001-2006. Prepared for Environment Southland.

Robertson, B.M. and Stevens, L. 2007. Wellington Harbour, Kapiti, Southwest and South Coasts - Risks and Monitoring. Prepared for Greater Wellington Regional Council. 57p.

Robertson, B.M. and Stevens, L. 2008. Porirua Harbour: Fine Scale Monitoring 2007/08. Prepared for Greater Wellington Regional Council. 32p.

Robertson, B.M. and Stevens, L. 2009. Porirua Harbour: Fine Scale Monitoring 2008/09. Prepared for Greater Wellington Regional Council. 26p.

Robertson, B.M. and Stevens, L. 2010. Porirua Harbour: Fine Scale Monitoring 2009/10. Prepared for Greater Wellington Regional Council. 39p.

Robertson, B.M. and Stevens, L. 2012. Tasman Coast - Waimea Inlet to Kahurangi Point, habitat mapping, risk assessment and monitoring recommendations. Prepared for Tasman District Council. 167p.

Robertson, B.M. and Stevens, L. 2013. Lake Vincent. Broad scale habitat mapping 2013. Report prepared for Environment Southland. 27p.

Robertson, B.M. and Stevens, L. 2014. Waimea Inlet: Fine Scale Monitoring 2013/14. Prepared for Tasman District Council.

Robertson, B.P. 2013. Determining the sensitivity of macro-invertebrates to fine sediments in representative New Zealand estuaries. Honours thesis, University of Victoria, Wellington.

Schartup, A. T., Balcom, P. H., & Mason, R. P. 2014. Sediment-porewater partitioning, total sulfur, and methylmercury production in estuaries. Environmental Science & Technology, 48(2), 954–60.

9. REFERENCES (CONTINUED)

Stevens, L. and Robertson, B.M. 2008. Porirua Harbour: Broad Scale Habitat Mapping 2007/08. Prepared for Greater Wellington Regional Council. 29p.

Stevens, L. and Robertson, B.M. 2013. Porirua Harbour: Broad Scale Habitat Monitoring 2012/13. Prepared for Greater Wellington Regional Council. 30p.

Stevens, L. and Robertson, B.M. 2014. Porirua Harbour Estuary: Sediment Monitoring 2013/14. Prepared for Greater Wellington Regional Council. 11p.

Stevens, L. and Robertson, B.M. 2014. Porirua Harbour: Intertidal Macroalgal Monitoring 2013/14. Prepared for Greater Wellington Regional Council. 6p.

Stewart, J.R., Gast, R.J., Fujioka, R.S., Solo-Gabriele, H.M., Meschke, J.S., Amaral-Zettler, L.A., Castillo, E. Del., Polz, M.F., Collier, T.K., Strom, M.S., Sinigalliano, C.D., Moeller, P.D.R. and, Holland, A.F. 2008. The coastal environment and human health: microbial indicators, pathogens, sentinels and reservoirs. Environmental Health 7 Suppl 2, S3.

Swales, A., and Hume, T. 1995. Sedimentation history and potential future impacts of production forestry on the Wharekawa Estuary, Coromandel Peninsula. Prepared for Carter Holt Harvey Forests Ltd. NIWA report no. CHH004.

Valiela, I., McClelland, J., Hauxwell, J., Behr, P., Hersh, D., and Foreman, K. 1997. Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. Limnology and Oceanography 42, 1105–1118.

Wade, T.J., Pai, N., Eisenberg, J.N.S., and Colford, J.M., 2003. Do U.S. Environmental Protection Agency Water Quality Guidelines for Recreational Waters Prevent Gastrointestinal Illness? A Systematic Review and Meta-analysis. Environmental Health Perspective 111, 1102–1109.

APPENDIX 1. BROAD SCALE HABITAT CLASSIFICATION DEFINITIONS.

Seagrass meadows: Seagrasses are the sole marine representatives of the Angiospermae. They all belong to the order Helobiae, in two families: Potamogetonaceae and Hydrocharitaceae. Although they may occasionally be exposed to the air, they are predominantly submerged, and their flowers are usually pollinated underwater. A notable feature of all seagrass plants is the extensive underground root/rhizome system which anchors them to their substrate. Seagrasses are commonly found in shallow coastal marine locations, salt-marshes and estuaries.

Macroalgal bed: Algae are relatively simple plants that live in freshwater or saltwater environments. In the marine environment, they are often called seaweeds. Although they contain cholorophyll, they differ from many other plants by their lack of vascular tissues (roots, stems, and leaves). Many familiar algae fall into three major divisions: Chlorophyta (green algae), Rhodophyta (red algae), and Phaeophyta (brown algae). Macroalgae are algae observable without using a microscope.

Rock field: Land in which the area of residual rock exceeds the area covered by any one class of plant growth-form. They are named from the leading plant species when plant cover is ≥1%.

Boulder field: Land in which the area of unconsolidated boulders (>200mm diam.) exceeds the area covered by any one class of plant growth-form. Boulder fields are named from the leading plant species when plant cover is ≥1%.

Cobble field: Land in which the area of unconsolidated cobbles (20-200 mm diam.) exceeds the area covered by any one class of plant growth-form. Cobble fields are named from the leading plant species when plant cover is ≥1%.

Gravel field: Land in which the area of unconsolidated gravel (2-20 mm diameter) exceeds the area covered by any one class of plant growth-form. Gravel fields are named from the leading plant species when plant cover is ≥1%.

Mobile sand: The substrate is clearly recognised by the granular beach sand appearance and the often rippled surface layer. Mobile sand is continually being moved by strong tidal or wind-generated currents and often forms bars and beaches. When walking on the substrate you'll sink <1 cm.

Firm sand: Firm sand flats may be mud-like in appearance but are granular when rubbed between the fingers, and solid enough to support an adult's weight without sinking more than 1-2 cm. Firm sand may have a thin layer of silt on the surface making identification from a distance difficult.

Soft sand: Substrate containing greater than 99% sand. When walking on the substrate you'll sink >2 cm.

Firm mud/sand: A mixture of mud and sand, the surface appears brown, and may have a black anaerobic layer below. When walking you'll sink 0-2cm.

Soft mud/sand: A mixture of mud and sand, the surface appears brown, and many have a black anaerobic layer below. When you'll sink 2-5 cm.

Very soft mud/sand: A mixture of mud and sand, the surface appears brown, and many have a black anaerobic layer below. When walking you'll sink >5cm.

Cockle bed /Mussel reef/ Oyster reef: Area that is dominated by both live and dead cockle shells, or one or more mussel or oyster species respectively.

Sabellid field: Area that is dominated by raised beds of sabellid polychaete tubes.

Shell bank: Area that is dominated by dead shells.

Artificial structures: Introduced natural or man-made materials that modify the environment. Includes rip-rap, rock walls, wharf piles, bridge supports, walkways, boat ramps, sand replenishment, groynes, flood control banks, stopgates.

APPENDIX 2. DETAILS ON ANALYTICAL METHODS

Indicator	Laboratory	Method	Detection Limit
Grain Size	R.J Hill	Wet sieving, gravimetric (calculation by difference).	0.1 g/100g dry wgt
Total Organic Carbon	R.J Hill	Acid pretreatment to remove carbonates if present, neutralisation, Elementar Combustion Analyser.	0.05g/100g dry wgt
Total Sulphur	R.J Hill. Subcontracted to SGS, Waihi.	LECO SC32 Sulphur Determinator, high temperature furnace, infra-red detector. ASTM 4239.	0.005 g/100g dry wt

APPENDIX 3. DETAILED RESULTS

Site coordinates, field measures, and analytical results for Onepoto Arm sediment sampling sites, Porirua Harbour January, 2014.

Site	NZTM East	NZM North	Substrate	Depth below MLWS	aRPD	Mud	Sands	Gravel	TOC	TS	Mapping class
				m	cm	%					
001	1754818.0	5445730.0	mS	0.4	>5	5.4	93.8	0.8	0.43	0.04	soft MUD
002	1754402.9	5446139.9	mshelS	0.4	>5	7.9	87.5	4.6	1.05	0.05	soft MUD
003	1754647.2	5446062.9	sM	1.5	2	78.5	21.5	< 0.1	2.6	0.17	very soft MUD
004	1755204.4	5445991.5	sM	1.4	2	81.8	17.9	0.3	2.5	0.15	very soft MUD
005	1754890.4	5446149.1	sM	2.1	3	81.9	18.1	< 0.1	2.4	0.12	very soft MUD
006	1754579.5	5446449.6	mS	1.1	>5	13.3	85.7	1	0.58	0.06	soft MUD
007	1754937.4	5446461.2	sM	2.2	>5	84.7	15.3	< 0.1	2.4	0.18	very soft MUD
008	1755535.9	5446389.7	sM	1.8	5	80.3	19.5	0.2	1.94	0.11	very soft MUD
009	1755037.6	5446762.6	sM	1.6	>5	30	69.6	0.5	0.79	0.05	very soft MUD
010	1755546.4	5446654.0	sM	1.9	3	72.5	27.3	0.2	1.93	0.13	very soft MUD
011	1755288.1	5446844.6	mS	0.8	1	6.4	93.3	0.3	0.29	0.03	soft MUD
012	1755663.4	5447030.7	mS	0.5	1	5.5	94.5	< 0.1	0.36	0.04	firm muddy SAND
013	1755799.3	5446992.4	mS	0.6	3	3.2	96.6	0.1	0.49	0.03	firm muddy SAND
014	1756056.5	5446941.9	mS	0.6	1	5.8	93.7	0.5	0.56	0.06	firm muddy SAND
015	1755741.1	5447268.1	mS	0.7	3	7	88.6	4.3	0.51	0.05	firm muddy SAND
016	1755815.6	5447237.9	mS	1.8	3	11.3	84.6	4.2	0.82	0.08	firm muddy SAND
017	1756001.1	5447231.1	mS	0.3	3	11.4	88.5	< 0.1	0.73	0.07	firm muddy SAND
018	1755967.5	5447540.2	mS	2.5	3	9.6	83.4	7	0.8	0.07	firm muddy SAND
019	1756024.1	5447694.7	mS	1.2	3	11.4	81.3	7.3	0.77	0.07	firm muddy SAND
020	1756062.6	5447693.5	mS	3.3	3	12.1	52.1	35.8	0.58	0.08	firm muddy SAND
021	1756098.1	5447688.4	mS	1.8	4	8.4	91.5	< 0.1	0.95	0.08	firm muddy SAND
022	1756277.9	5448028.0	gmS	2.1	>5	11.7	73.4	14.9	0.72	0.07	firm muddy SAND
023	1756281.1	5447961.9	mS	2.0	>5	8.9	91	< 0.1	0.79	0.06	firm muddy SAND
024	1756465.9	5447915.3	mS	1.1	1	8.2	91.5	0.3	0.71	0.09	firm muddy SAND
025	1756518.4	5448144.7	S	2.3	>5	3.1	96.6	0.3	0.57	0.06	firm SAND

Substrate: s=sand, m=mud, g=gravel, shel=shell. Capital letters signify dominance
Mapping class: sediment type ascribed based on field observations of sediment cohesiveness, and sediment mud content analyses.

APPENDIX 3. DETAILED RESULTS (CONTINUED)

Site coordinates, field measures, and analytical results for Pauatahanui Arm sediment sampling sites, Porirua Harbour January, 2014.

Site	NZTM East	NZM North	Substrate	Depth below MLWS	aRPD	Mud	Sands	Gravel	TOC	TS	Mapping class
	Mapping code			m	cm	%					
P01	1757398.5	5448096.4	mS	1.1	1	8.5	91.5	< 0.1	0.92	0.15	firm muddy SAND
P02	1757389.8	5448144.5	fshelS	6.1	1	8.5	91.4	< 0.1	0.83	0.08	firm SAND
P03	1757385.7	5448186.5	fshelS	2.1	1	4.5	92.9	2.7	0.78	0.11	firm SAND
P04	1757433.5	5448603.2	mS	0.6	1	8.8	90.6	0.6	0.82	0.08	soft muddy SAND
P05	1757351.8	5448921.0	mS	1.0	1	23.3	76.5	0.2	1.05	0.11	very soft MUD
P06	1757812.7	5448567.9	fshelS	1.7	3				0.74	0.06	firm SAND
P07	1757805.3	5448601.0	fshelS	3.5	3	5.8	80.1	14	0.86	0.08	firm SAND
P08	1757781.8	5448633.7	fmS	1.5	3	4.2	94.1	1.6	0.71	0.1	firm SAND
P09	1757899.2	5448948.2	fmS	0.2	2	15.1	82.1	2.8	1.2	0.13	firm muddy SAND
P10	1757721.8	5449188.3	shelmudS	1.3	1	25.7	58	16.3	1.16	0.09	very soft MUD
P11	1757975.1	5449110.0	fmS	0.2	1	19.9	79.4	0.7	1.08	0.13	very soft MUD
P12	1758090.5	5448802.8	mshelS	1.5	>5	6.3	78.7	14.9	0.83	0.05	firm SAND
P13	1758120.2	5448765.6	S	1.8	>5	3.9	93.1	3	0.68	0.04	firm SAND
P14	1758153.5	5448726.4	S	1.3	>5	3.2	95.6	1.2	0.69	0.07	firm SAND
P15	1758306.6	5448790.0	mS	0.6	>5	6.8	92.1	1	0.99	0.07	firm muddy SAND
P16	1758290.9	5448658.1	mS	2.0	>5	7.1	92.6	0.3	0.86	0.09	firm muddy SAND
P17	1758254.1	5448518.8	sshelM	2.8	1				1.21	0.08	soft muddy SAND
P18	1758109.9	5448227.8	mMud	1.7	>5	81.6	18.2	0.2	1.89	0.1	very soft MUD
P19	1758295.5	5448209.5	mS	0.4	1	14.1	85.6	0.3	1.02	0.09	firm muddy SAND
P20	1758678.3	5448215.9	mS	0.4	2	12.1	87.8	< 0.1	0.94	0.07	firm muddy SAND
P21	1759253.7	5448680.4	mMud	0.7	3	89.4	10.4	0.2	1.68	0.1	very soft MUD
P22	1758726.2	5448718.6	mS	0.3	2	3.7	95.9	0.4	0.5	0.06	firm muddy SAND
P23	1758484.8	5449104.2	mMud	1.2	3	72.4	27.6	< 0.1	1.83	0.13	very soft MUD
P24	1758403.1	5449426.7	mMud	0.5	2	80.1	19.8	0.1	1.1	0.09	very soft MUD
P25	1758801.8	5449350.2	mMud	0.2	2	86.6	13.4	< 0.1	1.58	0.12	very soft MUD
P26	1758753.1	5449009.9	mMud	1.0	3	77.7	22.2	< 0.1	1.55	0.1	very soft MUD
P27	1758864.6	5448123.9	mMud	1.6	3	64.1	35.6	0.3	2.5	0.14	very soft MUD
P28	1759055.0	5448486.2	mMud	1.5	3	84.2	15.8	< 0.1	1.82	0.1	very soft MUD
P29	1759107.4	5449261.3	mMud	0.3	2	81.4	18.3	0.3	1.42	0.14	very soft MUD
P30	1759614.8	5448586.2	mMud	0.7	2	88	11.8	0.1	1.84	0.18	very soft MUD
P31	1759458.5	5448324.4	mMud	1.1	1	84.7	14.9	0.4	1.7	0.06	very soft MUD
P32	1759882.3	5448360.4	mS	0.6	2	19.1	78.8	2.1	0.64	0.15	very soft MUD

Substrate: s=sand, m=mud, g=gravel, shel=shell. Capital letters signify dominance
Mapping class: sediment type ascribed based on field observations of sediment cohesiveness, and sediment mud content analyses.

APPENDIX 3. DETAILED RESULTS (CONTINUED)

Mean vales of specified risk indicators within dominant substrate types, Porirua Harbour, January 2014

Mud content

Dominant Substrate	n=	%mud	SE
SAND firm	9	4.8	0.5
SAND firm muddy	21	9.0	0.7
SAND soft muddy	6	8.5	1.2
MUD very soft	29	61.7	4.8

Total Organic Carbon

Dominant Substrate	n=	%TOC	SE
SAND firm	0.7	0.03	9
SAND firm muddy	0.8	0.05	20
SAND soft muddy	0.7	0.15	6
MUD very soft	1.7	0.12	22

Total Sulphur

Dominant Substrate	n=	%TS	SE
SAND firm	0.07	0.008	9
SAND firm muddy	0.08	0.006	20
SAND soft muddy	0.06	0.008	6
MUD very soft	0.12	0.007	22

aRPD depth

Dominant Substrate	n=	aRPD (cm)	SE
SAND firm	3.4	0.5	10
SAND firm muddy	2.8	0.3	29
SAND soft muddy	3.3	0.8	7
MUD soft	3.7	0.7	3
MUD very soft	2.8	0.2	76


Intertidal seagrass beds in the middle of the Pauatahanui Arm.

APPENDIX 4.

ESTUARY CONDITION RISK RATINGS FOR KEY INDICATORS

DEVELOPED BY WRIGGLE COASTAL MANAGEMENT

JUNE 2014

GUIDELINES FOR USE

The estuary monitoring approach used by Wriggle has been established to provide a defensible, cost-effective way to help quickly identify the likely presence of the predominant issues affecting NZ estuaries (i.e. eutrophication, sedimentation, disease risk, toxicity and habitat change), and to assess changes in the long term condition of estuarine systems. The design is based on the use of primary indicators that have a documented strong relationship with water or sediment quality. In order to facilitate this process, “risk indicator ratings” have been proposed that assign a relative level of risk of adversely affecting estuarine conditions (e.g. very low, low, moderate, high, very high) to each indicator. Each risk indicator rating is designed to be used in combination with relevant information and other risk indicator ratings, and under expert guidance, to assess overall estuarine condition in relation to key issues, and make monitoring and management recommendations. When interpreting risk indicator results we emphasise:

- The importance of taking into account other relevant information and/or indicator results before making management decisions regarding the presence or significance of any estuary issue.
- That rating and ranking systems can easily mask or oversimplify results. For instance, large changes can occur within a risk category, but small changes near the edge of one risk category may shift the rating to the next risk level.
- Most issues will have a mix of primary and secondary ratings, primary ratings being given more weight in assessing the significance of indicator results. It is noted that many secondary estuary indicators will be monitored under other programmes and can be used if primary indicators reflect a significant risk exists, or if risk profiles have changed over time.
- Ratings have been established in many cases using statistical measures based on NZ estuary data. However, where such data is lacking, or has yet to be processed, ratings have been established using professional judgement, based on our experience from monitoring numerous NZ estuaries. Our hope is that where a high level of risk is identified, the following steps are taken:

    1. Statistical measures be used to refine indicator ratings where information is lacking.
    2. Issues identified as having a high likelihood of causing a significant change in ecological condition (either positive or negative), trigger intensive, targeted investigations to appropriately characterise the extent of the issue.
    3. The outputs stimulate discussion regarding what an acceptable level of risk is, and how it should best be managed.

The indicators and risk ratings used in the Porirua Harbour subtidal monitoring programme, and their justifications, are summarised in the following sections.

APPENDIX 4. ESTUARY CONDITION RISK RATINGS (CONTINUED)

1. SEDIMENT PERCENT MUD CONTENT

In their natural state, most NZ estuaries would have been dominated by sandy or shelly substrates, while most NZ beaches are dominated by sandy substrates due to their relatively high wave exposure. In estuaries or beaches not naturally prone to muddy conditions, a significant shift towards elevated concentrations of mud (grain size <63um) is likely to result in detrimental and difficult to reverse changes in biotic community composition, and adverse impacts to human uses and values (e.g. through reduced water clarity and increased muddiness). Consequently, mud content can indicate where changes in land management may be needed.

Subsequent to the development of NEMP (Robertson et al. 2002) which uses sediment grain size as one indicator of sediment condition, the relationships between sediment mud content, the benthic macrofaunal community, sediment cohesiveness or stickiness, and organic carbon concentration have been further defined (see supporting evidence below). This included a widespread Wriggle funded study of NZ estuarine habitats (Robertson 2013) which found estuarine sediments with low to intermediate mud concentrations (i.e. 2-25% mud) were more likely to have a diverse and abundant macroinvertebrate assemblage and low organic enrichment (<1% TOC) than muddier sediments. Based on this, and other supporting work, the associated characteristics of the sediment % mud content indicator can be summarised as follows:

"% Mud Content" Characteristics

- Sediments are relatively incohesive at mud contents below 20-30% (i.e. are not sticky and are relatively firm to walk on), but lose cohesion and become "sticky" at higher mud contents (i.e. you begin to sink into the muds).
- There is a marked shift in the macroinvertebrate assemblage when mud content exceeds 25-30% to one dominated by mud tolerant and/or species of intermediate tolerance. This shift is most apparent when elevated mud content is contiguous with high total organic carbon (TOC) concentrations.
- As % mud content increases, the concentrations of organic carbon and nutrients (total organic carbon and total nitrogen) also generally increase, particularly for estuaries with highly developed catchments. As a consequence, such sediments are often poorly oxygenated and, when present in intertidal flats of tidal lagoon estuaries (particularly in poorly flushed areas), are often overlain with dense nuisance macroalgal blooms.
- In typical NZ shallow tidal lagoon estuaries, muddy sediments (>40% mud) and elevated nitrogen loadings (100mgN.m^{-2}.d^{-1}), commonly coincide with dense macroalagal cover (>80% cover) and gross eutrophic conditions (TOC >3%, RPD at surface). Similar gross eutrophic conditions occur in shallow coastal lagoons or ICOLLs where conditions are not too turbid, but the minimum mud content at which they occur is expected to be much less than for tidal lagoon estuaries. In narrow tidal river estuaries, which are well flushed and lack large settling basins, such gross eutrophic conditions are rare.

These characteristics indicate that NZ estuary sediments with a widespread mud content of greater than 20-30% are likely to have a degraded macroinvertebrate community, and sediments that are non-cohesive (soft and muddy). Such impacts are most significant if such conditions are occurring in estuaries with a naturally low mud content. Of particular importance are the typical NZ shallow, tidal lagoon and ICOLL estuaries.

SUPPORTING EVIDENCE

1. Mud Content - Relationship to Macroinvertebrate Community

A review of monitoring data from 25 typical NZ estuaries (shallow, short residence time estuaries) (Wriggle database 2009-2014) confirmed a "high" risk of reduced macrobenthic species richness for NZ estuaries when mud values were >25-30% mud and a "very high" risk at >55% (this last value is more tentative given the low number of data-points beyond this mud content) (Figure 1). This is supported statistically (canonical analysis of the principal coordinates (CAP) for the effect of mud content) by the increasing dissimilarity in the macrobenthic community as mud contents increase above 25-30% mud (Figure 2).

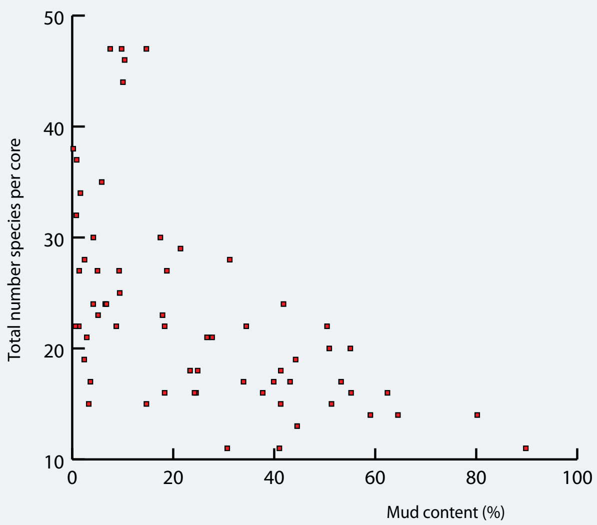


Figure 1. Sediment mud content and number of macrobenthic species per core from 12 estuaries scattered throughout NZ, and representing most NZ shallow, short residence time estuary types. (Wriggle Coastal Management database 2009-14).

1. SEDIMENT PERCENT MUD CONTENT (CONTINUED)

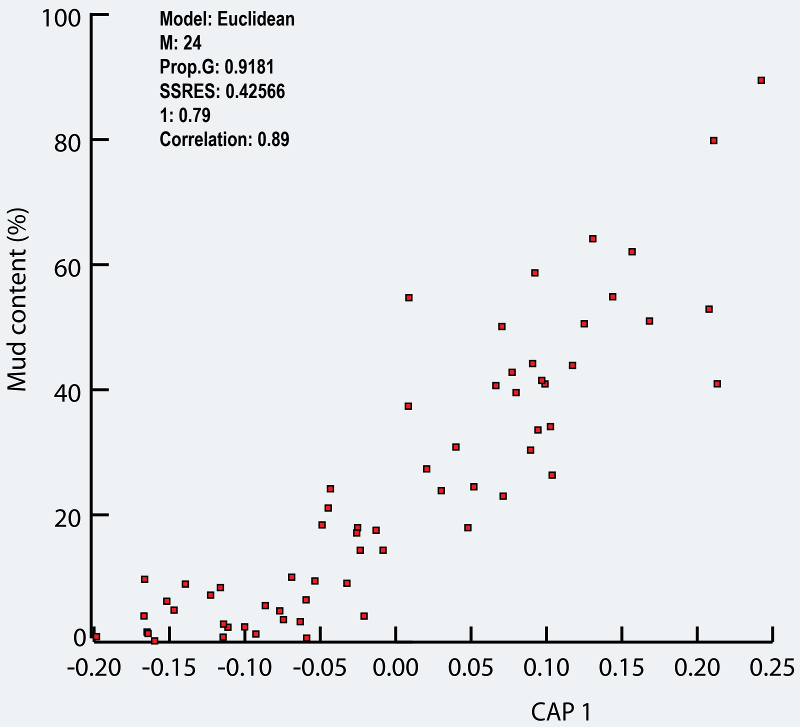


Figure. 2. Canonical analysis of the principal coordinates (CAP) for the effect of sediment mud content (exclusively) on the macroinvertebrate assemblages from 25 typical NZ estuaries (i.e. CAP1) among sites. Note: M = the number of PCO axes used for the analysis, Prop.G = the proportion of the total variation in the dissimilarity matrix explained by the first m PCO axes, SSRES = the leave-one-out residual sum of squares, 1 = the squared canonical correlation for the canonical axis, Correlation = the correlation between the canonical axis and the sediment mud content or pollution gradient.

2. Mud Content - Relationship to Sediment Cohesiveness

Studies show that sediments become "cohesive" or sticky once the % mud content increases above approximately 20-30% mud depending on such factors as the clay content (Houwing 2000).

3. Mud Content- Relationship to Gross Nuisance Conditions

The trophic response to muddy sediments under elevated nitrogen loadings, in this case macroalgal cover, has been explored for 15 shallow tidal lagoon estuaries in NZ (tidal lagoon type with flushing potentials <0.1 days, mean depth 0.5-2m, intertidal flats >50% estuary area). The results (Figure 3) showed that where mud content was greater than 40% and the nitrogen load to the estuary was greater than 100mgN.m^{-2}.d^{-1}, macroalgal cover was greater than 80% and was accompanied by gross eutrophic conditions (mud content >30%, TOC >3%, RPD at surface).

Similar gross eutrophic conditions have been found to occur in shallow coastal lagoons or ICOLLs where conditions are not too turbid (e.g. Hoopers Inlet, Waituna Lagoon), but the minimum mud content at which they occur is expected to be much less than for tidal lagoon estuaries. Further work is however required to confirm this.

The trophic response to muddy sediments under elevated nitrogen loadings, in this case macroalgal cover, has been explored for 5 shallow tidal river estuaries in NZ (tidal river type with flushing potentials <0.1 days, mean depth 0.5-2m, intertidal flats <5% estuary area). In these narrow, well flushed, tidal river estuaries, where intertidal area is small and therefore the opportunity for nuisance macroalgal growth limited, such gross eutrophic conditions were rare (Figure 4).

APPENDIX 4. ESTUARY CONDITION RISK RATINGS (CONTINUED)

1. SEDIMENT PERCENT MUD CONTENT (CONTINUED)

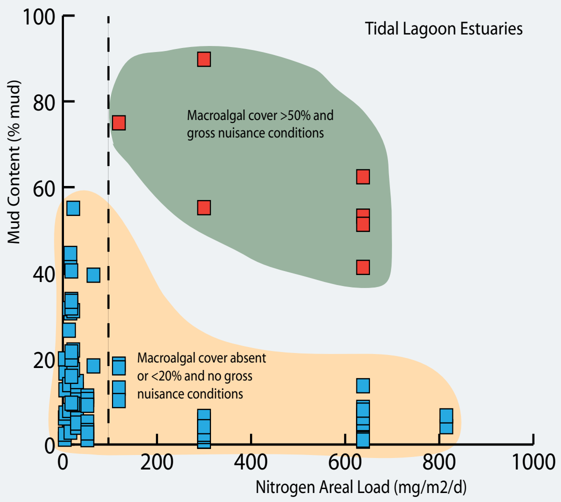


Figure 3. Mud content of sediment and nitrogen load (per unit area of the estuary) for fine scale monitoring sites at 15 typical NZ tidal lagoon estuaries (shallow, residence time <3d, >50% of estuary intertidal) (data sourced from Wriggle Coastal Management monitoring reports 2006-2013, Robertson et al. 2002).

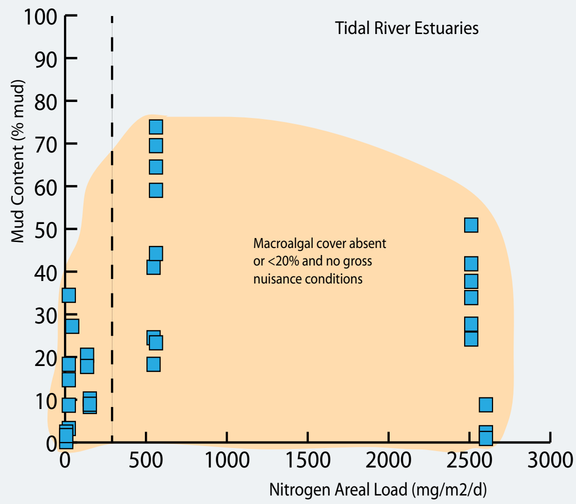


Figure 4. Mud content of sediment and nitrogen load (per unit area of the estuary) for fine scale monitoring sites at 5 typical NZ tidal river estuaries (data sourced from Wriggle Coastal Management monitoring reports 2006-2013).

RECOMMENDED SEDIMENT MUD CONTENT RISK RATING (INTERIM)

It is recommended that the estuary sediment-macroinvertebrate-mud thresholds (primarily adapted from Robertson 2013) be used to provide an interim indicator of estuary risk based on the magnitude of likely impact on sediment biota from measured % mud content as follows:

Estuary Condition Risk Rating (Interim): Sediment Mud Content					
Risk Rating	Very Low	Low	Moderate	High	Very High
Sediment Mud Content (% mud)	<2%	2-5%	>5-15%	>15-25%	>25%

Clearly, this rating is intended for the determination of site-specific conditions at monitoring sites, not for whole estuary assessments (unless representative sites have been monitored over the whole estuary).

RECOMMENDED RESEARCH

Undertake extensive grain size validation monitoring of the following habitat types: firm muddy sand, soft mud, and very soft mud to confirm and refine the measured range of % mud found in each these broad scale monitoring categories from estuaries throughout NZ.

Undertake further studies in typical NZ estuaries on % mud and the incidence of:

- gross eutrophic conditions,
- adverse impacts macroinvertebrates, seagrass, saltmarsh, fish, and/or birds.

References

Houwing, E.J. 2000. Sediment dynamics in the pioneer zone in the land reclamation area of the Wadden Sea, Groningen, The Netherlands. PhD thesis, University of Utrecht, Utrecht.

Robertson, B.M. Gillespie, P.A. Asher, R.A. Frisk, S. Keeley, N.B. Hopkins, G.A. Thompson, S.J. Tuckey, B.J. 2002. Estuarine Environmental Assessment and Monitoring: A National Protocol. Part A. Development, Part B. Appendices, and Part C. Application. Prepared for supporting Councils and the Ministry for the Environment, Sustainable Management Fund Contract No. 5096. Part A. 93p. Part B. 159p. Part C. 40p plus field sheets.

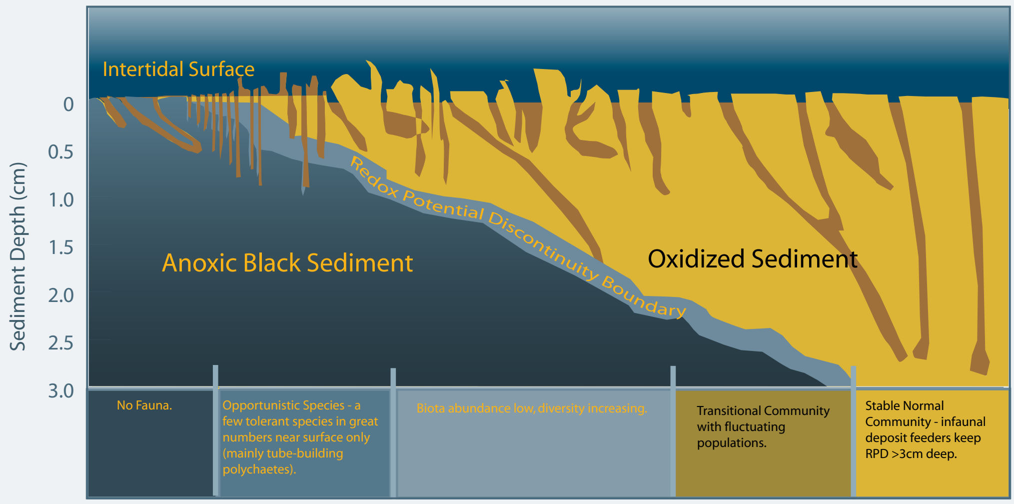
Robertson, B.P. 2013. Determining the sensitivity of macroinvertebrates to fine sediments in representative New Zealand estuaries. Honours dissertation, Victoria University of Wellington - Note: In preparation for journal publication.

APPENDIX 4. ESTUARY CONDITION RISK RATINGS (CONTINUED)

2. REDOX POTENTIAL DISCONTINUITY (RPD) DEPTH

Redox Potential Discontinuity (RPD) depth measures the transition between oxygenated sediments near the surface and deeper anoxic sediments. It is a primary condition indicator as it is a direct measure of whether nutrient and organic enrichment exceeds levels causing nuisance (anoxic) conditions. Anoxic sediments contain toxic sulphides, which support very little aquatic life, and as the RPD layer gets close to the surface, a "tipping point" is reached where the pool of sediment nutrients (which can be large), suddenly becomes available to fuel algal blooms and worsen sediment conditions. In sandy porous sediments, the RPD layer is usually relatively deep (>3cm) and is maintained primarily by current or wave action that pumps oxygenated water into the sediments. In finer silt/clay sediments, physical diffusion limits oxygen penetration to <1cm (Jørgensen and Revsbech 1985) unless bioturbation by infauna oxygenates the sediments. The tendency for sediments to become anoxic is much greater if the sediments are muddy.

The RPD layer is an effective ecological barrier for most, but not all, sediment-dwelling species. A rising RPD will force most macrofauna towards the sediment surface to where oxygen is available. Pearson and Rosenberg (1978) developed a useful organic enrichment tool that indicates the likely benthic macrofauna community that is supported at a particular site based on the measured RPD depth (see Figure below for summary). This tool has been used extensively to date to help interpret intertidal monitoring data in New Zealand and its relationship to organic enrichment. However, it is important to note that this tool was based primarily on studies conducted in stable subtidal sediments of coastal estuaries and embayments rather than the more unstable intertidal sediments of beach habitat or shallow, well-flushed estuaries commonly found in NZ.



An indication of the likely benthic community supported at measured RPD depths **(adapted from Pearson and Rosenberg 1978).**

In addition, a recent study (Gerwing et al. 2013) describe two common methods for measuring RPD as follows:

- **Visual assessment** (often by digital imaging e.g. Munari et al. 2003) based on the assumption that in the absence of oxygen, ferrous sulphides produced by microbial sulphate reduction precipitate as Fe-sulphides, which produce a grey or black coloration of the sediment, which signifies the RPD depth (Valdemarsen et al. 2009). When redox measurements (Eh) are not considered simultaneously, the RPD is termed the apparent RPD (aRPD) (Birchenough et al. 2012).
- **Redox potential (Eh) measurements** represent a bulk measurement that reflects the occurrence of multiple redox equilibria at the surface of an electrode and reflects a system's tendency to receive or donate electrons. Electrodes are inserted either vertically or horizontally at different depths (Rosenberg et al. 2001, Diaz & Trefry 2006) into the sediment. The depth of the RPD is identified as the zone where conditions change from oxidizing to reducing or the transition from positive to negative mV readings (Birchenough et al. 2012).

Gerwing et al. (2013) compared the methods and found similar results for stable subtidal (Rosenberg et al. 2001) and deep sea sediments (Diaz & Trefry 2006), but different results for relatively dynamic intertidal sediments.

Such findings, indicate two important points:

1. The use of the Pearson-Rosenberg (1978) approach for assessing macrobenthic response to organic enrichment in dynamic, shallow intertidal sediments (i.e. the dominant habitats in most NZ estuaries and beaches) has yet to be proven, and
2. The appropriate RPD method for use in such intertidal sediments and its relationship with biotic indicators needs to be identified.

APPENDIX 4. ESTUARY CONDITION RISK RATINGS - (CONTINUED)

2. REDOX POTENTIAL DISCONTINUITY (RPD) DEPTH (CONTINUED)

RECOMMENDED RPD RISK RATING (INTERIM)

In the interim period prior to the results of proposed Otago University research being available (see recommended research section below), it is recommended that the RPD risk rating be based on aRPD results and predicted ecological response bands similar to those proposed by Pearson-Rosenberg (1978) as presented in the Table below. In addition, it is recommended that other indicators are used to further assess sediment oxygenation if the aRPD indicates a high/very high risk of ecological impacts. The measurement of redox potential and/or various sulphur fractions are the most common approaches.

Estuary and Beach Condition Risk Indicator Rating (Interim): Apparent RPD Depth

Risk Rating	Very Low	Low	Moderate	High	Very High
aRPD depth (cm)	>10cm	3-10cm	1-<3cm	0-<1cm	Anoxic at surface

RECOMMENDED RESEARCH

Clearly, there is an urgent requirement for a direct comparison between both RPD methods (visual and redox) for intertidal and subtidal estuary and beach habitats in NZ, and particularly the relationship between the RPD depth measured by each, and other indicators, especially biotic factors such as macroinvertebrates and macroalgal cover, and environmental factors such as sulphur species. This is to be included as part of Wriggle sponsored PhD research being undertaken by Ben Robertson (commenced in June 2014).

References

Birchenough S., Parker N., McManus E, and Barry J. 2012. Combining bioturbation and redox metrics: potential tools for assessing seabed function. Ecological Indicators 12:8–16.

Diaz R.J., and Trefry J.H. 2006. Comparison of sediment profile image data with profiles of oxygen and Eh from sediment cores J. Mar Syst 62: 164-172.

Gerwing T. G., Gerwing A.M., Drolet D., Hamilton D.J., and Barbeau M.A. 2013. Two methods of measuring the depth of potential discontinuity in intertidal mudflat sediments. Marine Ecology Progress Series, 487: 7-13.

Jorgenson N., and Revsbach N.P. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnology and Oceanography 30:111-112.

Munari C., Modugno S., Ghion F., Casteldelli G., Fano E.A., Rossi R., and Mistri M. 2003. Recovery of the macrobenthic community in the Valli di Comacchio, Northern Adriatic Sea, Italy. Oceanol Acta 26:67-75.

Pearson T. H., and Rosenberg R. 1978. Macrobenthic succession in relation to organic enrichment and pollution in the marine environment. Oceanography and Marine Biology: an Annual Review, 16: 229-311.

Rosenberg R., Nilsson H.C., and Diaz R.J. 2001. Response of benthic fauna and changing sediment redox profiles over a hypoxic gradient. Estuarine Coast Shelf Sci 53: 343-350.

Veldemarsen T., Kristensen E., and Holmer M. 2009. Metabolic threshold and sulfide-buffering in diffusion controlled marine sediments impacted by continuous organic enrichment. Biogeochemistry 95: 335-353.

APPENDIX 4. ESTUARY CONDITION RISK RATINGS (CONTINUED)

3. TOTAL ORGANIC CARBON (TOC) AND RELATED NUTRIENTS

Estuaries with a high sediment organic content can result in anoxic sediments and bottom water, which contribute to the release of excessive nutrients and have adverse impacts on biota - key symptoms of eutrophication. Elevated sediment organic content (measured as total organic carbon, TOC) is generally caused by excessive plant growth within an estuary, or from catchment inputs (including point sources). In NZ's shallow, short residence time estuaries (SSRTEs), decaying macroalgae, seagrass and saltmarsh vegetation are the major sources of sediment TOC. In in deep, long residence time estuaries (DLRTEs), the major source is phytoplankton.

Hyland et al. (2005) recently expanded upon the Pearson and Rosenberg (1978) model (which describes benthic community response along an organic enrichment gradient) by using it as a conceptual basis for defining lower and upper thresholds in TOC concentrations corresponding to low versus high levels of benthic species richness in samples from seven coastal regions of the world. Specifically, it was shown that risks of reduced macrobenthic species richness from organic loading and other associated stressors in sediments should, in general, be relatively low where TOC values were <1%, and relatively high where values were >3.5%.

While not a direct measure of causality (i.e. it does not imply that the observed bioeffect was caused by TOC itself), it was anticipated that these TOC thresholds may serve as a general screening-level indicator, or symptom, of ecological stress in the benthos from related factors. Such factors may include high levels of ammonia and sulphide, or low levels of dissolved oxygen associated with the decomposition of organic matter, or the presence of chemical contaminants co-varying with TOC in relation to a common controlling factor such as sediment particle size. Subsequently, the TOC threshold values have been confirmed by several sources:

- Analysis of TOC sediment data collected in EMAP-Virginian Province Study indicated that TOC values in the 1 to 3% range were associated with impacted benthic communities, while values less than 1% were not (Paul et al. 1999).
- Magni et al. (2009) confirmed a high risk of reduced macrobenthic species richness for Mediterranean coastal lagoons when TOC values were >2.8%.
- A review of monitoring data from 25 typical NZ estuaries (SSRTEs) (Wriggle database 2009-2014) confirmed a "high" risk of reduced macro-benthic species richness when TOC values were >2% and a "very high" risk at >3.5% (this last value is more tentative given the low number of data-points beyond this TOC concentration) (Figure 1). This is supported statistically (canonical analysis of the principal coordinates (CAP) for the effect of TOC content, Figure 2) by the increasing dissimilarity in the macrobenthic community as TOC concentrations increase above 2%.

SUPPORTING EVIDENCE

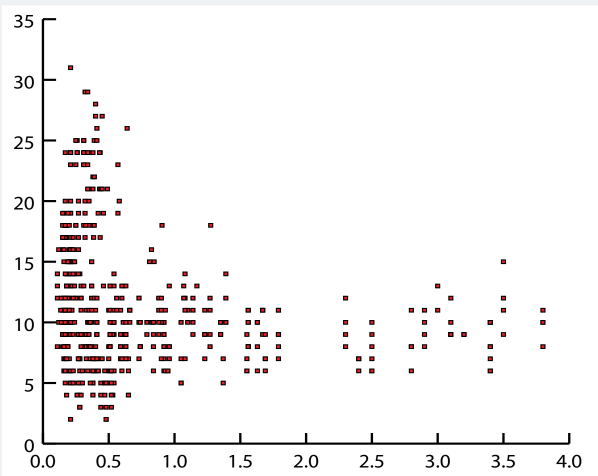


Figure 1. Sediment TOC concentrations and number of macrobenthic species per core from 12 estuaries scattered throughout NZ, and representing most NZ shallow, short residence time estuary types. (Wriggle Coastal Management database 2009-14).

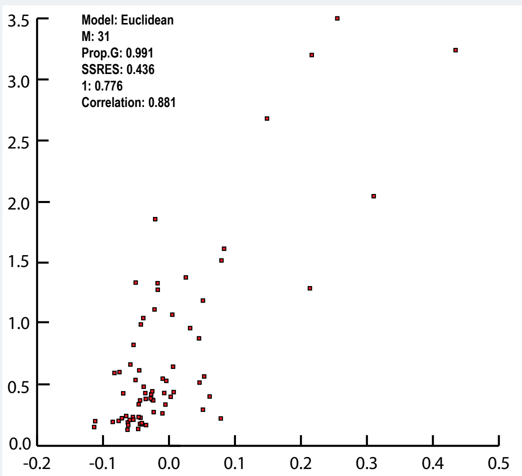


Figure 2. Canonical analysis of the principal coordinates (CAP) for the effect of total organic carbon content, on the macroinvertebrate assemblages from 12 typical NZ estuaries (i.e. CAP1) among sites.

Note: M = the number of PCO axes used for the analysis, Prop.G = the proportion of the total variation in the dissimilarity matrix explained by the first m PCO axes, SSRES = the leave-one-out residual sum of squares, 1 = the squared canonical correlation for the canonical axis, Correlation = the correlation between the canonical axis and the sediment mud content or pollution gradient.

APPENDIX 4. ESTUARY CONDITION RISK RATINGS (CONTINUED)

3. TOTAL ORGANIC CARBON (TOC) AND RELATED NUTRIENTS (CONTINUED)

Data from 12 estuaries scattered throughout NZ, and representing most NZ estuary types were reviewed in relation to TOC and nutrients (Figure 3). Total nitrogen was found to be very strongly correlated with TOC (r^2 =0.90). Total phosphorus was less strongly correlated (r^2 =0.68), but preliminary analysis of the data suggests a likely explanation for the variability at elevated P concentrations. Surface P concentrations can become elevated if P that is released from intense sulphate reduction process at depth in sediment, is trapped by iron oxyhydroxides in the surface oxygenated layer. This process is likely to be expressed in a variable way, being most intense in situations with dense macroalgal cover, and less intense where macroalgal cover is moderate (Figure 3).

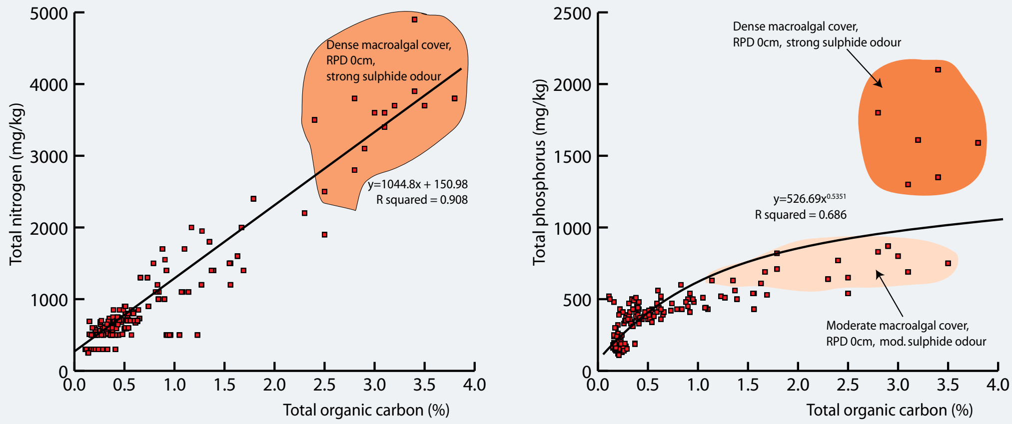


Figure 2. Sediment TOC and TN, and sediment TOC and TP concentrations from 12 estuaries scattered throughout NZ, and representing most NZ estuary types (Wriggle Coastal Management database 2009-2013).

RECOMMENDED TOC AND RELATED NUTRIENTS RISK RATING (INTERIM)

In order to assess the likely risk of estuary ecological condition being affected by the sediment TOC concentration it is recommended that the following thresholds be used.

Estuary Condition Risk Indicator Rating: TOC and Related Nutrients (TN and TP)						
Indicator	**Risk Rating**	Very Low	Low	Moderate	High	Very High
Primary	**Total Organic Carbon**	<0.5%	0.5-1%	1-2%	2-3.5	>3.5
Secondary	**Total Nitrogen**	<250mg/kg	250-1000mg/kg	1000-2000mg/kg	2000-4000mg/kg	>4000mg/kg
	Total Phosphorus	<100mg/kg	100-300mg/kg	300-500mg/kg	500-1000mg/kg	>1000mg/kg

However, it is emphasised that in order to assess the condition of NZ estuaries using TOC, a multi-criteria approach (physical, chemical and biotic indicators) is recommended, so that TOC concentration measurements are supported by related indicators, in particular mud content, RPD, macroinvertebrates, macroalgal cover, and the secondary indicators TP and TN.

RECOMMENDED RESEARCH

- Undertake studies to further expand the sediment macroinvertebrate/TOC relationships for NZ estuaries into highly eutrophic habitats, particularly those with >3.5% TOC concentrations.
- Develop a list of macrobenthic species sensitivities to TOC concentrations under varying mud, redox, and heavy metal concentrations.

References

Hyland, J.L., Balthis, L., Karakassis, I., Magni, P., Petrov, A.N., Shine, J.P., Vestergaard, O. and Warwick, R.M. 2005. Organic carbon content of sediments as an indicator of stress in the marine benthos. Mar Ecol. Prog. Ser., 295, 91-103.

Magni, P., Tagliapietra, D., Lardicci, C. 2009 Animal-sediment relationships: evaluating the "Pearson-Rosenberg paradigm" in Mediterranean coastal lagoons. Marine pollution bulletin 58, 478–86.

Paul, J.F., Gentile, J.H., Scott, K.J., Schimmel, S.C., Campbell, D.E., Latimer, R.W. 1999. EMAP-Virginian Province Four-Year Assessment Report (1990–93). EPA 600/R-99/004. U.S. Environmental Protection Agency, Atlantic Ecology Division, Narragansett: Rhode Island.

Pearson T. H., and Rosenberg R. 1978. Macrobenthic succession in relation to organic enrichment and pollution in the marine environment. Oceanography and Marine Biology: an Annual Review, 16: 229-311.