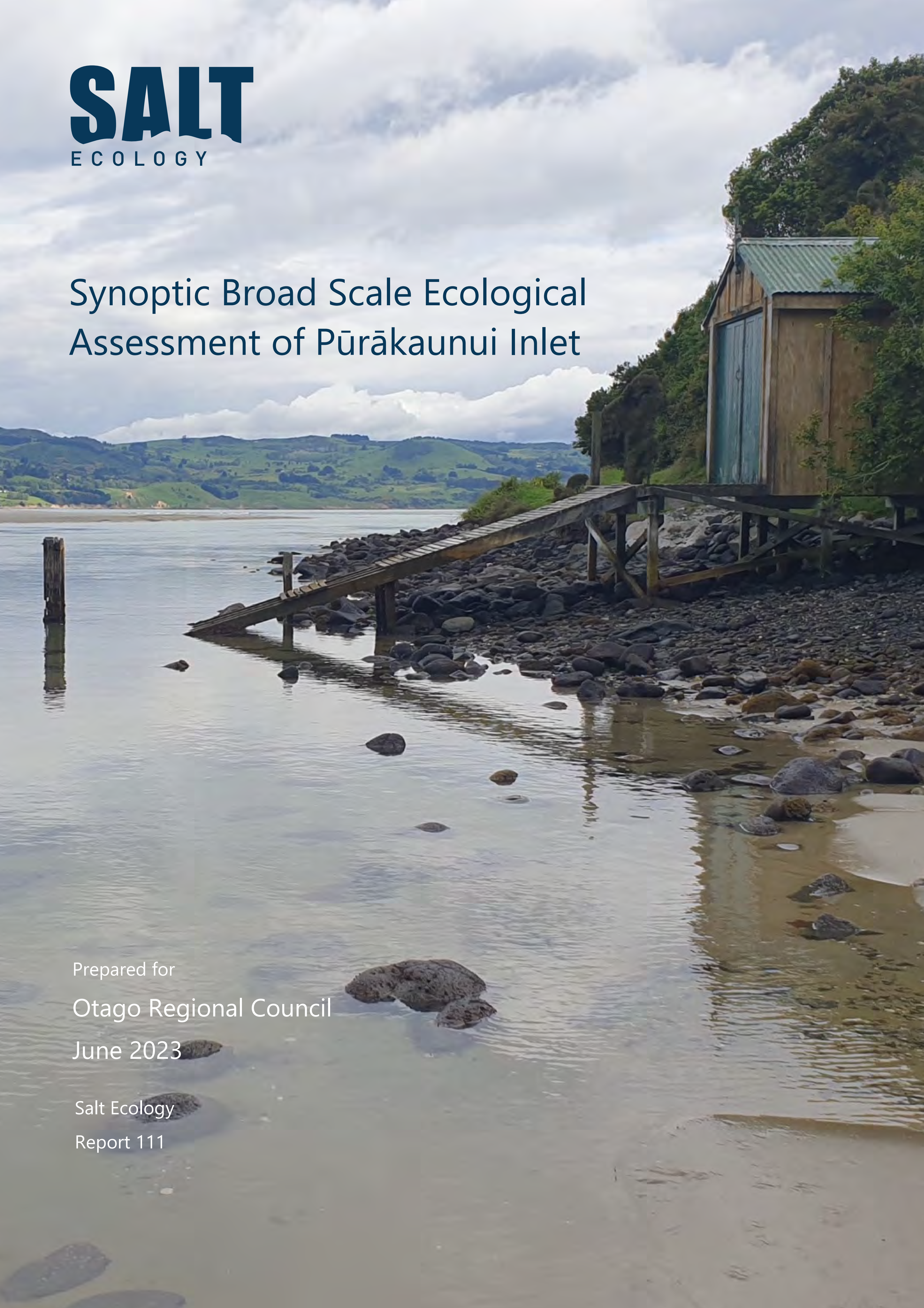
SALT ECOLOGY

Synoptic Broad Scale Ecological Assessment of Pūrākaunui Inlet



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Salt Ecology

Report 111

Cover and back photo: Pūrākaunui entrance showing clear water, clean sands and rocky margin, November 2022.

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SALT ECOLOGY

For the People
Mō ngā tāngata

Synoptic Broad Scale Ecological Assessment of Pūrākaunui Inlet

Prepared by

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for

Otago Regional Council

June 2023

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For the environment
Mō te taiao

GLOSSARY

AA	Affected Area (OMBT metric)
AIH	Available Intertidal Habitat (OMBT metric)
AMBI	AZTI Marine Biotic Index
ANZG	Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2018)
aRPD	Apparent Redox Potential Discontinuity
As	Arsenic
Cd	Cadmium
Cr	Chromium
Cu	Copper
DGV	Default Guideline Value (ANZG 2018)
EQR	Ecological Quality Rating (OMBT metric)
ETI	Estuary Trophic Index
HEC	High Enrichment Conditions
Hg	Mercury
NEMP	National Estuary Monitoring Protocol
Ni	Nickel
OMBT	Opportunistic Macroalgal Blooming Tool
ORC	Otago Regional Council
Pb	Lead
SACFOR	Epibiota categories of Super abundant, Abundant, Common, Frequent, Occasional, Rare
SIDE	Shallow, intertidally dominated estuary
SOE	State of Environment (monitoring)
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TS	Total Sulfur
Zn	Zinc

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Many thanks to Sam Thomas (ORC) for reviewing the draft report. The tools used to QA the GIS data and produce summaries and maps were developed by Megan Southwick (Salt Ecology).

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SUMMARY

Pūrākaunui Inlet is a medium sized (130ha) shallow, intertidally dominated, tidal lagoon type estuary (SIDE) located approximately 20km northeast of Dunedin on New Zealand's southeast coast.

This report describes a survey conducted on 22 November 2022, which mapped intertidal habitats according to the general approach described in New Zealand's National Estuary Monitoring Protocol (NEMP), supported by synoptic sampling of sediment quality, sediment-dwelling biota, and water quality.

KEY FINDINGS

The survey showed that Pūrākaunui Inlet is in a healthy state overall. In contrast to many of the estuaries in the Otago region, it is sand-dominated, supports a relatively species-rich and abundant macroinvertebrate community, and has extensive areas of remaining salt marsh. A summary of key monitoring indicators assessed against preliminary condition rating thresholds for estuary health are provided in the tables below and on the next page. The rating tables show that most indicators meet the classification of 'good' or 'very good', with the exception being the extent of densely vegetated 200m terrestrial margin, which was rated 'fair'. The features that contribute to favourable rating values include the following:

- Relatively extensive salt marsh (23ha or 19.5% of the intertidal area). Historic imagery (earliest from 1956) shows a relatively small decline of ~24% in salt marsh extent compared to natural state, attributable to both natural erosion of the seaward edges of herbfield, and drainage and reclamation of salt marsh for pasture.
- Clean, sand-dominated sediment in most areas, the main exception being the mud-dominated area behind the road causeway at the southern end of the estuary.
- Sparse growths of opportunistic macroalgal species that can become prolific under eutrophic conditions.
- An absence of High Enrichment Condition (HEC) areas displaying persistent symptoms of an enriched and eutrophic sediment state.
- Very low trace metal contaminant concentrations, consistent with the low level of catchment development and absence of significant contaminant sources.
- Low inputs of nutrients and sediment from the surrounding catchment relative to the estuary size.
- A relatively species-rich and abundant sediment-dwelling macrofaunal community, characterised largely by the presence of taxa that are sensitive to disturbance (intolerant of degraded conditions).

Summary of broad scale indicator condition ratings.

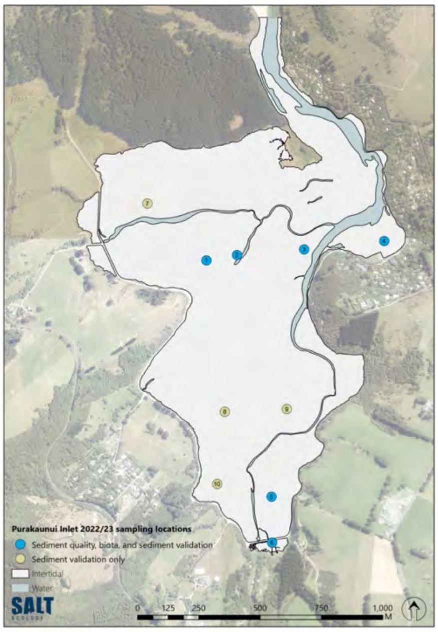
Broad scale Indicators	Unit	Value	Rating
Mapped indicators			
200m terrestrial margin	% densely vegetated	37.1	Fair
Mud-elevated substrate	% intertidal area >25% mud[1]	2.1	Very Good
Macroalgae (OMBT[2])	Ecological Quality Rating (EQR)	0.982	Very Good
Seagrass	% decrease from baseline	no seagrass present	na
Salt marsh extent (current)	% of intertidal area	19.5	Good
Historical salt marsh extent[3]	% of historical remaining	~76%	Good
High Enrichment Conditions	ha	0	Very Good
High Enrichment Conditions	% of estuary	0	Very Good
Estuary-wide sedimentation indicators			
Mean sedimentation ratio[4]	CSR:NSR ratio	1.7	Good
Sedimentation rate[4]	mm/yr	0.2	Very Good

[1]Excludes salt marsh area; [2]OMBT = Opportunistic Macroalgal Blooming Tool; [3]Estimated from historic aerial imagery, [4]CSR=Current Sedimentation Rate, NSR=Natural Sedimentation Rate (predicted from catchment modelling). na = not applicable.

Synoptic sampling sites (1-6) and indicator condition ratings for sediment quality and macrofauna AMBI.

Parameter	Unit	1	2	3	4	5	6
Mud	%	4.8	6.0	3.5	19.2	10.7	78.3
aRPD	mm	8	3	40	12	10	2
TN	mg/kg	< 500	< 500	< 500	< 500	< 500	2300
TP	mg/kg	290	310	270	240	290	600
TOC	%	0.15	0.21	0.14	0.18	0.17	3.30
TS	%	0.03	0.05	0.04	0.06	0.04	0.24
As	mg/kg	3.3	3.4	2.9	2.1	2.8	3.5
Cd	mg/kg	< 0.010	0.011	0.013	0.013	0.013	0.098
Cr	mg/kg	6.0	6.2	4.3	5.2	6.2	12.7
Cu	mg/kg	0.9	1.1	1.0	1.0	1.0	5.9
Hg	mg/kg	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.04
Ni	mg/kg	2.6	2.9	2.3	2.2	2.5	8.1
Pb	mg/kg	1.6	1.9	1.4	2.0	1.8	7.8
Zn	mg/kg	11.7	13.5	9.7	11.9	13.0	48.0
AMBI	na	2.3	1.4	1.3	1.4	2.1	3.5

See Glossary for abbreviations. < Values below lab detection limit. Colour bandings are based on thresholds provided in Table 3.



Seagrass was not present in the estuary and was therefore not rated as an indicator. Historic aerial photographs (earliest 1956) suggests that the estuary has never supported any significant areas of seagrass. As discussed in the main report, Pūrākaunui Inlet has very few of the factors that commonly limit seagrass growth, therefore it is unclear what the driver for seagrass absence is.

Based on model predictions, and considering current catchment land use, we suggest that the estuary may be particularly vulnerable to any future increase in muddy sediment loads. The main factors that contribute to this vulnerability are a predicted high sediment retention (98% trapping efficiency) in the estuary, and two thirds of the catchment being in land-uses that are known to generate a high fine-sediment run-off to waterways, namely pastoral farming and exotic plantation forestry. Currently, the area of mud-elevated substrate (>25% mud content) is very low at 2.1% of the unvegetated intertidal area (rated 'very good'). Changes in land-use, including future harvesting of ~13% of the catchment that is in exotic plantation forest, has the potential to increase the mass load of sediment to the estuary and create muddier, more degraded habitats on the main intertidal flats.

Another key threat to Pūrākaunui Inlet is the potential loss of salt marsh through impacts from drainage, reclamation or grazing, or as a consequence of inundation under predicted sea level rise (SLR) scenarios. Because of the steep-sided or armoured landforms around much of the estuary, there are limited areas for salt marsh to migrate to in response to SLR. The opportunity exists to consider management options that could mitigate or offset these risks.

RECOMMENDATIONS

To mitigate against potential future inputs of catchment-derived muddy sediment and losses of salt marsh in Pūrākaunui Inlet, the following is recommended:

- Undertake broad scale mapping every 5 years, including repeat measurements of sediment grain size.
- Establish sediment plates to measure sediment accretion and mud content in representative areas.
- Undertake an assessment of the predicted impact of SLR on estuary salt marsh, and identify areas where salt marsh may naturally expand or be facilitated by restoration initiatives.
- Evaluate potential future sediment sources to the estuary, and investigate options for a reduction of inputs through either targeted management of land use or the implementation of simple mitigation measures.
- Include Pūrākaunui Inlet in a broader review of the Otago estuary SOE monitoring programme, in order to prioritise long term monitoring needs.

1. INTRODUCTION

Estuary monitoring is undertaken by most councils in New Zealand as part of their State of the Environment (SOE) programmes. The most widely-used monitoring framework is that outlined in New Zealand's National Estuary Monitoring Protocol (NEMP; Robertson et al. 2002). The NEMP is intended to provide resource managers nationally with a scientifically defensible, cost-effective and standardised approach for monitoring the ecological status of estuaries in their region. The results establish a benchmark of estuarine health in order to better understand human influences, and against which future comparisons can be made. The NEMP approach involves two main types of survey:

- Broad scale mapping of estuarine intertidal habitats. This type of monitoring is typically undertaken every 5 to 10 years.
- Fine scale monitoring of estuary biota and sediment quality. This type of detailed monitoring is typically conducted at 2-3 fixed sites in the dominant habitat of the estuary and is repeated at intervals of ~5 years after initially establishing a multi-year baseline.

The approaches are intended to detect and understand changes in estuaries over time, with a particular focus on changes in habitat type (e.g., salt marsh or mud extent), as well as changes within habitats from the input of nutrients, fine (muddy) sediments and contaminants, which are key drivers of degraded estuary sediment condition as well as of eutrophication symptoms such as prolific macroalgal (seaweed) growth.

Otago Regional Council (ORC) has undertaken monitoring of selected estuaries in the region since 2005 using NEMP methods (or extensions of that approach), with key locations being (from north to south) Kakanui, Shag River, Pleasant River, Waikouaiti, Blueskin Bay, Hoopers Inlet, Kaikorai, Tokomairiro, Akatore, Catlins, Tahakopa (Papatowai), Waipati (Chaslands) and Tautuku estuaries. The current report describes the methods and results of a broad scale assessment undertaken on 26 November 2022 in a new location, Pūrākaunui Inlet, located northeast of Dunedin between Waitati and Aramoana (Fig. 1).

The primary purpose of the work was to characterise substrate, salt marsh and the presence and extent of any seagrass or macroalgae, using NEMP broad scale mapping approaches. While NEMP fine scale monitoring focuses on the dominant habitat within an estuary, the protocol does not broadly characterise the ecology of other unvegetated habitats. To address this gap, a synoptic assessment was undertaken of sediment quality, biota and water quality at representative sites throughout the estuary, using some of the same indicators as are typically used for NEMP fine scale monitoring. The purpose of this additional work was two-fold: (1) provide additional information on the ecological condition of unvegetated habitats to support the broad scale assessment, and (2) inform decisions regarding the need for implementation of long-term fine scale SOE monitoring, and provide a basis for identifying potential monitoring sites.

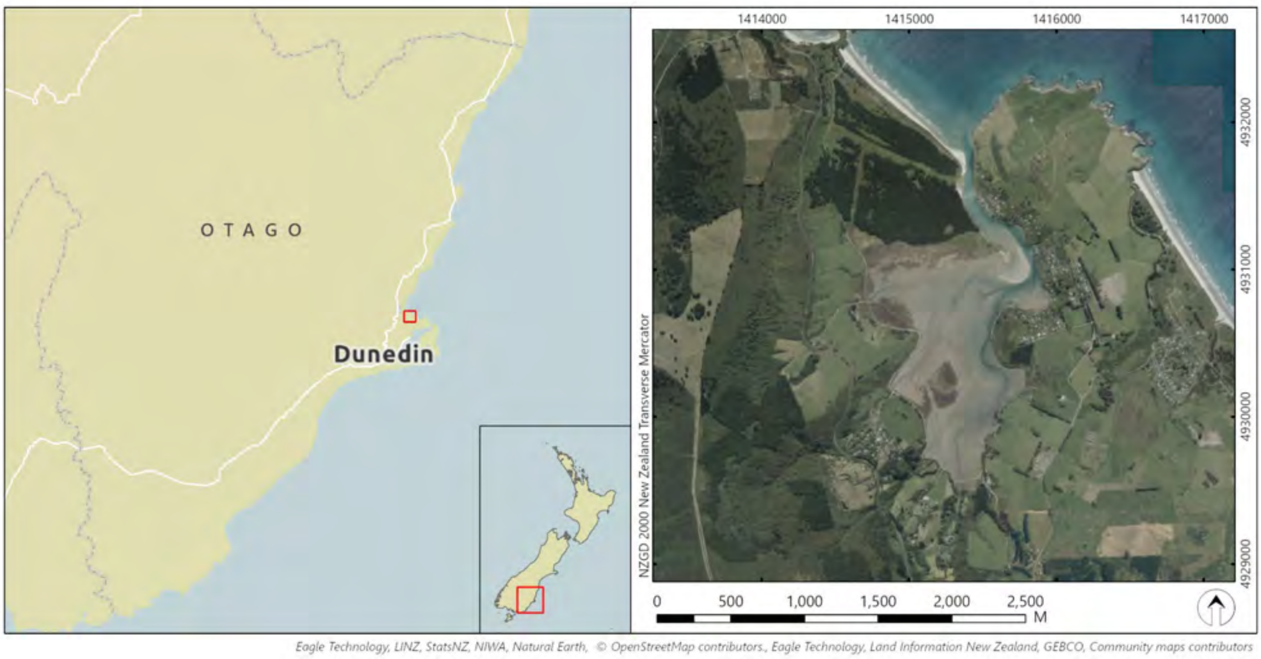


Fig. 1. Location of Pūrākaunui Inlet, Otago.

2. OVERVIEW OF PŪRĀKAUNUI INLET

Pūrākaunui Inlet is a medium sized (130ha) estuarine system located approximately 20km northeast of Dunedin on New Zealand's southeast coast. The estuary's typology is classified a shallow, intertidally dominated, tidal lagoon type estuary (SIDE). It comprises a single, simple basin, with a narrow entrance and extensive tidal flats. The central basin of the estuary is well protected from the ocean by a protruding headland on the true right, and a pine tree covered sand spit on the true left. The estuary drains almost completely at low tide, exposing ~93% of the estuary area. It receives a mean freshwater input of ~0.05m^3/sec, and has an estimated flushing time of 11.5 days (Plew et al. 2018). The freshwater fraction within the estuary is very small (4%), indicating high dilution of freshwater flows by seawater. There appears to be no monitoring of estuary catchment waters by ORC.

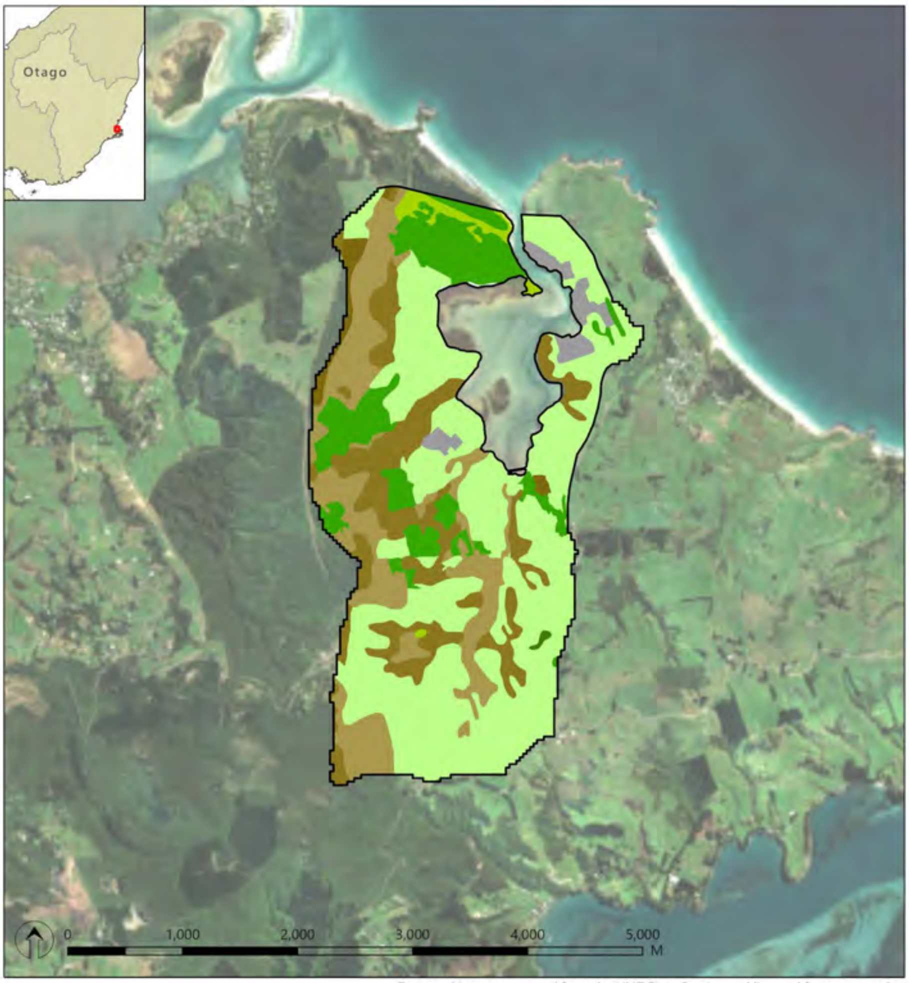
The estuary was rated by Moore (2015) as having 'medium' natural character due to a degree of degradation of the natural forms and processes of the estuary, mainly as a consequence of forest clearance, compromised ecology of the inlet due to a reduction in the indigenous vegetation in and around it, and diminished perceptual natural character due to the presence of cribs and other structures. Despite these issues, Moore (2015) noted that it remained highly scenic, supported cockles and an abundance of other infauna, and was important for wading birds and water fowl. The estuary and surrounds also fall within the Ecosanctuary Predator Free Outer Halo established as part of "The Halo Project - Beyond Orokonui".

Pūrākaunui Inlet was an early Māori settlement, with a fishing camp on the dune (Anderson 1981) and fortified Pā (Māpoutahi) on the narrow headland on the nearby coast. The location provided shelter, kaimoana, including shellfish (pipi, mussels and cockles), seals and birds along the coast, and access to an abundant offshore fishery; and was an important pounamu manufacturing site (Otago Regional Plan (Water)). Several important archaeological sites exist including middens, and much of the northwestern margin of the estuary remains as Māori freehold land where 208ha of land was set aside by the Native Land Court in 1848 and 1868 and, since 1973, Pūrākaunui Incorporation has been responsible for management, use and development of the land (kahurumanu.co.nz/atlas).

We are unaware of any previous comprehensive ecological studies of Pūrākaunui Inlet, hence the broad scale survey described here appears to be one of the first efforts to characterise its main features and current condition.

Despite the absence of direct information on the state of Pūrākaunui Inlet and the quality of catchment freshwater inputs, we expect pressures on the system are likely to be low-to-moderate by comparison with many other estuaries in the region. This is in part due to the low mean freshwater input to the estuary and, based on the LCDB5 (2017/2018) database, approximately one third (~34.6%, 326ha excluding exotic forestry) of the 942ha catchment remains densely vegetated, comprising a mix of native and exotic vegetation (15.4% manuka/kanuka and 17.5% broadleaf indigenous hardwood). The remaining area is predominantly intensive pasture (~48.4%,) low producing pasture (~1.5%), exotic forestry (12.8%), and a small area of urban development (2.5%) on the northern true right near the entrance (Fig. 2).

The estuary nearly completely drains at low tide (top) with eroding sand dunes present near the estuary entrance (bottom).



Catchment Land Use in 2018	ha	%
Artificial Surfaces	0	0
Built-up Area (settlement)	24.0	2.5
Surface Mines and Dumps	0	0
Transport Infrastructure	0	0
Urban Parkland/Open Space	0	0
Bare or Lightly Vegetated Surfaces	0	0
Sand and Gravel	0.4	0.0
Landslide	0	0
Alpine Grass/Herbfield	0	0
Gravel and Rock	0	0
Water Bodies	0	0
River, Lake or Pond	0	0
Cropland	0	0
Short-rotation Cropland	0	0
Orchard Vineyard and Other Perennial Crops	0	0
Grassland, Sedge and Saltmarsh	0	0
High Producing Exotic Grassland	455.7	48.4
Low Producing Grassland	14.0	1.5
Tall Tussock Grassland	0	0
Depleted Grassland	0	0
Herbaceous Freshwater Vegetation	0	0
Herbaceous Saline Vegetation	0.9	0.1
Flaxland	0	0
Scrub and Shrubland	0	0
Fernland	0	0
Gorse and/or Broom	13.9	1.5
Manuka and/or Kanuka	145.2	15.4
Broadleaved Indigenous Hardwoods	164.4	17.5
Sub Alpine Shrubland	0	0
Mixed Exotic Shrubland	0	0
Matagouri or Grey Scrub	0	0
Forest	0	0
Forest Harvested	0	0
Deciduous Hardwoods	1.2	0.1
Indigenous Forest	0	0
Exotic Forest	120.5	12.8
	941.9	100

Data and imagery sourced from the LINZ Data Service and licensed for re-use under the Creative Commons Attribution 4.0 New Zealand license.

Fig. 2. Pūrākaunui Inlet catchment land use classifications from LCDB5 (2017/2018) database.

Much of the estuary margin is modified, with a road around the estuary edge that is protected by a rock wall, which will significantly constrain any future landward migration of the estuary in response to sea level rise.

Roading along the western side of Pūrākaunui Inlet.

Entrance of Pūrākaunui Inlet.

Boatsheds on the eastern side of Pūrākaunui Inlet.

3. METHODS

3.1 OVERVIEW

The survey of Pūrākaunui Inlet was carried out on 26 November 2022. It consisted of broad scale habitat mapping of substrates and vegetation and targeted sampling of sediment quality and macrofauna in representative areas. Fig. 3 shows the estuary area surveyed, and indicates where the sampling described below was undertaken. Details of the survey approach, sampling methods and analyses are provided in Appendix 1, and are summarised below and in Table 1 and Table 2.

3.2 BROAD SCALE HABITAT MAPPING

Broad scale mapping characterised the dominant intertidal substrates and vegetation types, with the spatial extent and location of different habitat types, and temporal changes in features, providing valuable indicators of estuary condition. Mapping was based on NEMP methods (Robertson et al. 2002), and included refinements by Salt Ecology that improve the utility and accuracy of the NEMP approach.

The approach combined the use of aerial imagery, detailed field ground-truthing (e.g., annotation of laminated aerial photos, spot data on macroalgae and substrate type recorded in a web-based app, and field photos), and post-field digital mapping using Geographical Information System (GIS) technology. Aerial imagery for Pūrākaunui Inlet was sourced from LINZ Data Service and consisted of 30cm/pixel colour aerial imagery captured in the summer of 2018-2019. QA/QC procedures, applied through the phases of field data collection, digitising, and GIS data collation processing, are described in Appendix 1.

The main broad scale survey elements were as follows.

- Substrate mapping subjectively classified sediments (e.g., mud, sand, gravel, cobble, bedrock) according to the scheme described in Table A2 of Appendix 1. As mud is a key stressor on estuary habitats, an important focus was to map the spatial extent of soft-sediment (mud and sand) habitats, with laboratory analyses of grain size collected from 10 representative locations (Fig. 3) used to validate field classifications.
- Vegetation mapping characterised high-value features, namely salt marsh (e.g., rushland, herbfield, sedgeland) and seagrass (*Zostera muelleri*), and also described the occurrence and extent of algae species that can be symptomatic of estuary degradation. Particularly important among the latter were nuisance 'opportunistic' macroalgae that can 'bloom' in response to conditions such as excess nutrient inputs, including the red seaweed *Agarophyton* spp. and green 'sea lettuce' *Ulva* spp.
- To assist with percent cover estimates of seagrass and opportunistic macroalgae, a visual rating scale was used based on photographs shown in Fig. 4. For macroalgae, field data collection also included wet-weighing of macroalgae biomass, to enable calculation of Opportunistic Macroalgal Blooming Tool (OMBT) scores. The OMBT is a multi-metric index that combines different measures of opportunistic macroalgal proliferation into an integrated measure of ecological condition (see Table 1; Appendix 1; WFD-UKTAG 2014; Stevens et al. 2022).

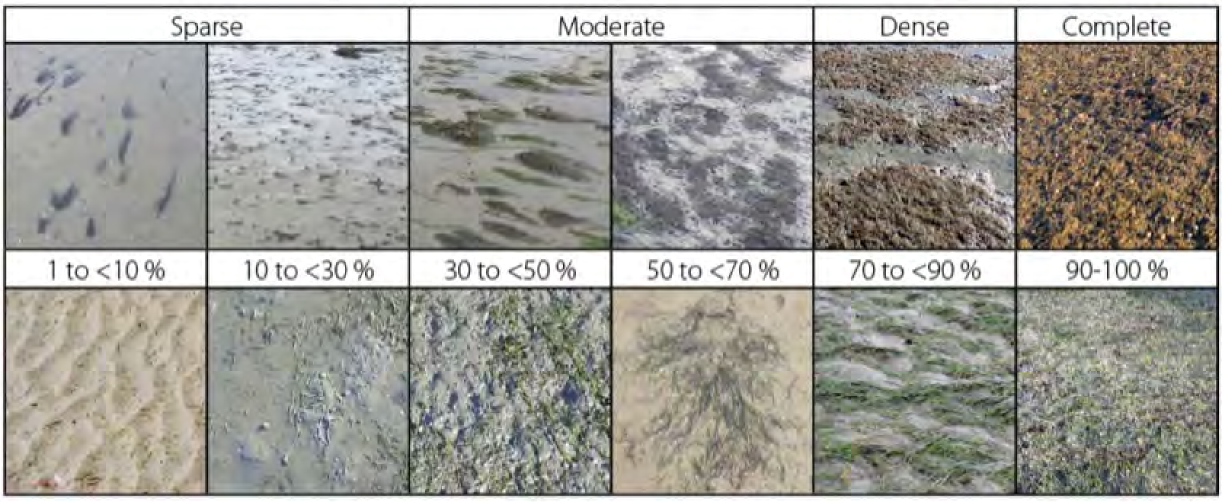


Fig. 3. Visual rating scale for percentage cover estimates. Macroalgae (top), seagrass (bottom). Modified from FGDC (2012).

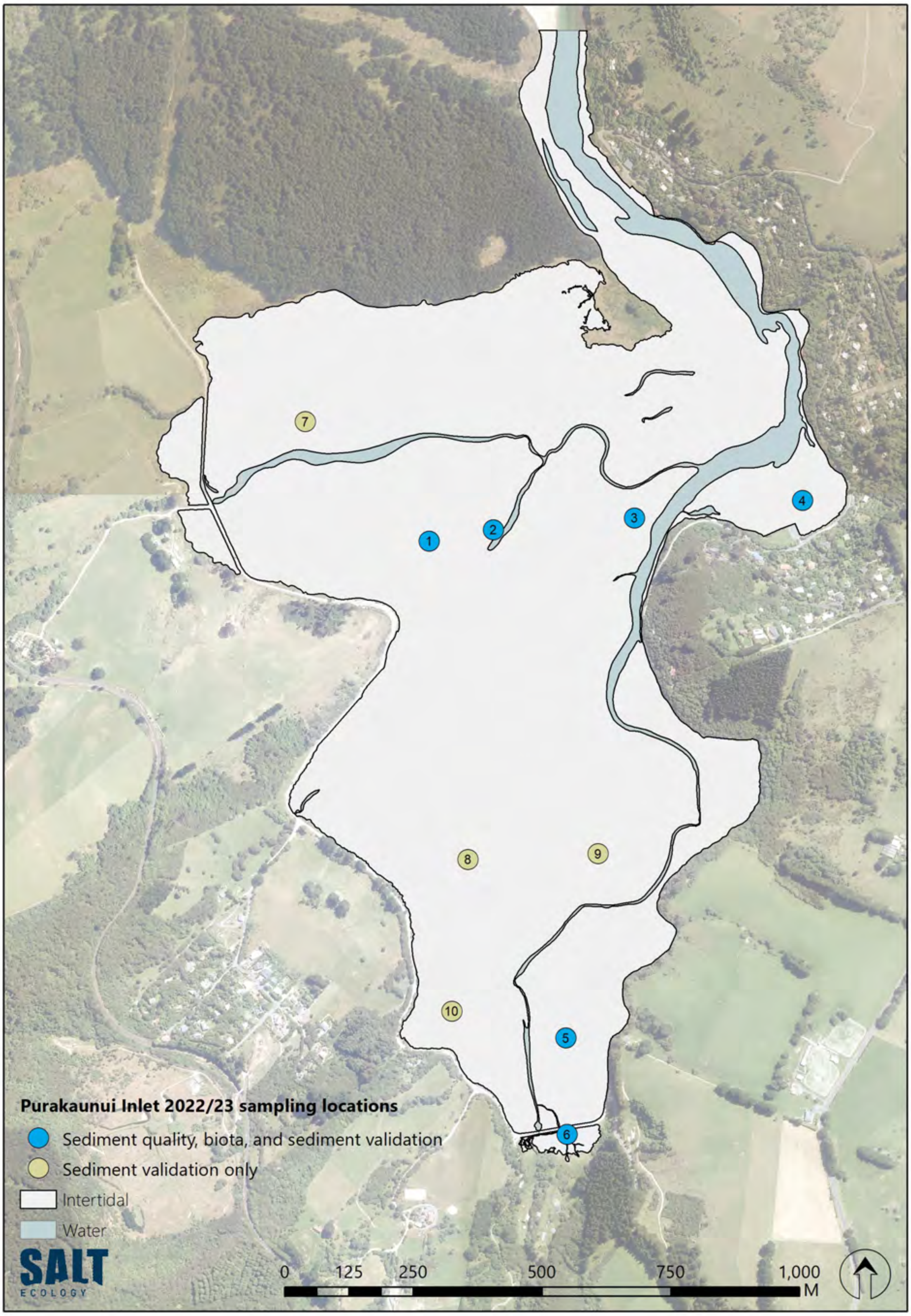


Fig. 4. Location of sites for sediment quality and biota samples (1-6) and sediment validation (1-10).

Table 1. Broad scale indicators of estuary condition that are assessed by field mapping and related methods.

Indicator	General rationale	Method description
Terrestrial margin vegetation	A densely vegetated terrestrial margin filters and assimilates sediment and nutrients, is a buffer to introduced grasses and weeds, is an important food source and habitat for a variety of species and, in waterway riparian zones, provides shade that moderates stream temperature fluctuations, and improves estuary biodiversity.	Mapped based on aerial extent and classified using the LCDB5 classes, dominant species are also recorded as meta data where known.
Substrate type	High substrate heterogeneity generally supports high estuary biodiversity. Increases in fine sediment (i.e., mud <63µm) can reduce heterogeneity, concentrate contaminants, nutrients and organic matter, and lead to degradation of benthic communities by displacing sensitive species including shellfish. Enrichment of muddy sediments (i.e., high TOC and nutrients; Table 2) can additionally fuel algal growth and deplete sediment oxygen.	Mapped based on aerial extent and classified using a modified version of the NEMP system (see Table A2, Appendix 1). The improved classification frame-work, developed by Salt Ecology, characterises substrate type based on mud content and is supported by grain size validation samples. Substrate type is also recorded beneath vegetation.
Salt marsh	Salt marsh (vegetation able to tolerate saline conditions where terrestrial plants are unable to survive) is important in estuaries as it is highly productive, naturally filters and assimilates sediment and nutrients, mitigates shoreline erosion, and provides an important habitat for a variety of species including insects, fish and birds.	Mapped based on aerial extent. Dominant salt marsh species are recorded and categorised into sub-classes (e.g., rushland, herbfield). Pressures on salt marsh (e.g., drainage, grazing, erosion) are also recorded.
Seagrass	Seagrass (*Zostera muelleri*) beds enhance primary production and nutrient cycling, stabilise sediments, elevate biodiversity, and provide nursery and feeding grounds for invertebrates and fish. Seagrass is vulnerable to muddy sediments in the water column (reducing light), sediment smothering (burial), excessive nutrients (primarily secondary impacts from macroalgal smothering), and sediment quality (e.g., low oxygenation).	Mapped based on aerial extent, and percent cover recorded within each seagrass patch. Pressures on seagrass beds (e.g., sediment or macroalgae smothering, leaf discolouration) are also recorded.
Opportunistic macroalgae	Opportunistic macroalgae (species of *Agarophyton* and *Ulva*) are a symptom of estuary eutrophication (nutrient enrichment). At nuisance levels, these algae can form mats on the estuary surface that can adversely impact underlying sediments and fauna, other algae, fish, birds, seagrass, and salt marsh. The Opportunistic Macroalgal Blooming Tool (OMBT) is a multi-metric index that combines different measures of macroalgae (see text) and is calculated as an indicator of ecological condition.	Mapped based on aerial extent. Species, percent cover, biomass and level of entrainment are recorded in each macroalgae patch to apply the OMBT (WFD-UKTAG 2014). The application of the OMBT incorporates New Zealand-based improvements described in Plew et al. (2020) and Stevens et al. (2022).
High Enrichment Conditions	HECs characterise substrates with extreme levels of organic or nutrient enrichment (i.e., eutrophication). HECs are sediments depleted in (or devoid of) oxygen, which have a very shallow aRPD (e.g., <10mm; Table 2), an intense black colour in the sediment profile, and typically have a strong hydrogen sulfide (i.e., rotten egg) smell. Sediment samples are likely to have a quantitatively high nutrient or organic content (e.g., TOC >2%; Table 2). In a broad scale context, the HEC metric is intended as an initial guide to highlight areas of enrichment that may require further investigation.	Mapped based on aerial extent where there are obvious low sediment oxygen conditions (e.g., black sediments with rotten egg smell), conspicuous surface growths of sulfur-oxidising bacteria, stable, entrained, dense (>50% cover) beds of opportunistic macroalgae, or the extensive presence of surface micro-algae or filamentous-algae.

3.3 SEDIMENT QUALITY AND BIOTA

Sampling of sediment quality and associated biota was undertaken in representative soft-sediment habitats at six discrete sites (Fig. 3). Table 2 summarises sediment and biota indicators, field sampling methods, and the rationale for their use. These indicators, and the associated sampling methods, largely adhered to the NEMP protocol for 'fine scale' surveys of estuaries (except as noted in Table 2). However, whereas NEMP fine scale surveys involve intensive (high replication) sampling of 1-3 sites (typically) in the most common estuary habitat, the current survey had a less intensive, estuary-wide focus to provide a synoptic picture of ecological health across the range of soft-sediment habitat types present. The key sampling elements can be summarised as follows:

- Sediment quality: Indicators included sediment mud content, oxygenation status (measured as the apparent Redox Potential Discontinuity depth; aRPD), nutrients and organic content, and chemical contaminants (selected trace elements). Sediment aRPD was measured in the field. For the other variables a single sample for sediment quality analyses at each site was composited from three sub-samples, and sent to Hill Labs for analysis.
- Biota: The focus was on macrofauna, which are small organisms that live within or on the sediment matrix, which were sampled quantitatively using sediment cores (130mm diameter, 150mm deep). The composition of the core samples in terms of macrofauna species (or higher taxa) and their abundance, was determined by taxonomic experts at NIWA. We also used qualitative field methods to estimate the abundance or percent cover of conspicuous surface-dwelling estuary snails, macroalgae and microalgae.

In addition to the raw indicator data, three measures of macrofauna health were derived. Two of these (richness and abundance) are simple measures that describe the number of different species present in a sample (i.e., richness), and total organism abundance. A third derived variable ('AMBI') was also calculated. The AMBI is an international biotic health index (Borja et al. 2000) whose calculation is based on the proportion of macrofauna species falling into one of five eco-groups (EG) that reflect sensitivity to pollution, ranging from relatively sensitive (EG-I) to relatively resilient (EG-V).

The QA/QC procedures applied through the phases of field data collection, lab dispatch of samples, data transfer, macrofauna naming, EG standardisation, and other QA procedures, are described in Appendix 1.

Collection of sediment core (top), and rinsing the core sieve bags in the subtidal channel (bottom).

3.4 ASSESSMENT OF ESTUARY CONDITION

In addition to the authors' expert interpretation of the data and summaries, results are assessed against established or developing estuarine health metrics ('condition ratings'), drawing on approaches from New Zealand and overseas (Table 3). These metrics assign different indicators to one of four colour-coded 'health status' bands, as shown in Table 3.

In previous reports for ORC, we have also calculated scores for the New Zealand Estuary Trophic Index (ETI). The ETI is a multi-metric index developed in New Zealand to provide a single score for estuary health. However, as the ETI documentation provides no clear guidance on the estuary area (and associated data) that should be used for the calculation, ETI scores can vary according to the data choices made; for example, whether scores are calculated from the most degraded sections of an estuary, or for the estuary overall. As such, we have deferred the further application of the ETI approach until the methodology issues are resolved.

Note that there are two broad scale rating indicators (salt marsh and seagrass) that rely on assessment of differences between current state and historic or baseline state. For this purpose we undertook the following:

- For salt marsh, we looked at historic aerial imagery captured in 1956, 1967, 1971, 1982, 2000 and 2019 (retrolens.co.nz). In ArcMap 10.8 the imagery was geo-referenced and then the area of salt marsh digitised to get an estimate of historic salt marsh extent.
- For seagrass % decrease from baseline, the same aerial imagery showed no historic areas of distinguishable seagrass.

Table 2. NEMP sediment quality and biota indicators, rationale for their use, and sampling method. Any significant departures from the NEMP are described in footnotes.

Indicator	General rationale	Sampling method
Physical and chemical		
Sediment grain size	Indicates the relative proportion of fine-grained sediments that have accumulated.	Composited surface scrape to 20mm sediment depth.
Nutrients (nitrogen and phosphorus), organic matter & total sulfur	Reflects the enrichment status of the estuary and potential for algal blooms and other symptoms of enrichment.	Surface scrape to 20mm sediment depth. Organic matter measured as Total Organic Carbon (TOC) (note 1).
Trace elements (arsenic copper, chromium, cadmium, lead, mercury, nickel, zinc)	Common toxic contaminants generally associated with human activities. High concentrations may indicate a need to investigate other anthropogenic inputs, e.g., pesticides, hydrocarbons.	Surface scrape to 20mm sediment depth (note 2).
Substrate oxygenation (apparent Redox Potential Discontinuity depth; aRPD)	Measures the enrichment/trophic state of sediments according to the depth of the apparent Redox Potential Discontinuity layer (aRPD). This is the visual transition between brown oxygenated surface sediments and deeper less oxygenated black sediments. The aRPD can occur closer to the sediment surface as organic matter loading or sediment mud content increase.	Sediment core, split vertically, with average depth of aRPD recorded in the field where visible.
Biological		
Macrofauna	Abundance, composition and diversity of infauna living with the sediment are commonly-used indicators of estuarine health.	130mm diameter sediment core to 150mm depth (0.013m^2 sample area, 2L core volume), sieved to 0.5mm to retain macrofauna.
Epibiota (epifauna)	Abundance, composition and diversity of epifauna are commonly-used indicators of estuarine health.	Abundance based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (macroalgae)	The composition and prevalence of macroalgae are indicators of nutrient enrichment.	Percent cover based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (microalgae)	The prevalence of microalgae is an indicator of nutrient enrichment.	Visual assessment of conspicuous growths based on SACFOR in Appendix 1, Table B3 (notes 3, 4).

[1] Since the NEMP was published, Total Organic Carbon (TOC) has become available as a routine low-cost analysis which provides a more direct and reliable measure than the NEMP recommendation of converting Ash Free Dry Weight (AFDW) to TOC.

[2] Arsenic and mercury are not specified in the NEMP, but can be included in the trace element suite by the analytical laboratory.

[3] Assessment of epifauna, macroalgae and microalgae uses SACFOR instead of quadrat sampling outlined in the NEMP. Quadrat sampling is subject to considerable within-site variation for epibiota that have clumped or patchy distributions.

[4] NEMP recommends taxonomic composition assessment for microalgae but this is not typically undertaken due to clumped or patchy distributions and the lack of demonstrated utility of microalgae as a routine indicator.

Table 3. Indicators used to assess results in the current report. See Glossary for definitions.

a. Broad scale

Indicator	Unit	Very good	Good	Fair	Poor
Mapped indicators					
200m terrestrial margin[1]	% densely vegetated	≥ 80 to 100	≥ 50 to 80	≥ 25 to 50	< 25
Mud-elevated substrate[2, 3]	% intertidal area >25% mud	< 1	1 to 5	> 5 to 15	> 15
Macroalgae (OMBT)[2,4]	Ecological Quality Rating	≥0.8 to 1.0	≥0.6 to <0.8	≥0.4 to <0.6	0.0 to <0.4
Seagrass[1]	% decrease from baseline	< 5	≥ 5 to 10	≥ 10 to 20	≥ 20
Salt marsh extent (current)[1]	% of intertidal area	> 20	> 10 to 20	> 5 to 10	0 to 5
Historical salt marsh extent[1,5]	% historical remaining	≥ 80 to 100	≥ 60 to 80	≥ 40 to 60	< 40
High Enrichment Conditions[1,6]	ha	< 0.5	≥ 0.5 to 5	≥ 5 to 20	≥ 20
High Enrichment Conditions[1,6]	% of estuary	< 1	≥ 1 to 5	≥ 5 to 10	≥ 10
Estuary-wide sedimentation indicators					
Mean sedimentation ratio[2,7]	CSR:NSR ratio	1 to 1.1 x NSR	>1.1 to 2	>2 to 5	> 5
Sedimentation rate[8]	mm/yr	< 0.5	≥0.5 to < 1	≥1 to < 2	≥ 2

1. General guidance as used in SOE reports for council(s) since 2007.
2. Ratings derived from Robertson et al. (2016).
3. Mud-elevated substrate modified from Robertson et al. (2016) to apply to the intertidal area excluding salt marsh, not the whole estuary area.
4. OMBT = Opportunistic Macroalgal Blooming Tool (WFD-UKTAG 2014).
5. Estimated from historic aerial imagery.
6. The final condition rating is based on the worst of the two High Enrichment Condition (HEC) scores.
7. Current Sedimentation Rate (CSR) to Natural Sedimentation Rate (NSR) ratio derived from catchment models (Hicks et al. 2019).
8. Condition rating adapted from Townsend and Lohrer (2015). Sedimentation rate derived from catchment models (Hicks et al. 2019).

b. Sediment quality and macrofauna

Indicator	Unit	Very good	Good	Fair	Poor
Sediment quality and macrofauna					
Mud content[1]	%	< 5	5 to < 10	10 to < 25	≥ 25
aRPD depth[2]	mm	≥ 50	20 to < 50	10 to < 20	< 10
TN[1]	mg/kg	< 250	250 to < 1000	1000 to < 2000	≥ 2000
TP			Requires development		
TOC[1]	%	< 0.5	0.5 to < 1	1 to < 2	≥ 2
TS			Requires development		
Macrofauna AMBI[1]	na	0 to 1.2	> 1.2 to 3.3	> 3.3 to 4.3	≥ 4.3
Sediment trace contaminants[3]					
As	mg/kg	< 10	10 to < 20	20 to < 70	≥ 70
Cd	mg/kg	< 0.75	0.75 to <1.5	1.5 to < 10	≥ 10
Cr	mg/kg	< 40	40 to <80	80 to < 370	≥ 370
Cu	mg/kg	< 32.5	32.5 to <65	65 to < 270	≥ 270
Hg	mg/kg	< 0.075	0.075 to <0.15	0.15 to < 1	≥ 1
Ni	mg/kg	< 10.5	10.5 to <21	21 to < 52	≥ 52
Pb	mg/kg	< 25	25 to <50	50 to < 220	≥ 220
Zn	mg/kg	< 100	100 to <200	200 to < 410	≥ 410

1. Ratings from Robertson et al. (2016).
2. aRPD based on FGDC (2012).
3. Trace element thresholds scaled in relation to ANZG (2018) as follows: Very good <0.5 x DGV; Good 0.5 x DGV to <DGV; Fair DGV to <GV-high; Poor >GV-high. DGV = Default Guideline Value, GV-high = Guideline Value-high.

4. BROAD SCALE MAPPING

A summary of the November 2022 mapping survey in Pūrākaunui Inlet is provided below. Supporting GIS files have been separately supplied to ORC, with ground-truthing tracks shown in Appendix 2.

4.1 TERRESTRIAL MARGIN

Table 4 and Fig. 5 summarise the land cover of the 200m terrestrial margin, which comprises primarily high and low producing grassland (43.7%), exotic forest (18%) and built-up areas of urban settlement (16.5%). A road encroaches on much of the western edge of the estuary, with a causeway also cutting across the southern end. The dune areas near the entrance are dominated by exotic forest interspersed with marram grass, tree lupin, gorse and bracken fern, and retain few natural dune habitat features. A total of 37% of the margin was categorised as densely vegetated, mainly mixed native scrub, which corresponds to a condition rating of 'fair'.

Table 4. Summary of 200m terrestrial margin land cover.

LCDB Class		%
1	Built-up Area (settlement)	16.5
2	Urban Parkland/Open Space	0.1
5	Transport Infrastructure	2.6
40	High Producing Exotic Grassland	29.9
41	Low Producing Grassland	13.7
47	Flaxland	0.2
50	Fernland	0.1
51	Gorse and/or Broom	0.0
52	Mānuka and/or Kānuka	2.4
54	Broadleaved Indigenous Hardwoods	16.3
56	Mixed Exotic Shrubland	0.2
71	Exotic Forest	18.0
Grand Total		100
Total dense vegetated margin*		37.1

*LCDB classes 45-71.

Road bordering the estuary constraining landward migration of salt marsh.

Mixed native and exotic scrub on the western margin.

Cleared and drained salt marsh on the western margin was historically fenced and grazed.

A causeway cuts across the southern end of the estuary.

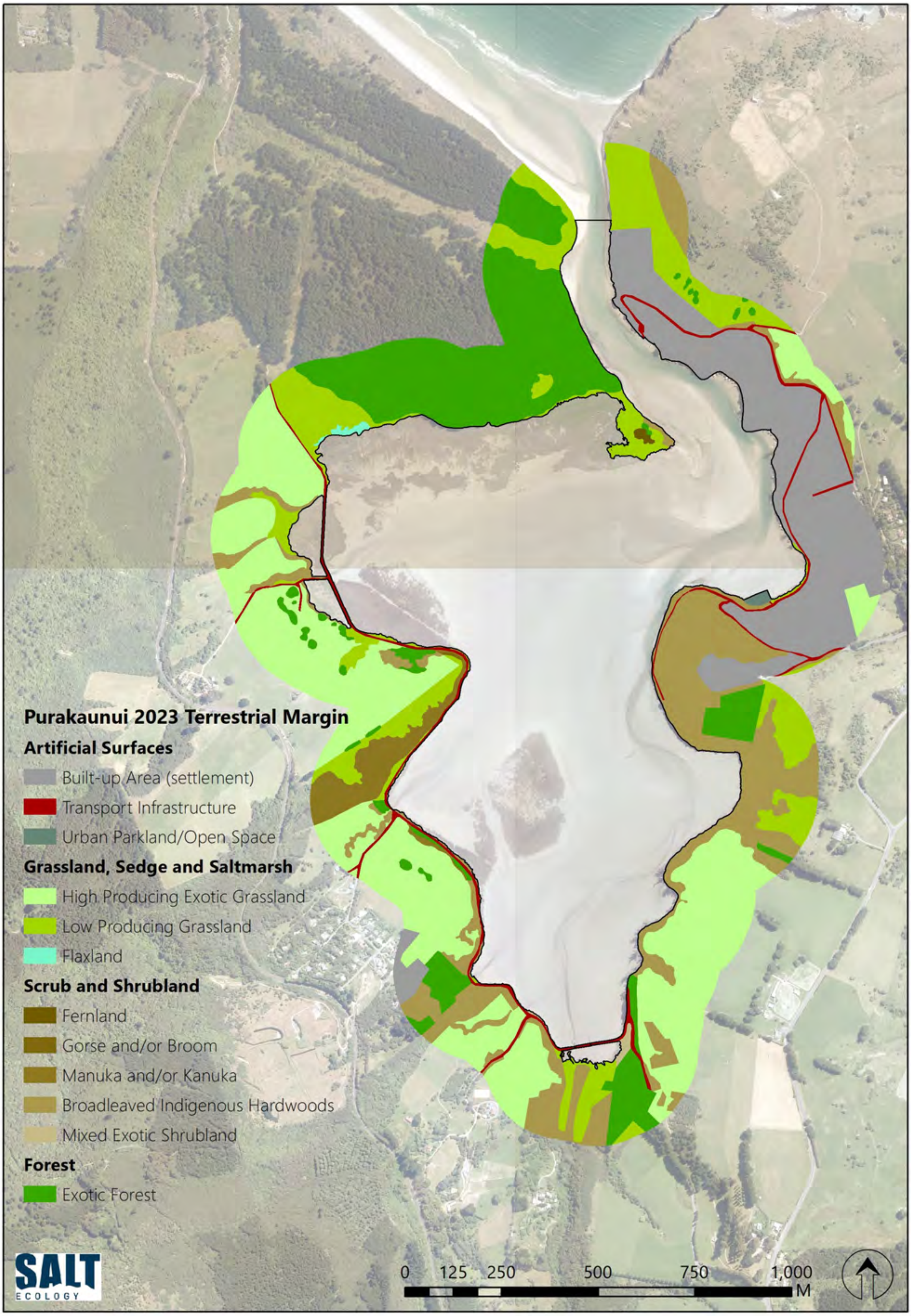


Fig. 5. Map of 200m terrestrial margin land cover.

4.2 SALT MARSH

The total mapped intertidal area of 130ha had 23.6ha of salt marsh (Table 4). The majority was located in the north and west of the main basin (Fig. 6), and was dominated by herbfield (77.7%), with the dominant species being glasswort (*Sarcocornia quinqueflora)* and, to a lesser extent, remuremu (*Selliera radicans*). There were also prominent areas of rushland and smaller areas of estuarine shrub, with the main species noted in Table 5 and Appendix 3.

Table 5. Summary of salt marsh area (ha and %).

Sub-class	Dominant species	Ha	%
Estuarine Shrub		0.1	0.2
	Plagianthus divaricatus (Salt marsh ribbonwood)	0.1	0.2
Rushland		5.2	22.1
	Apodasmia similis (Jointed wirerush)	0.7	3.0
	Juncus kraussii (Searush)	4.5	19.1
Herbfield		18.3	77.7
	Leptinella dioica	<0.1	<0.1
	Samolus repens (Primrose)	<0.1	0.2
	Sarcocornia quinqueflora (Glasswort)	16.1	68.0
	Selliera radicans (Remuremu)	2.2	9.4
	Suaeda novaezelandiae (Sea blite)	<0.1	<0.1
Total		23.6	100

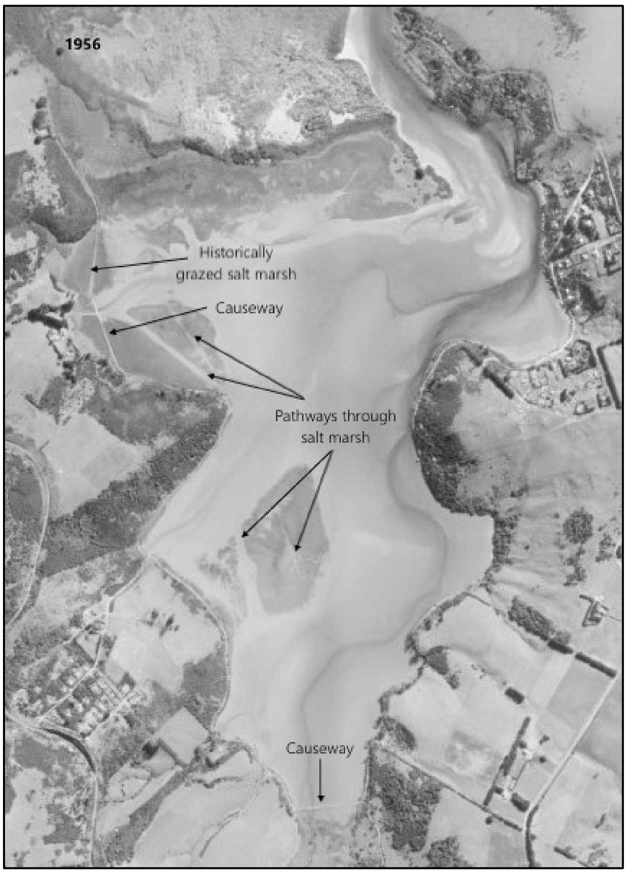
Most (~87%) of the substrate within salt marsh had an elevated mud component (>25% mud), with 77% being classified as muddy sand (25-50% mud) and 10% being sandy mud (50-90% mud). Substrate details for salt marsh and other vegetated habitats are provided in Appendix 4.

LiDAR data (Appendix 5) and historic aerial imagery dating back to 1956 (see photo opposite) were used to estimate the extent of salt marsh prior to modification of the estuary through drainage and reclamation. Although photo resolution limited the accuracy with which changes could be estimated, and the earliest imagery reflected the state of the estuary after extensive modification had already occurred, we estimate the historic extent of salt marsh to have been ~31ha (Fig. 7), and likely comprised a similar ratio of herbfield and rushland as is currently present.

Extensive changes were evident within the salt marsh present in 1956, with straight narrow strips of unvegetated habitat on the western side of the estuary likely reflecting historical transport pathways through the herbfields, which remain evident to the present day. Drainage and reclamation of the salt marsh in the low-lying northwest of the estuary, and causeways restricting tidal exchange, are also likely to have reduced the extent and ecological condition of the remaining salt marsh.

Based on the current salt marsh extent, there has been an estimated loss of 7.4ha (or 24% of salt marsh) when compared to the estimated historic extent. Although the magnitude of the loss is relatively high, the percentage of salt marsh remaining (i.e., 76% of natural cover remains) equates to a condition rating of 'good' (see Table 3). This partly reflects that most of the development of the estuary margin has occurred on the eastern side of the estuary, where steep hillsides would have naturally precluded the establishment of extensive salt marsh habitat, limiting losses in an overall estuary context.

The largest losses have occurred on the seaward edges of herbfield in the central and northwest of the estuary, where where a comparison with historic imagery suggests that there has been erosion of the beds, resulting in a 20-50m retreat of their margin, and in the south and west of the estuary where salt marsh has been drained and reclaimed for pasture (Fig. 7).



Historic image from 1956 with annotations highlighting causeways and transport pathways through salt marsh.

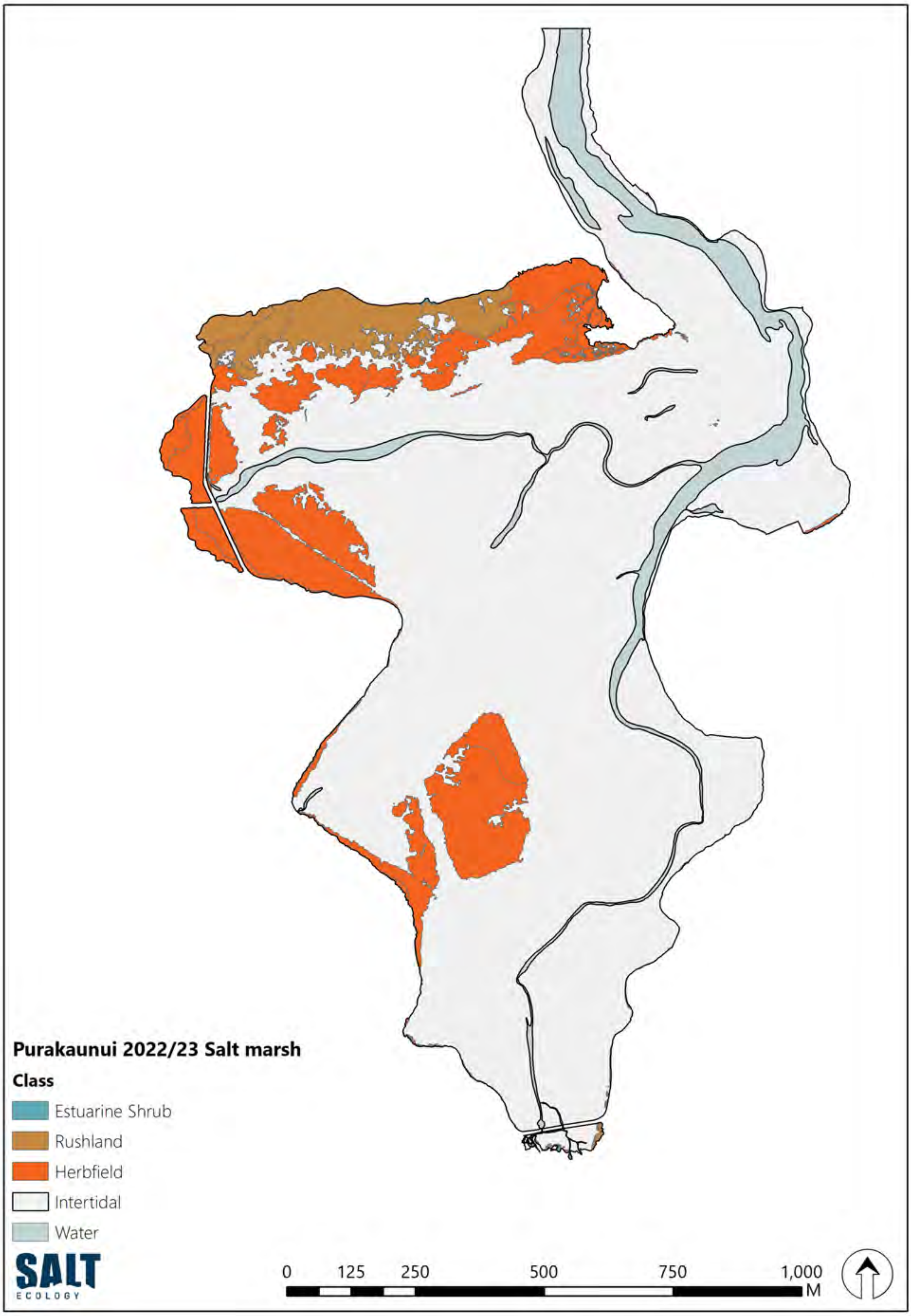


Fig. 6. Salt marsh sub-classes and their distribution.

Road cutting through salt marsh on the western side of the estuary.

Drainage channels cut through previously grazed herbfield.

Old fence line indicating the extent of historical salt marsh grazing well into the main estuary basin.

The photos opposite illustrate the modification of the saltmarsh in the northwest of the estuary, with the road causeway constructed through the middle of the herbfield, restricting both tidal exchange and freshwater drainage. On the landward side of the causeway, drainage channels have been historically cut throughout the herbfield in an effort to drain the area for grazing. While estuarine herbfield species persist in these areas, many plants intolerant of regular saltwater inundation are now also present, highlighting the reduced saline influence.

It was noted that the margins of salt marsh in this part of the estuary have been recently planted in native species as part of an extensive restoration initiative (see photos below). Combined with stock exclusion from the salt marsh, this initiative is expected to significantly enhance the biodiversity value of the estuary and lead to long-term improvements in salt marsh condition. Such efforts would be further enhanced by increasing tidal exchange through the removal of flapgates or other flow barriers, and minimising the influence of drainage channels, e.g., allowing historical drains to naturally infill over time.

Restoration planting along the terrestrial margin in the west of the estuary, and fence line indicating historical grazing of salt marsh.

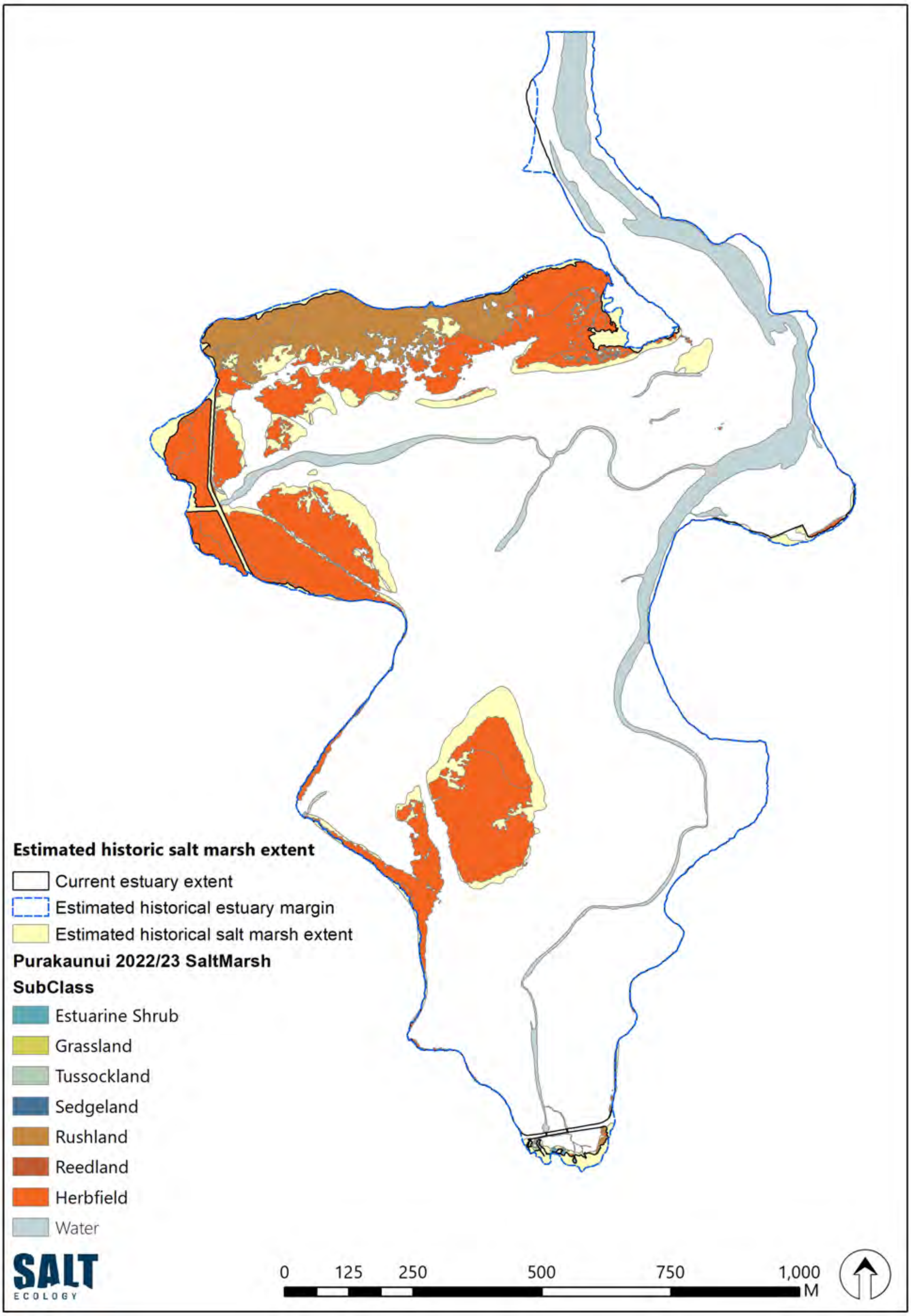


Fig. 7. Salt marsh sub-classes and their distribution compared to the estimated historical salt marsh extent.

4.3 SUBSTRATE

The mapped intertidal area outside the 24ha of saltmarsh was 121ha, and had substrates dominated by sandy sediments but also including large numbers of shellfish as a sub-dominant component (Table 6, Fig. 8). The subjective sediment classifications applied during field mapping matched 8 of the 10 sediment grain size laboratory validation measures, with the other 2 samples being <5% different from the subjective mud threshold boundaries, and within the tolerance adopted for this method (Appendix 6).

Table 6. Summary of dominant intertidal substrate outside areas of salt marsh.

Substrate Class	Features	Ha	%
Bedrock	Rock field	0.3	0.3
Coarse substrate (>2mm)	Boulder field	0.3	0.3
	Artificial Boulder field	0.1	0.1
	Cobble field	1.5	1.2
	Gravel field	0.7	0.6
	Shell bank	0.3	0.3
Sand (0-10% mud)	Firm shell/sand	5.0	4.1
	Mobile sand	8.5	7.0
	Firm sand	42.8	35.3
Muddy Sand (>10-25% mud)	Firm muddy shell/sand	0.9	0.7
	Firm muddy sand	37.7	31.1
Muddy Sand (>25-50% mud)	Firm muddy sand	12.8	10.6
	Soft muddy sand	7.0	5.8
Sandy Mud (>50-90% mud)	Soft sandy mud	2.5	2.1
	Very soft sandy mud	0.8	0.6
Total		**121**	**100**

Around 57% of the intertidal estuary area consisted of sand (<10% mud content), comprising rippled mobile sand mostly towards the estuary entrance (9%) and firm sand and sand/shell in the central basin (49%). Small areas of harder substrates (cobble, gravel and bedrock) comprised 3% and were located mainly on the true right of the lower estuary.

As a general trend, the sediments became muddier with distance up-channel, although sediments remained relatively low in mud content (37% of the intertidal area outside salt marsh was 10-25% mud), and there were very few areas with a mud content elevated above the 25% threshold generally regarded as being biologically significant (2.6ha, 3% of intertidal area outside salt marsh). The muddiest sediments were in the embayment behind the causeway at the south of the estuary. The overall low area of mud-elevated sediments (>25% mud) corresponded to a condition rating of 'good'.

Estuary entrance showing boulder and rock (foreground) and firm and mobile sand (background).

Mobile sand and cockle shell in the lower estuary.

Firm estuary sand flats in the central estuary.

Very soft sandy mud trapped behind the causeway in the south of the estuary. Mud snails visible on the surface.

Mobile sands near the estuary entrance.

Sand and cockle beds near the low tide channel in the central basin.

Artificial rock wall and gravel field in the lower eastern estuary.

Sediment core showing cockles growing in sandy surface sediments. Note the relatively deep aRPD depth (~40mm) indicating good sediment oxygenation.

Cobble and gravel field habitat along the western upper tidal margin, flanked by extensive flats of muddy sand (10-25% mud).

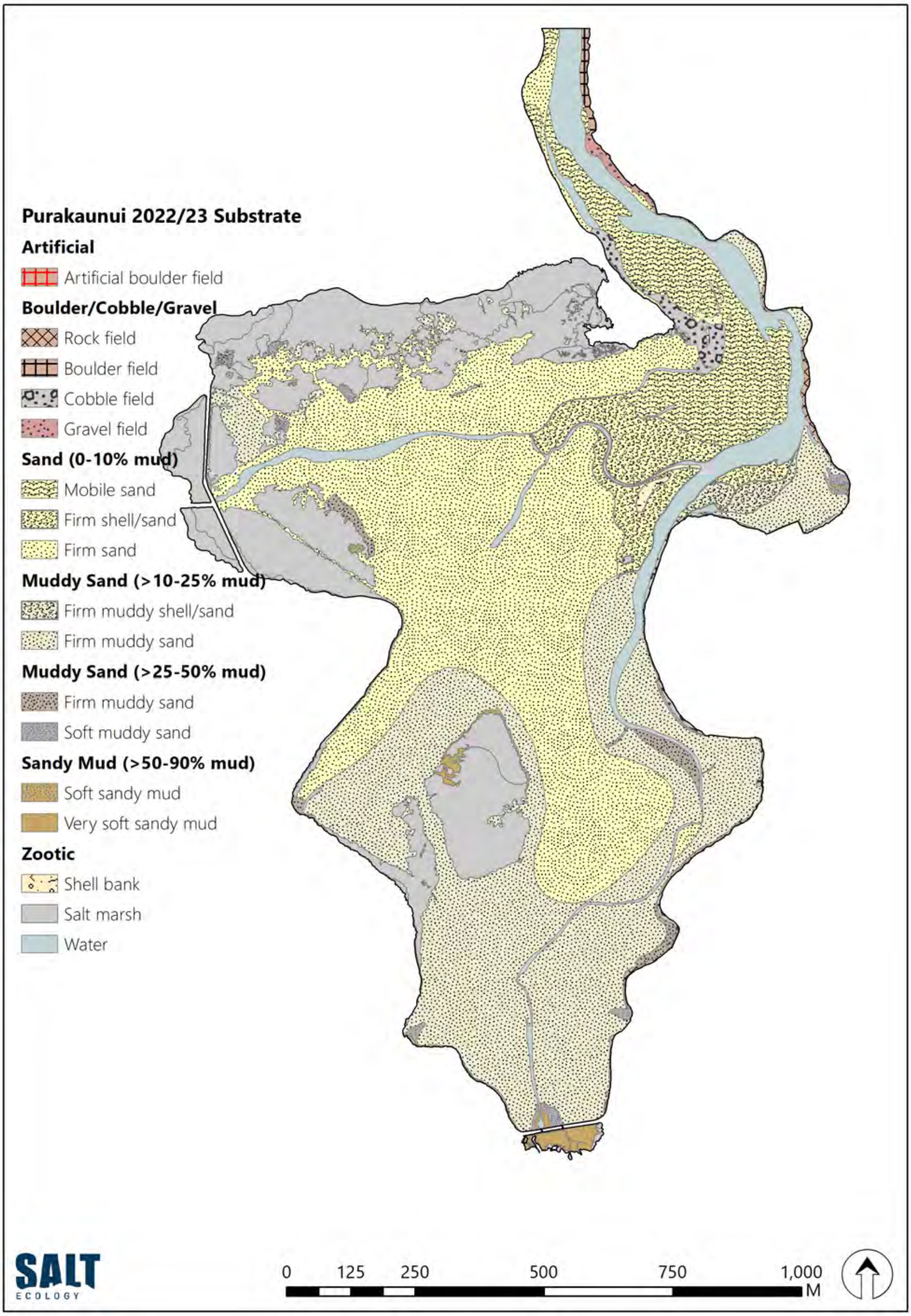


Fig. 8. Dominant intertidal substrate outside of salt marsh.

4.4 SEAGRASS

No seagrass was recorded in the estuary. See Section 6.1 for further discussion.

4.5 OPPORTUNISTIC MACROALGAE

Macroalgae species and biomass information is included in Appendix 7, with key information summarised in Table 7 and Fig. 9. Opportunistic macroalgae in the available habitat (i.e., intertidal flats outside of salt marsh) was mapped as absent or trace (<1% cover) across 98.5% of the area (Table 7). Where present, cover was generally sparse to moderate and comprised a mix of the red seaweed *Agarophyton* spp., and an unidentified red (see photos).

Table 7. Summary of intertidal macroalgal cover (A) and biomass (B), in areas outside salt marsh.

A. Percent Cover

Percent cover category	Ha	%
Absent or trace (<1%)	119.3	98.5
Very sparse (1 to <10%)	0.5	0.5
Sparse (10 to <30%)	0.6	0.5
Low-Moderate (30 to <50%)	0.6	0.5
High-Moderate (50 to <70%)	0.2	0.1
Dense (70 to <90%)	0	0
Complete (≥90%)	0	0
Total	121	100

B. Biomass

Biomass category (g/m^2)	Ha	%
Absent or trace (<1)	119.3	98.5
Very low (1 - 100)	0.5	0.4
Low (101 - 200)	0.2	0.1
Moderate (201 - 500)	0	0
High (501 - 1450)	1.1	0.9
Very high (>1450)	0	0
Total	121	100

Macroalgal cover exceeded 10% cover in two patches in the central estuary, and biomass was relatively high (0.61-1kg/m^2; Appendix 7). In these two patches, *Agarophyton* spp. had become entrained in the underlying sediment. These conditions indicate that stable beds could potentially establish and create nuisance conditions. However, macroalgal growth at the time of the survey was not considered to reflect a significant problem.

Macroalgae was also noted subtidally within low tide channels where it was attached to hard substrate (e.g., gravel, cobble or cockles) which enabled the growth of long filamentous strands of both *Ulva* and *Agarophyton* spp. Sediment conditions did not appear degraded among subtidal beds, likely due to regular tidal flows maintaining high levels of oxygenation.

Along the seaward edge of herbfield in the central western arm, patches of filamentous green seaweed (possibly *Chaetomorpha*) had stranded (see bottom photo below). The alga was rotting and causing localised, but relatively severe, sediment degradation due to oxygen depletion.

Due to the very low overall prevalence of macroalgae (<1.5% of the available intertidal habitat outside salt marsh) the OMBT EQR score was 0.982, which equates to a condition rating of 'very good'. No areas were classified as having persistent High Enrichment Conditions (HEC).

Sparse cover of *Agarophyton* spp. on the west side of the estuary.

Localised patches of unidentified red alga and *Agarophyton* spp. were present in mid-intertidal areas near low tide channels.

Small patches of filamentous green alga had deposited along the seaward margins of the herbfield in the central southwest.

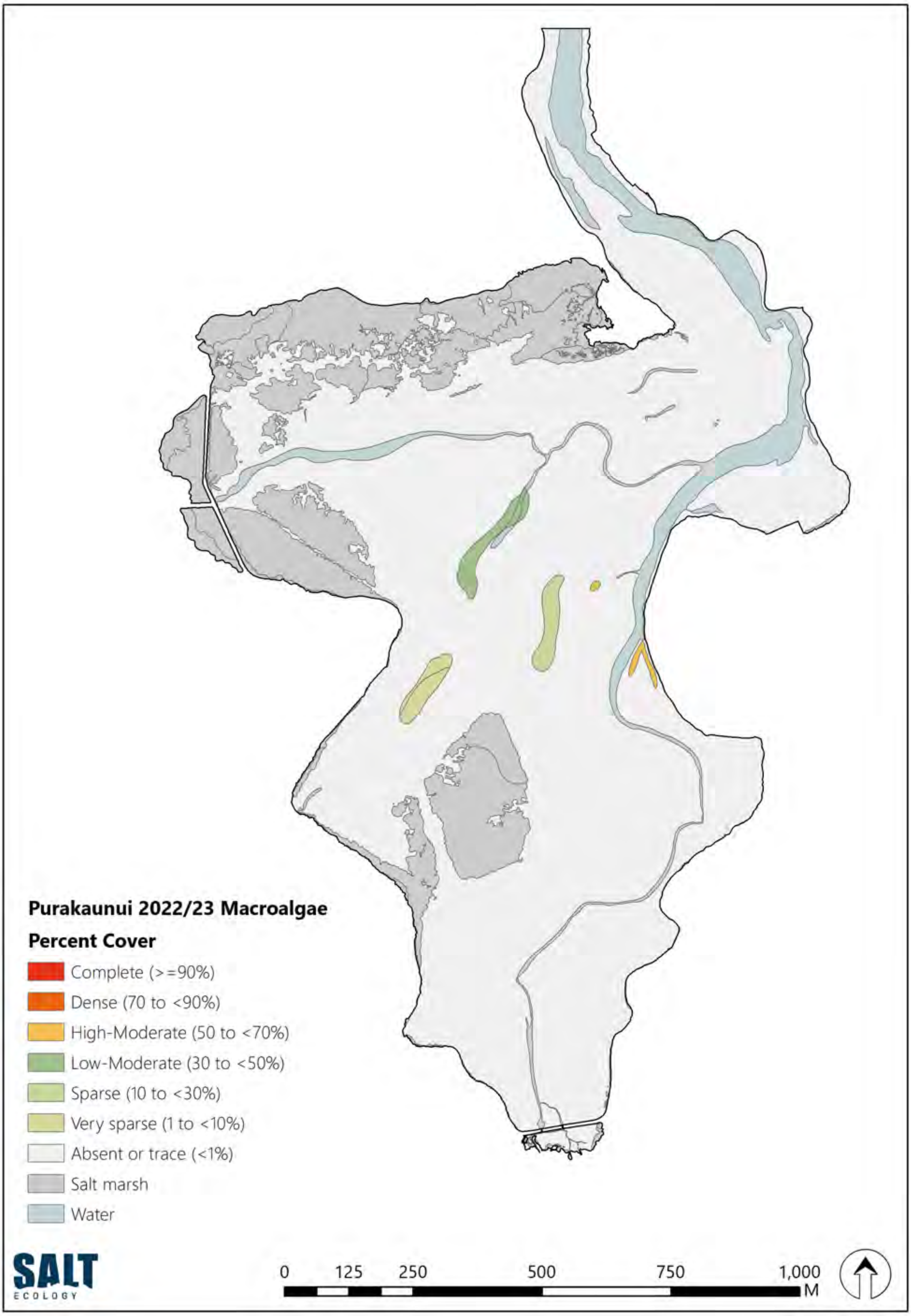


Fig. 9. Distribution and percent cover classes of macroalgae.

5. SEDIMENT QUALITY AND BIOTA

Illustrative photos of sediment quality and macrofauna sampling Sites 1-6 are provided on the next page, including examples of sediment core profiles. Photos of the four additional sites (Sites 7-10) from which sediment validation (i.e., grain size only) samples were collected are presented in Appendix 6.

5.1 SEDIMENT QUALITY INDICATORS

Sampling confirmed the general broad scale mapping pattern of increased mud in the upper tidal reaches (Sites 4, 5 and 6) and low mud nearer to the estuary entrance (Sites 1, 2 and 3; Fig. 10). The sediment quality results show that the poorest sediment conditions were in the muddiest sediments at Site 6, but elsewhere sediment condition was good.

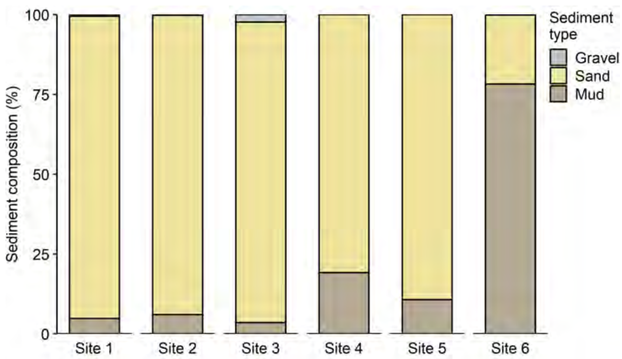


Fig. 10. Sediment grain size in composite samples. Size fractions are mud (<63µm), sand (≥63µm to <2mm) and gravel (≥2mm).

Sediment quality indicators are compared to condition rating thresholds in Fig. 11, with key points as follows:

- The high mud content (78%) of upper estuary Site 6 was rated 'poor', as it exceeded the 25% threshold generally regarded as being biologically significant. All other sites were below this threshold with the sandiest downstream sites rated as 'very good'.
- The muddy sediment at Site 6 had high total organic carbon (TOC) and total nitrogen (TN). At other sites TOC was low, with TN values at Sites 1-5 all less than method detection limits.
- Sediment oxygenation was poorest (shallowest aRPD) at Site 6, as mud particles restrict the diffusion of oxygen into the sediment matrix. By contrast, at sandy sites the more porous sediment was relatively well-flushed and oxygenated. Despite this, the aRPD was only rated 'very good' (aRPD deeper than 20mm) at Site 3 where cockles were also abundant. Other sites were rated either 'poor' or 'fair'.
- Two other trophic state indicators were measured (total phosphorus, TP; total sulfur, TS), but have no condition ratings. These parameters similarly showed a general trend of a highest values in the muddy Site 6, and being similar and relatively low across all other sites (see Table 12).
- Overall, despite the elevated values of trophic state indicators in the small area of muddy sediment around Site 6, there appear to be no symptoms of highly degraded sediments in the estuary associated with strong enrichment (e.g., intense black sediment profile, emission of a strong sulfide odour).

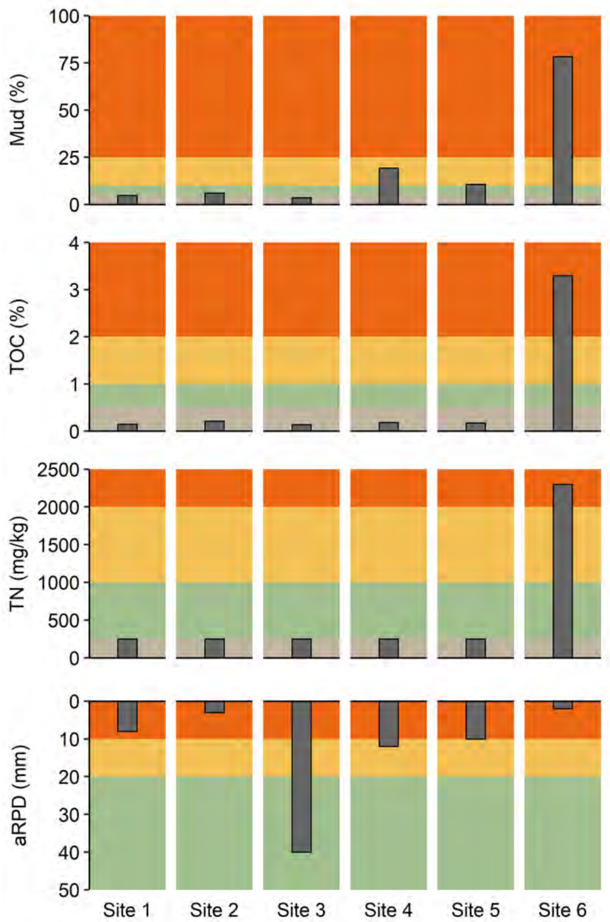


Fig. 11. Grey bars show sediment %mud, total organic carbon (TOC), and total nitrogen (TN) in composite samples, relative to condition ratings. TN at Sites 1-5 was less than method detection limits (MDL), hence half of the MDL value is shown.

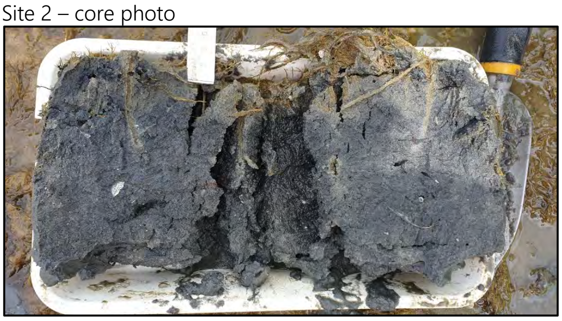
Very Good	Good	Fair	Poor

Site 1

Site 1 – core photo

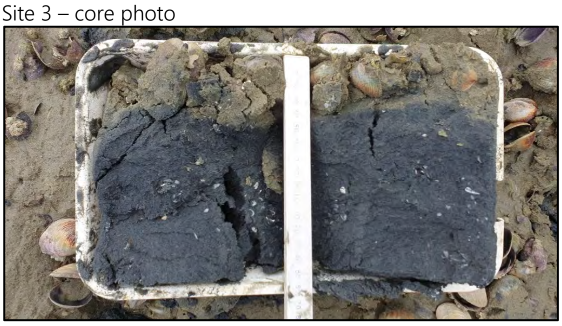
Site 2

Site 2 – core photo



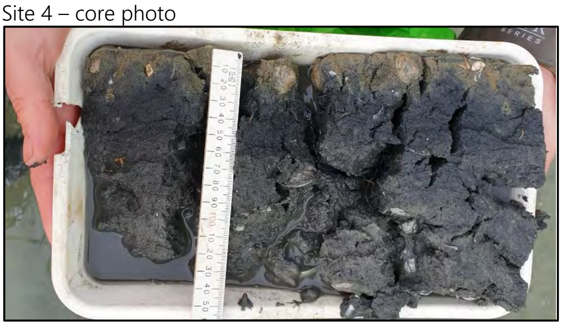
Site 3

Site 3 – core photo



Site 4

Site 4 – core photo



Site 5

Site 5 – core photo

Site 6

Site 6 – core photo

Trace element concentrations were very low in all samples relative to ANZG (2018) Default Guideline Values, and rated 'very good' (Table 8). These results are consistent with the relatively small extent of urban development in the catchment, a common source of many of the chemical contaminants measured.

Table 8. Trace element concentrations relative to ANZG (2018) Default Guideline Values (DGV). Shading corresponds to a 'very good' condition rating, which represents less than half of the DGV.

Site	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
1	3.3	< 0.010	6.0	0.9	< 0.02	2.6	1.6	11.7
2	3.4	0.011	6.2	1.1	< 0.02	2.9	1.9	13.5
3	2.9	0.013	4.3	1.0	< 0.02	2.3	1.4	9.7
4	2.1	0.013	5.2	1.0	< 0.02	2.2	2.0	11.9
5	2.8	0.013	6.2	1.0	< 0.02	2.5	1.8	13.0
6	3.5	0.098	12.7	5.9	0.04	8.1	7.8	48.0
DGV	20	1.5	80	65	0.15	21	50	200

< Values below lab detection limit. The DGV indicates the concentrations below which there is a low risk of unacceptable effects.

5.2 BIOTA

No visible surface microalgae were noted at the sampling sites, although surface-dwelling epifauna were relatively common. Mud snails (*Amphibola crenata*) were present at all sites except the cockle-dominated Site 3, and were most conspicuous at upper estuary Site 6 (~35/m^2). Mud whelks (*Cominella glandiformis*) were present but sparse at Sites 1-5 (<1/m^2). Macroalgae cover was classified as either absent or trace (<1% cover) at all sites except Site 2 where there was a 40% cover of the red seaweed *Agarophyton* spp. in the first stages of entrainment in the sediment. Occasional topshells (*Diloma subrostratum*) were present among the algae at Site 2 and were also present at Site 3 along with *Micrelenchus huttonii*.

Sediment-dwelling macrofauna in the core samples comprised a total of 52 species or higher taxa, representing 15 main organism groups (Appendix 8). From a regional and national perspective, this represents a relatively diverse community. Fig. 12 shows reasonably high average species richness and organism abundances at each site, although both were variable between sites, being highest at Site 2 (where macroalgal cover was 40%) and lowest at Site 6 (the muddy and enriched site upstream of the causeway in the south of the estuary).

From a summary of the most dominant species in Table 9, it can be seen that the high abundance at Site 2 was primarily due to the presence of hundreds of amphipods (*Paracalliope novizealandiae*), most likely associated with the macroalgal cover present at the site.

Shellfish (bivalves) from EG II were relatively common at Sites 1-4, but absent from Sites 5 and 6, possible due to being located nearer to the head of the estuary where sediments are exposed at low tide for longer, or more freshwater conditions occur. A small deposit feeding bivalve that lives buried in the mud (*Arthritica* sp. 5), and which is tolerant of muddy sediments and moderate levels of organic enrichment, was only present at Sites 2 and 6.

Overall, from the descriptions of the dominant species in Table 9 and the full species mix in Appendix 8, it is evident that most are in eco-groups I-III, representing a relatively sensitive and diverse suite of organisms. The resulting AMBI scores (Fig. 13) suggest 'good' ecological conditions at Sites 1-5 and 'fair' ecological conditions at Site 6.

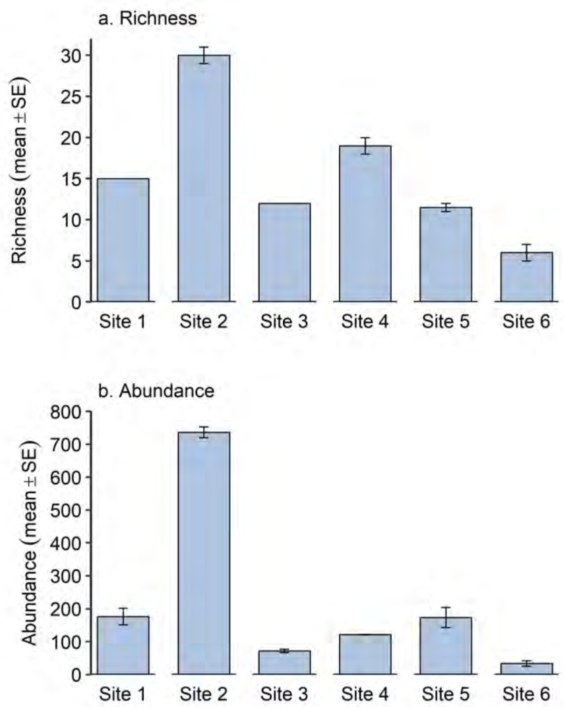
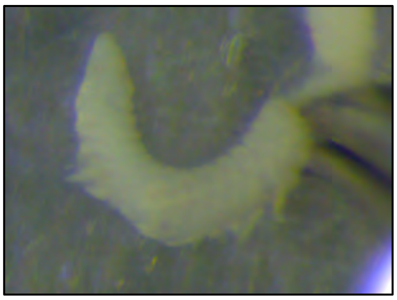


Fig. 12. Mean (± SE) taxon richness and abundance in duplicate core samples.

Table 9. Dominant macrofauna at the six sites. Numbers are total abundances summed across duplicate cores. Examples of key species shown in images at bottom, courtesy of NIWA (pink colour due to a vital stain). EG=eco-group.

Main group	Taxa	EG	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Description
Amphipoda	*Paracalliope novizealandiae*	I	30	534	3	-	2	1	Amphipods are shrimp-like crustaceans. Despite the international EG-I classification, this species in NZ appears indifferent to sedimentation and can tolerate muddy habitats to some extent.
Bivalvia	*Arthritica* sp. 5	III	-	22	-	-	-	36	A small sedentary deposit feeding bivalve that lives buried in the mud. Tolerant of muddy sediments and moderate levels of organic enrichment.
Bivalvia	*Austrovenus stutchburyi*	II	5	16	51	36	-	-	Cockles are suspension feeding bivalves, living near the sediment surface. Sensitive to organic enrichment. Important in diet of certain birds, rays and fish.
Bivalvia	*Nucula nitidula*	I	2	47	-	47	-	-	Small estuarine bivalve mollusc, commonly called a nutshell. Considered to prefer sandy habitats, and sensitive to excess sedimentation. Probably a prey item in the diet of birds and fish.
Cirripedia	*Austrominius modestus*	II	-	-	35	-	-	-	Filter feeding estuarine barnacle, very common where there is shell material or other hard surfaces for attachment. Considered sensitive to muddy sediment.
Gastropoda	*Notoacmea scapha*	II	-	9	18	-	-	-	Endemic to NZ. Small limpet attached to stones and shells in intertidal zone.
Polychaeta	*Exogoninae* sp. 1	II	10	45	-	33	3	-	Small syllid polychaete worm. Common but poorly understood. Considered to be free-burrowing or epifaunal omnivores.
Polychaeta	*Macroclymenella stewartensis*	II	36	47	-	51	85	-	A sub-surface, deposit-feeding bamboo worm usually found in tubes of fine sand or mud. This species may have a key role in turn-over of sediment. Tolerant of mud, but optimum range 10-15%. Intolerant of anoxic conditions.
Polychaeta	*Paradoneis lyra*	III	230	277	-	-	169	-	Common paraonid worm that is reasonably tolerant of muddy sediment and organic enrichment. Paraonids are considered to be deposit feeders, possibly selectively feeding on microscopic diatoms and protozoans.
Polychaeta	*Scolecolepides benhami*	IV	-	-	-	-	2	22	A spionid, surface deposit feeder. It is rarely absent in sandy/mud estuaries in NZ.

Paracorophium excavatum



Paradoneis lyra

Scolecolepides benhami

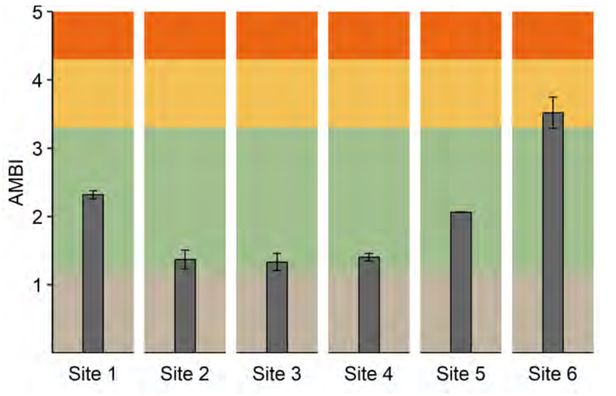


Fig. 13. Mean (± SE) macrofauna AMBI scores in duplicate cores, relative to condition ratings.
Condition rating key:

Very Good	Good	Fair	Poor

A multivariate analysis of macrofauna community composition is summarised in Fig. 14. The top panel illustrates the magnitude of difference between sites in terms of their macrofauna composition. Sites 1, 2, 4 and 5 were all quite similar, whereas Sites 3 and 6 were the most different. Relative to other sites, Site 3 was characterised by having a large amount of shell material at the surface and this was reflected in the presence of high numbers of barnacles and limpets compared to other sites. Site 6 differences primarily reflected the absence of certain species that were common at some or all of the other sites; e.g., cockles (*Austrovenus stutchburyi*) and nutshells (*Nucula nitidula*), but also the presence of species that were not recorded at other sites; e.g., the hardy polychaete worm *Scolecolepides benhami*.

Both panels in Fig. 14 illustrate the sediment quality attributes that were most closely correlated with the changes in macrofauna community composition, with the vector plot in the bottom panel highlighting their relative importance. For Site 6, the most important attributes were increased sediment mud content, total sulphur (TS), total organic content (TOC) and total phosphorus (TP). Note that TP may not itself be important, but is a proxy for total nitrogen (TN) with which it is typically highly correlated. Nitrogen rather than phosphorus is regarded as the nutrient that is most important for algal growth in estuaries. In this instance TN was not well-quantified, due to it being below the method detection limit at Sites 1-5.

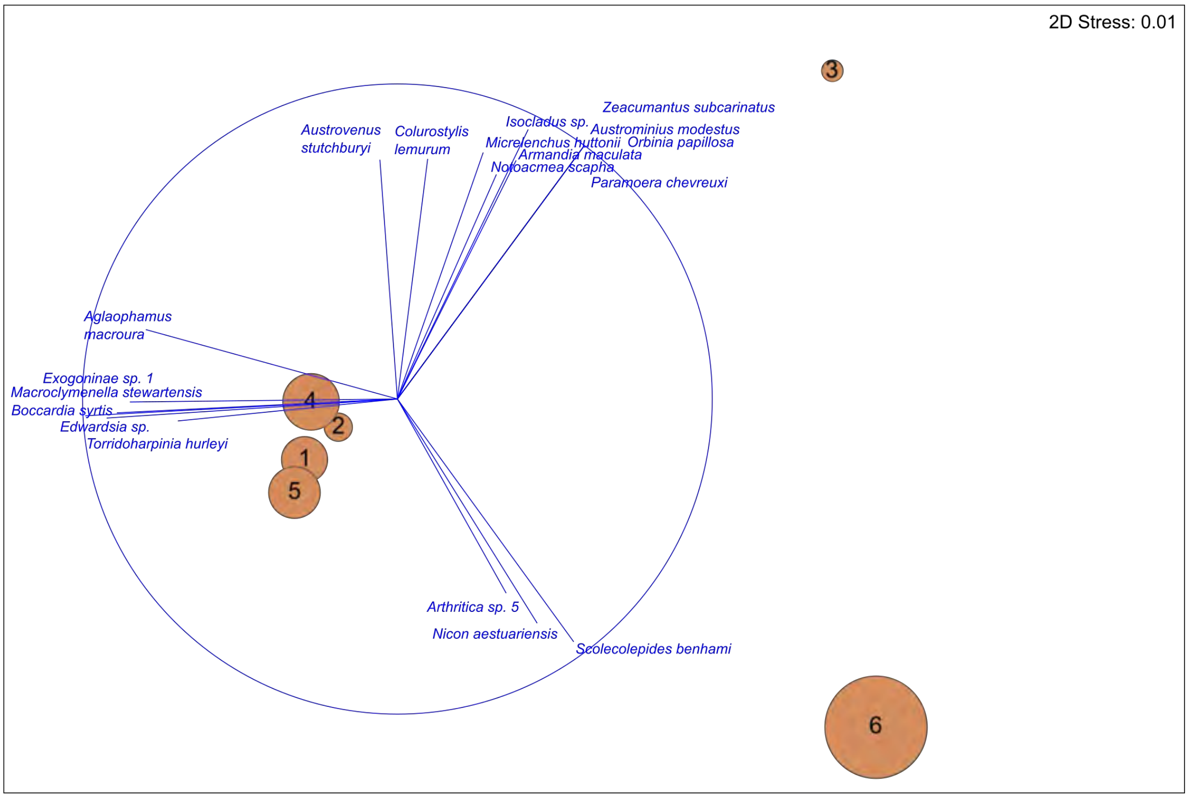
Site 3 was differentiated primarily by an increase in aRPD depth (i.e., indicating increased sediment oxygenation). This may reflect its location low in the tidal range adjacent to the main subtidal channel of the estuary, meaning it is likely better flushed and inundated for longer periods of the tide than the other sites. The site also supported the largest densities of cockles relative to the other sites sampled. Cockles can improve sediment oxygenation, increasing nutrient fluxes and influencing the type of macrofauna present.

Other unmeasured factors are also likely to be important determinants of macrofauna composition differences, and include the effect of the causeway and influence of low-salinity water in the upper estuary, and the presence of effects of wave and current action in the lower estuary.

Cockles contribute to well-oxygenated sediments at Site 3.

Upstream of the causeway near Site 6 mud snails were common on the soft sandy mud.

a. Species overlay



b. Sediment quality overlay

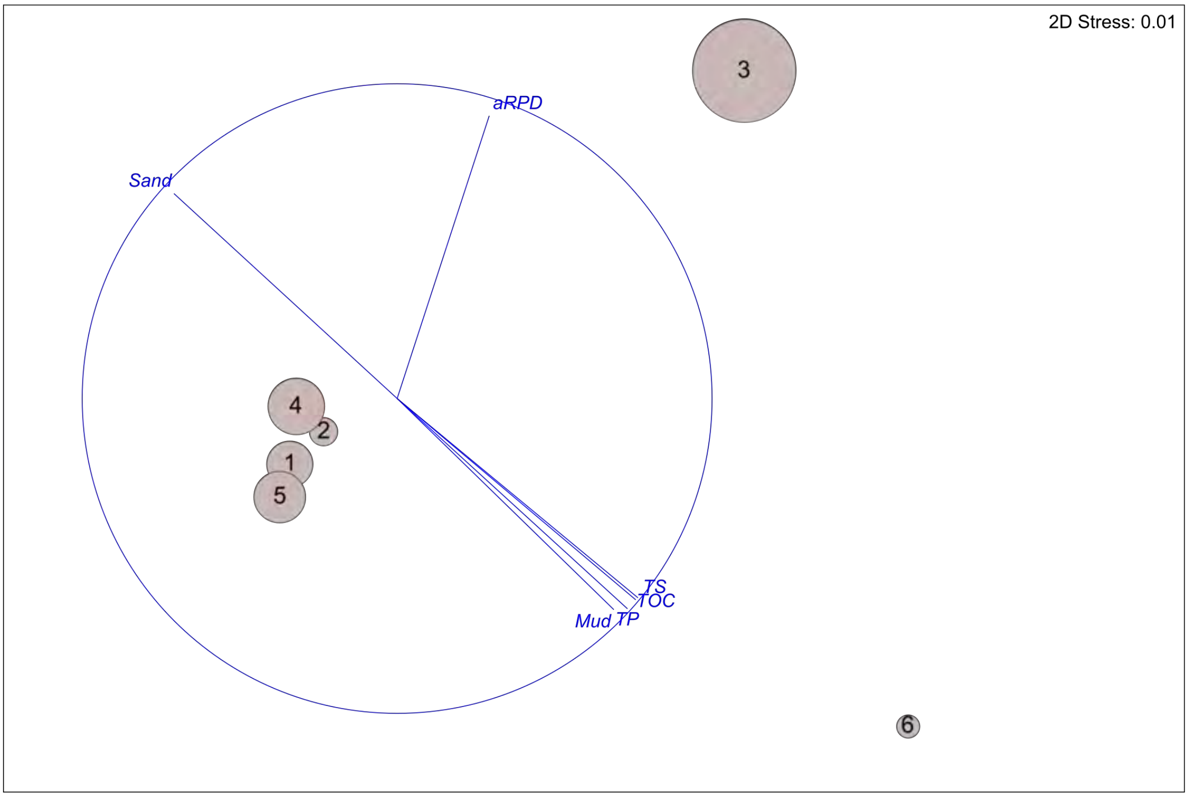


Fig. 14. Non-metric MDS ordination of macrofaunal core samples for each site.

Sites are placed such that those closer to each other are more similar than distant ones in terms of macrofauna composition. A 'stress' value of near zero indicates that a 2-dimensional plot provides a highly accurate representation of site differences. Vector overlays indicate the direction and strength of association (length of line relative to circle) of site grouping patterns in terms of the most correlated macrofauna species (top) and sediment quality variables (bottom). Bubble sizes are scaled to sediment mud content (top) and aRPD (bottom), which were among the variables that were correlated with macrofauna composition differences.

6. SYNTHESIS OF KEY FINDINGS

6.1 OVERVIEW

The 26 November 2022 survey showed that Pūrākaunui Inlet is in a healthy state overall. In contrast to many of the estuaries in the Otago region, it is sand-dominated, supports a relatively species-rich and abundant macroinvertebrate community, and has extensive areas of remaining salt marsh.

A summary of key broad scale features is provided in Table 10, with condition ratings for broad scale and fine scale indicators summarised in Table 11 and Table 12, respectively. Supporting data used to assess and interpret estuary condition were derived from catchment-scale nutrient and sedimentation models (CLUES; Hicks et al. 2019) and are provided in Table 13.

Table 10. Summary of key broad scale features as a percentage of total estuary, intertidal or margin area, Pūrākaunui Inlet, November 2022.

Component	Area (ha)	Percentage
a. Area summary		**% Estuary**
Intertidal area	121.2	93.4
Subtidal area	8.6	6.6
Total estuary area	**129.7**	**100**
b. Key substrate features		**% Intertidal**
Mud-enriched (25 to <50%)	19.8	16.4
Mud-dominated (≥50%)	3.3	2.7
c. Key habitat features		**% Intertidal**
Salt marsh	23.6	19.5
Seagrass (≥50% cover)	0	0
Macroalgal beds (≥50% cover)	0.2	0.1
High Enrichment Conditions	0	0
d. Terrestrial margin (200m)		**% Margin**
200m densely vegetated margin		37.1

Note: Summary statistics for substrate, seagrass and macroalgae are for the 121.2ha of intertidal area that excludes salt marsh.

Herbfield in the mid-estuary.

The rating tables show that most indicators meet the classification of 'good' or 'very good', with the exception being the extent of densely vegetated terrestrial margin, which was rated 'fair', as well as some of the fine scale indicators (mud and aRPD) discussed below. The features that contribute to favourable rating values include the following:

- Salt marsh comprised 23ha or 19.5% of the intertidal area. Nonetheless, historic imagery (earliest from 1956) shows a decline of ~24% in salt marsh extent compared to natural state, attributable to both natural erosion of the seaward edges of herbfield, and drainage and reclamation of salt marsh for pasture.
- Clean, sand-dominated sediment in most areas, the main exception being the mud-dominated area behind the road causeway in the southern estuary.
- Sparse growths of opportunistic macroalgal species that can become prolific under eutrophic conditions.
- An absence of High Enrichment Condition (HEC) areas displaying persistent symptoms of an enriched and eutrophic sediment state.
- Very low trace metal contaminant concentrations, consistent with the absence of significant contaminant sources in the catchment.
- Low inputs of nutrients and sediment from the surrounding catchment relative to the estuary size.
- A relatively species-rich and abundant sediment-dwelling macrofaunal community, characterised largely by the presence of taxa that are sensitive to disturbance (intolerant of degraded conditions).

Seagrass was not present in the estuary and was therefore not rated as an indicator. An assessment of features visible in historic aerial photographs (earliest 1956) suggests that the estuary has never supported any significant areas of seagrass, which is in contrast to the nearby Blueskin Bay Estuary and several other SIDE type estuaries in the Otago region (e.g., Papanui, Hoopers, Catlins Lake/Pounawea, Waikouaiti).

Pūrākaunui Inlet has very few of the factors that commonly limit seagrass growth; e.g., excessive mud deposition or content, light limitation (from tannin-rich or turbid waters) that could inhibit photosynthesis; a strong freshwater influence (low salinity water), excessive nutrient inputs (which can promote smothering macroalgal growths), and high substrate mobility, which could prevent the establishment of beds. It is therefore unclear what the driver for seagrass absence is.

The dominance of the sediment-dwelling macrofaunal community by taxa that are sensitive to disturbance (intolerant of degraded conditions) was reflected in five of the six sampling sites having macrofauna AMBI scores meeting a 'good' condition rating (Table 12). The remaining site (Site 6 in the mud-dominated and enriched upper estuary behind the causeway) was rated 'fair'.

This situation is different to that found in many of the river-dominated estuary systems elsewhere in the region in which the combined influence of elevated mud inputs and strong freshwater influences result in the macrofauna community being less diverse, either naturally (e.g., Tautuku, Waipati estuaries) or in combination with catchment development (e.g., Tokomairiro, Shag River estuaries).

Table 13. Supporting data used to assess estuary ecological condition in Pūrākaunui Inlet.

Supporting Condition Measure	Pūrākaunui Inlet
Mean freshwater flow (m^3/s)[1]	0.04
Catchment Area (Ha)[1]	941.9
Catchment nitrogen load (tonnes TN/yr)[2]	2.0
Catchment phosphorus load (tonnes TP/yr)[2]	0.3
Catchment sediment load (KT/yr)[1]	0.2
Estimated N areal load in estuary ($mg/m^2/d$)[2]	4.3
Estimated P areal load in estuary ($mg/m^2/d$)[2]	0.6
CSR:NSR ratio[1]	1.7
Trap efficiency (sediment retained in estuary)[1]	98%
Estimated rate of sedimentation (mm/yr)[1]	0.2

[1] Hicks et al. (2019) & Oldman (2022).

[2] CLUES version 10.8 (LCBD5); Run date: 23 May 2023 (CLUES).

Table 11. Summary of broad scale indicator condition ratings.

Broadscale Indicators	Unit	Value	Rating
Mapped indicators			
200m terrestrial margin	% densely vegetated	37.1	Fair
Mud-elevated substrate	% intertidal area >25% mud[1]	2.1	Very Good
Macroalgae (OMBT[2])	Ecological Quality Rating (EQR)	0.982	Very Good
Seagrass	% decrease from baseline	no seagrass present	na
Salt marsh extent (current)	% of intertidal area	19.5	Good
Historical salt marsh extent[3]	% of historical remaining	~76%	Good
High Enrichment Conditions	ha	0	Very Good
High Enrichment Conditions	% of estuary	0	Very Good
Estuary-wide sedimentation indicators			
Mean sedimentation ratio[4]	CSR:NSR ratio	1.7	Good
Sedimentation rate[4]	mm/yr	0.2	Very Good

[1]Excludes salt marsh area; [2]OMBT = Opportunistic Macroalgal Blooming Tool; [3]Estimated from historic aerial imagery, [4]CSR=Current Sedimentation Rate, NSR=Natural Sedimentation Rate (predicted from catchment modelling). na = not applicable.

Table 12. Summary of fine scale indicator condition ratings for sediment quality and macrofauna AMBI.

Parameter	Unit	1	2	3	4	5	6
Mud	%	4.8	6.0	3.5	19.2	10.7	78.3
aRPD	mm	8	3	40	12	10	2
TN	mg/kg	< 500	< 500	< 500	< 500	< 500	2300
TP	mg/kg	290	310	270	240	290	600
TOC	%	0.15	0.21	0.14	0.18	0.17	3.30
TS	%	0.03	0.05	0.04	0.06	0.04	0.24
As	mg/kg	3.3	3.4	2.9	2.1	2.8	3.5
Cd	mg/kg	< 0.010	0.011	0.013	0.013	0.013	0.098
Cr	mg/kg	6.0	6.2	4.3	5.2	6.2	12.7
Cu	mg/kg	0.9	1.1	1.0	1.0	1.0	5.9
Hg	mg/kg	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.04
Ni	mg/kg	2.6	2.9	2.3	2.2	2.5	8.1
Pb	mg/kg	1.6	1.9	1.4	2.0	1.8	7.8
Zn	mg/kg	11.7	13.5	9.7	11.9	13.0	48.0
AMBI	na	2.3	1.4	1.3	1.4	2.1	3.5

See Glossary for abbreviations.< Values below lab detection limit. Colour bandings are based on thresholds provided in Table 3.

The macrofauna present indicate that the estuary overall is in a good condition. Based on relative differences between the sites in the estuary, the primary drivers for the presence of a diverse macrofauna community appear to be low levels of mud, nutrients and organic content in the sediment. If increases in these metrics were to occur in the main body of the estuary, then it could be expected that the macrofauna community would shift toward that more typical of the most degraded part of the estuary in the southern embayment (i.e., illustrated by Site 6). The sensitivity of macrofauna to these metric highlights the importance of good catchment management in order to prevent adverse changes from occurring.

6.2 VULNERABILITY TO MUDDY SEDIMENTS

The small spatial extent of mud-elevated sediment in Pūrākaunui Inlet is consistent with predictions from catchment models (Table 13), and it may also be the case that much of the sediment entering the southern part of the estuary is retained behind the causeway.

Nevertheless, total sediment inputs appear to be relatively low, with the annual sedimentation rate estimated to be 0.2mm/yr (Table 13), which is well below the Townsend and Lohrer (2015) guideline value for New Zealand estuaries of 2mm/yr.

However, the ratio of predicted Current to Natural Sedimentation Rate was only rated as 'good' (Table 11), indicating inputs are elevated compared to natural state. Combined with estimated 98% sediment trapping efficiency of the estuary (Table 13) indicative of high potential sediment retention, the CSR:NSR ratio suggests the estuary may be vulnerable to any change in current sediment loads.

This vulnerability is exacerbated by the fact that two thirds of the catchment is in land-uses that are known to generate a high fine-sediment run-off to waterways, namely pastoral farming and exotic plantation forestry. The latter can be a particularly significant source of muddy sediment during forest harvest and for a few years after, when it can contribute a disproportionately high sediment load per catchment hectare (e.g. Gibbs & Woodward 2018).

As noted in Section 2, the Pūrākaunui Inlet catchment consisted of 12.8% exotic plantation forestry (including harvested area) based on 2018 data (see Fig. 2). Although much of this is located on coastal duneland near the entrance, there are pockets of forestry throughout the catchment. There is also a potential for increased forestry to occur with the recent national trend of conversion from some farmland areas to plantation forestry in response to the high-value of pine forests for carbon sequestration. As such, it is timely for ORC to consider the current and future implications for the downstream receiving environment (see Section 6.4).

6.3 VULNERABILITY TO NUTRIENT ENRICHMENT AND EUTROPHICATION

Other than at Site 6, where elevated mud and relatively high levels of eutrophication indicators (TOC, TN, TP, & TS) were associated with a degraded macrofauna community, the remainder of the estuary did not exhibit any significant eutrophication symptoms. This was consistent with the estimated areal nitrogen load to the estuary of (~4mg/m^2/d; Table 13), which is substantially lower than the 100mgN/m^2/d threshold at which nuisance macroalgae problems are predicted to occur in intertidally-dominated estuaries (Robertson et al. 2017).

Despite this, there were small areas where the opportunistic species *Agarophyton* spp. had begun to establish and become entrained within sediments. While not currently resulting in eutrophication symptoms in terms of decreased sediment oxygenation and organic enrichment, these beds have previously been observed to rapidly expand and trap fine sediment in estuaries in Southland, which was directly linked to increased catchment nitrogen loads (Stevens et al. 2020; Stevens et al. 2022). It is therefore considered prudent to monitor changes in both land use and macroalgal growth to enable a timely response should conditions deteriorate.

In relation to phytoplankton proliferation, Plew et al. (2018) estimated the estuary had a flushing time of 11.5 days, due predominantly to low freshwater inputs relative to estuary size. Phytoplankton susceptibility was then assessed as a function of flushing time and potential TN concentration in estuaries with salinities <30ppt. From that work, it was predicted that Pūrākaunui Inlet would have a high susceptibility to eutrophication (i.e., chlorophyll-*a* predicted to be >10mg/m^3) in response to current predicted nitrogen concentrations.

However, the risk of phytoplankton issues is likely significantly reduced by the near complete draining of the estuary at low tide, and the absence of deep pools along the estuary channel. These observations suggest that salt water is easily flushed from the system and consequently, the development of eutrophic symptoms during summer low flows, which occurs in stratified bottom waters of some estuary systems (e.g., Roberts et al. 2021; Forrest et al. 2022c), is unlikely to eventuate in Pūrākaunui Inlet. Water quality monitoring would be required to confirm this hypothesis, however it is not considered a priority.

6.4 MANAGEMENT AND MONITORING CONSIDERATIONS

At present the spatial extent of mud-elevated sediment is very small at 2.1% of the unvegetated intertidal area. However, based on catchment model predictions, and considering current catchment land use, we suggest that the estuary may be particularly vulnerable to any future increase in muddy sediment loads. As such, it is desirable to minimise activities in the catchment that result in high inputs. The opportunity exists for ORC to assess potential changes in catchment land use that could lead to fine sediment load increases, and work with landowners to mitigate potential adverse effects. Land ownership in the catchment includes a substantial area of Māori freehold land on the northwest of the estuary where restoration work is already evident, as well as farm or forestry land in private ownership.

Examples of management opportunities include assessing exotic plantation forest harvest practices which, if poorly managed, could exacerbate sediment deposition across the tidal flats. It is particularly important to understand the current area of catchment land in growing or harvested forest, and future harvest schedules, especially given the possibility of land use conversion noted above. Other potential land use practices that could lead to an increase in sediment load to the estuary should also be considered; for example, intensification of existing farmland (e.g., increased stock densities, intensive winter grazing).

Another key threat to Pūrākaunui Inlet is the potential loss of salt marsh through impacts from drainage, reclamation or grazing, or as a consequence of inundation under predicted sea level rise (SLR) scenarios. Because of the steep-sided or armoured landforms around much of the estuary, there are limited areas for salt marsh to migrate to in response to SLR. Consequently, identifying areas where salt marsh may potentially establish in response to SLR is an important consideration to maintain this important habitat in the estuary.

There are many relatively simple and cost-effective measures that can improve estuary condition, for example fencing and riparian planting of waterways, or identifying low-lying areas that may be impacted by SLR in future and limiting infrastructure development to enable salt marsh retreat. In addition, ensuring forest harvesting adopts 'best use' practices, and assessing the specific impacts on the estuary of any proposed land use changes in the catchment are also measures that will likely lead to improved outcomes in the estuary.

Part of the rationale for the targeted sediment quality and biota monitoring was to consider the merits of ongoing SOE monitoring in Pūrākaunui Inlet. In light of the potential vulnerability to sedimentation, and predicted impacts on salt marsh from SLR, there is considered to be merit in undertaking ongoing monitoring of key easy-to-measure attributes. These include broad scale mapping of dominant habitats, particularly the extent of salt marsh and mud-elevated sediment, and measurements of sediment grain size and oxygenation. The installation of 'sediment plates' for the direct measurement of annual sedimentation rates is also considered worthwhile, bearing in mind that at least a 5-year annual dataset is needed for meaningful trends to be revealed.

The species-rich macrofaunal assemblage includes many taxa that are sensitive to disturbance (intolerant of degraded conditions), and is therefore suitable for monitoring temporal change. However, there is currently limited justification for implementing the full NEMP fine scale survey protocol in the estuary. This is partly because of the significant cost of macrofauna monitoring, and also due to the relatively low levels of pressure on the estuary from toxicant or nutrient related inputs. Instead, regular broad scale mapping, and measurements of sediment grain size and oxygenation, are considered sufficient for indicating whether adverse ecological changes are occurring and to trigger more detailed monitoring as appropriate.

With data now available for most of the larger estuaries across Otago, it would also be timely to assess available SOE estuary monitoring information in a holistic manner taking into account vulnerability, condition and current and future pressures in a regional context. A future regional monitoring programme can then be tailored to address key management questions and priorities, which will help to elucidate monitoring needs for Pūrākaunui Inlet.

7. RECOMMENDATIONS

By regional and national standards, Pūrākaunui Inlet is in a healthy state overall. However, it appears potentially vulnerable to future inputs of catchment-derived muddy sediment and losses of salt marsh due to predicted SLR. To monitor condition and mitigate against such risks the following is recommended:

- Undertake broad scale mapping every 5 years, including repeat measurements of sediment grain size at existing sites.
- Establish sediment plates to measure sediment accretion and mud content in representative parts of the central basin of the estuary.
- Undertake an assessment of the predicted impact of SLR on existing estuary salt marsh, and identify areas where salt marsh may naturally expand or be facilitated by restoration initiatives.
- Evaluate future sediment sources to the estuary, and investigate options for a reduction of inputs through either targeted management of land use or the implementation of simple mitigation measures.
- Include Pūrākaunui Inlet in a broader review of the Otago estuary SOE monitoring programme, in order to prioritise long term monitoring needs.

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APPENDIX 1. SAMPLING METHODS

This Appendix details the synoptic ecological assessment approach used by Salt Ecology for assessing intertidal estuary condition. It comprises estuary-wide broad-scale habitat mapping, and assessment of sediment quality (including associated biota) and water quality at discrete sites. In relation to these components, note that:

- The broad-scale habitat mapping methods largely follow the National Estuary Monitoring Protocol (NEMP; Robertson et al. 2002), with improvements to some of the assessment, analysis and QA/QC elements as described in Section A.
- Broad scale mapping seeks to characterise the spatial extent of dominant substrate types (with a particular focus on muddy sediments as a key indicator of catchment sediment inputs), opportunistic macroalgae (as an indicator of nutrient enrichment status), and ecologically important vegetated habitats vulnerable to human disturbance. The latter consist of intertidal seagrass (*Zostera muelleri*) and salt marsh, as well as vegetation of the 200m terrestrial margin bordering the estuary.
- The synoptic assessments of sediment quality and biota largely use the NEMP fine scale indicators and analytical methods described in Section B, but vary from the NEMP by incorporating more sites with reduced within-site replication to provide a synoptic picture of ecological health across a range of soft-sediment habitat types throughout the estuary. In contrast, NEMP fine-scale surveys are typically based on intensive (high replication) sampling of 1-3 sites in the dominant habitat type.
- The water quality methods are based on standard field measures that are an addition to NEMP methods. Comprehensive water quality sampling (e.g., numerous sites with high replication) is required characterise subtidal estuary condition. However one-off water quality parameters collected in synoptic surveys capture preliminary information to help assess whether an estuary may be vulnerable to water quality degradation (e.g., stratification, phytoplankton blooms and/or low dissolved oxygen).

For the key components outlined above, the final section of this Appendix describes the metrics and associated threshold values that are used to rate estuary condition on a four-point colour-coded scale ranging from 'very good' to 'poor'.

A. BROAD SCALE METHODS

A1. MAPPING

A1.1 Overview

For broad scale mapping purposes, the estuary was defined as a partly enclosed body of water where freshwater inputs (i.e., rivers, streams) mix with seawater. The seaward boundary (estuary entrance) was defined as a straight line between the seaward-most points of land that enclose the estuary, with the upper estuary (i.e., riverine) boundary at the estimated upper extent of saline intrusion. For further discussion on estuary boundary definitions see FGDC (2012) and Hume et al. (2016).

Broad scale NEMP surveys involve mapping the intertidal zone of estuaries, and their terrestrial margin, according to dominant surface habitat (substrate and vegetation) features. The type, presence and extent of estuary substrate, salt marsh, macroalgae or seagrass reflects multiple factors, for example the combined influence of sediment deposition, nutrient availability, salinity, water quality, clarity and hydrology or direct human disturbance. As such, broad scale mapping provides time-integrated measures of prevailing environmental conditions that are generally less prone to the small scale spatial or temporal variation commonly associated with instantaneous measures of water quality or, to a lesser extent, sediment quality. Once a baseline map has been constructed, changes in the position and/or size or type of dominant features can be monitored by repeating the mapping exercise, and temporal changes due to the effects of anthropogenic inputs of sediment or nutrients, or activities such as vegetation clearance, margin hardening (e.g., rock walls), reclamation, or drainage of salt marsh, can be elucidated.

The mapping procedure follows NEMP methods and combines aerial photography or satellite imagery, detailed ground-truthing, and digital mapping using Geographic Information System (GIS) technology. Field surveys are typically carried out during September to May, when most plants are still visible and seasonal vegetation has not died back, with experienced scientists ground truthing the estuary and margin on foot to directly map or validate the dominant vegetation and substrate visible on aerial imagery. Field maps are ideally >50cm/per pixel resolution at a scale of between 1:2000 and 1:5000, as at a coarser scale it becomes difficult to map features with sufficient resolution to reliably characterise features. The drawn or validated features, combined with field notes and georeferenced photographs, are later digitised into ArcMap (currently v10.8) shapefiles at a scale of at least 1:2000 using a drawing tablet to produce maps of the dominant estuary features.

A summary of the broad scale indicators and the rationale for their use is provided in the main body of the report, with methods for mapping and assessing each indicator also described.

A1.2 Catchment description and terrestrial margin mapping

Catchment land use maps are constructed from the most recent Landcare Research Land Cover Data Base (currently LCDB5 2017/2018) where dominant land cover has been classified based on the codes described in Table A1. Using the broad scale NEMP methods described in section A1.1, these same LCDB5 classes are used to categorise features within the 200m terrestrial margin of an estuary. The one exception is the addition of a new sub-class (410 – Duneland) to delineate coastal duneland from low producing grassland, due to the high value of duneland habitat type.

Table A1. Landcare Land Cover Database (LCDB5) classes used in the mapping of terrestrial features.

Artificial Surfaces		Grassland, Sedge and Saltmarsh	
1	Built-up Area (settlement)	40	High Producing Exotic Grassland
2	Urban Parkland/Open Space	41	Low Producing Grassland
5	Transport Infrastructure	410*	Duneland
6	Surface Mines and Dumps	43	Tussockland
Bare or Lightly Vegetated Surfaces		45	Herbaceous Freshwater Vegetation
10	Sand and Gravel	46	Herbaceous Saline Vegetation
12	Landslide	Scrub and Shrubland	
14	Permanent Snow and Ice	47	Flaxland
15	Alpine Grass/Herbfield	50	Fernland
16	Gravel and Rock	51	Gorse and/or Broom
Water Bodies		52	Manuka and/or Kanuka
20	Lake or Pond	54	Broadleaved Indigenous Hardwoods
21	River	55	Sub Alpine Shrubland
22	Estuarine water	56	Mixed Exotic Shrubland
Cropland		58	Matagouri or Grey Scrub Forest
30	Short-rotation Cropland	Forest	
33	Orchard Vineyard & Other Perennial Crops	64	Forest - Harvested
		68	Deciduous Hardwoods
		69	Indigenous Forest
		71	Exotic Forest

*Duneland is an additional category to the LCDB classes to help differentiate between "Low Producing Grassland" and "Duneland".

A1.3 Estuary substrate classification and mapping

NEMP substrate classification is based on the dominant surface features present, e.g., rock, boulder, cobble, gravel, sand, mud. However, many of the defined NEMP sediment classifications are inconsistent with commonly accepted geological criteria (e.g., the Wentworth scale), aggregate mud/sand mixtures into categories that can range in mud content from 10-100%, and use a subjective and variable measure of sediment 'firmness' (how much a person sinks) as a proxy for mud content. To address such issues, Salt Ecology has revised the NEMP classifications (summarised in Table A2) using terms consistent with commonly accepted geological criteria (e.g., Folk 1954) and, for fine unconsolidated substrate (<2mm), divided classes based on estimates of mud content where biologically meaningful changes in sediment macrofaunal communities commonly occur (e.g., Norkko et al. 2002, Thrush et al. 2003, Gibbs & Hewitt 2004, Hailes & Hewitt 2012, Rodil et al. 2013, Robertson et al. 2016c). Sediment 'firmness' is used as a descriptor independent of mud content. Salt Ecology also maps substrate beneath vegetation to create a continuous substrate layer for an estuary.

The Salt Ecology revisions (Table A2) use upper-case abbreviations to designate four fine unconsolidated substrate classes based on sediment mud content (S=Sand: 0-10%; MS=Muddy Sand: ≥10-50%; SM=Sandy Mud: ≥50-90%; M=Mud: ≥90%), with muddy sand further divided into two sub-classes of ≥10-25% or ≥25-50% mud content. These reflect categories that can be subjectively assessed in the field by experienced scientists, and validated by the laboratory analysis of particle grain size samples (wet sieving) collected from representative sites (typically ~10 per estuary) based on the methods described in Section B.

Lower-case abbreviations are used to designate sediment 'firmness' based on how much a person sinks (f=firm: 0-<2cm; s=soft: 2-5cm; vs=very soft: ≥5cm). Because this measure is highly variable between observers, it is only used as a supporting narrative descriptor of substrate type. Mobile substrate (m) is classified separately and, based on the NEMP, is considered to only apply to firm substrate.

Table A2 presents the revised classifications alongside the original NEMP equivalent classifications to facilitate consistent comparisons with previous work (by aggregating overlapping classes). The area (horizontal extent) of mud-elevated sediment (>25% mud content) is used as a primary indicator of sediment mud impacts, and in assessing susceptibility to nutrient enrichment impacts (trophic state).

Examples of substrate types: Top row (L to R); mobile sand (0-10%), firm shell/sand (0-10%), firm sand (0-10%),
Bottom row (L to R); firm muddy sand (10-25%), soft muddy sand (25-50%), very soft sandy mud (50-90%).

Table A2. Modified NEMP substrate classes and field codes.

Consolidated substrate			Code	NEMP equivalent (depth of sinking)	
Bedrock		Rock field "solid bedrock"	RF	RF	Rockland
Coarse Unconsolidated Substrate (>2mm)					
Boulder	>256mm	Boulder field "bigger than your head"	BF	BF	Boulder field
Cobble	64 to <256mm	Cobble field "hand to head sized"	CF	CF	Cobble field
Gravel	2 to <64mm	Gravel field "smaller than palm of hand"	GF	GF	Gravel field
Shell	2 to <64mm	Shell "smaller than palm of hand"	Shel	Shell	Shell bank
Fine Unconsolidated Substrate (<2mm) – see footnotes					
Sand (S)	Low mud (0-10%)	Mobile sand	mS	MS	Mobile sand (<1cm)
		Firm shell/sand	fShS	FSS	Firm shell/sand (<1cm)
		Firm sand	fS	FS	Firm sand (<1cm)
		Soft sand	sS	SS	Soft sand (>2cm)
		Very soft sand	vsS	SS	Soft sand (>2cm)
Muddy Sand (MS)	Moderate mud (≥10-25%)	Mobile muddy sand	mMS10	MS	Mobile sand (<1cm)
		Firm muddy shell/sand	fMShS10	FSS	Firm shell/sand (<1cm)
		Firm muddy sand	fMS10	FMS	Firm mud/sand (<2cm)
		Soft muddy sand	sMS10	SM	Soft mud/sand (2-5cm)
		Very soft muddy sand	vsMS10	VSM	Very soft mud/sand (>5cm)
	High mud (≥25-50%)	Mobile muddy sand	mMS25	MS	Mobile sand (<1cm)
		Firm muddy shell/sand	fMShS25	FSS	Firm shell/sand (<1cm)
		Firm muddy sand	fMS25	FMS	Firm mud/sand (<2cm)
		Soft muddy sand	sMS25	SM	Soft mud/sand (2-5cm)
		Very soft muddy sand	vsMS25	VSM	Very soft mud/sand (>5cm)
Sandy Mud (SM)	Very high mud (≥50-90%)	Firm sandy mud	fSM	FMS	Firm mud/sand (<2cm)
		Soft sandy mud	sSM	SM	Soft mud/sand (2-5cm)
		Very soft sandy mud	vsSM	VSM	Very soft mud/sand (>5cm)
Mud (M)	Mud (≥90%)	Firm mud	fM90	FMS	Firm mud/sand (<2cm)
		Soft mud	sM90	SM	Soft mud/sand (2-5cm)
		Very soft mud	vsM90	VSM	Very soft mud/sand (>5cm)
Zoogenic (living)					
Area dominated by both live cockle, mussel, oyster, shellfish or tubeworm species respectively.		Cocklebed	CKLE		Cockle
		Mussel reef	MUSS		Mussel
		Oyster reef	OYST		Oyster
		Shellfish bed	SHFI		
		Tubeworm reef	TUBE		Sabellid
Artificial Substrate					
Introduced natural or human-made materials that modify the environment. Includes rip-rap, rock walls, wharf piles, bridge supports, walkways, boat ramps, groynes, flood control banks, stop gates.		Substrate (bund, ramp, wall, whf)	aS		
		Boulder field	aBF		Boulder field
		Cobble field	aCF		Cobble field
		Gravel field	aGF		Gravel field
		Sand field	aSF		Firm/Soft sand

Sediment firmness: Subjectively classified as firm if you sink 0-<2cm, soft if you sink 2-5cm, or very soft if you sink >5cm.
Mobile: Sediment is firm but routinely moved by tidal currents or waves. Commonly characterised by having a rippled surface layer.
Sand: Sandy sediment that is granular when rubbed between the fingers and releases no conspicuous fines when sediment is disturbed.
Shell/Sand: Mixed sand and shell hash. See muddy sand sub-classes below for field guidance on estimating mud content.
Muddy Sand: Sand-dominated sediment that is mostly granular when rubbed between the fingers but has a smoother consistency than sand. Subdivided into two sub-classes based on estimated mud content (commonly validated by laboratory analysis of representative substrate);

i. Moderate mud (≥10-25%) content: Muddy fines evident when sediment is disturbed. Sediments generally firm to walk on.
ii. High mud (≥25-50%) content): Muddy fines conspicuous when sediment is disturbed. Sediments generally soft to walk on.

Sandy Mud (≥50-90% mud content): Mud-dominated sediment primarily smooth/silken when rubbed between the fingers, but retains a granular component. Sediments generally soft or very soft and only firm if dried out, or another component (e.g. gravel) prevents sinking.
Mud (≥90% mud content): Mud-dominated sediment with no obvious sand component. Smooth/silken when rubbed between the fingers. Sediments generally only firm if dried out, or another component (e.g. gravel underneath mud) prevents sinking.

A1.4 Estuary salt marsh

Salt marsh grows in the upper tidal extent of estuaries, usually bordering the terrestrial margin. NEMP methods are used to map and categorise salt marsh, with dominant estuarine plant species used to define broad structural classes (e.g., rush, sedge, herb, grass, reed, tussock; see Robertson et al. 2002). The following changes have been made to the original NEMP vegetation classifications:

- Forest (woody plants >10 cm density at breast height - dbh) and scrub (woody plants <10cm dbh) are considered terrestrial and mapped using LCDB codes as outlined in Table A1.
- Introduced weeds: Weeds are a common margin feature occasionally extending into upper intertidal areas and have been added to broad salt marsh structural classes.
- Estuarine shrubland: Woody plants <10 cm dbh growing in intertidal areas (e.g., mangroves, saltmarsh ribbonwood) have been added to broad salt marsh structural classes.

Two measures are used to assess salt marsh condition: i) intertidal extent (percent cover of total intertidal area) and ii) current extent compared to estimated historical extent.

LiDAR (where available) and historic aerial imagery are used to estimate historic salt marsh extent. All LiDAR geoprocessing is performed using ArcGIS Pro (currently v2.9.3). The terrain dataset is converted to raster using the Terrain to Raster (3D Analyst) tool. Contour lines are created using the Contour List (Spatial Analyst) tool. An elevation contour that represents the upper estuary boundary elevation is selected based on a comparison with existing estuary mapping and a visual assessment of aerial imagery. To estimate historic salt marsh extent, both the upper estuary boundary and historic aerial imagery (e.g., sourced from retrolens.co.nz or council archives) are used to approximate the margin of salt marsh which is digitised in ArcMap (currently v10.8) to determine areal extent.

In addition to mapping of the salt marsh itself, the substrate in which the salt marsh is growing is also mapped, based on the methods described in Section A1.3. As salt marsh can naturally trap and accrete muddy sediment, substrate mapping within salt marsh can provide an insight into ongoing or historic muddy sediment inputs.

A1.5 Estuary seagrass assessment

The NEMP provides no guidance on the assessment of seagrass beyond recording its presence when it is a dominant surface feature. To improve on the NEMP, the mean percent cover of discrete seagrass patches is visually estimated through ground-truthing, based on the 6-category percent cover scale in Fig. A1.

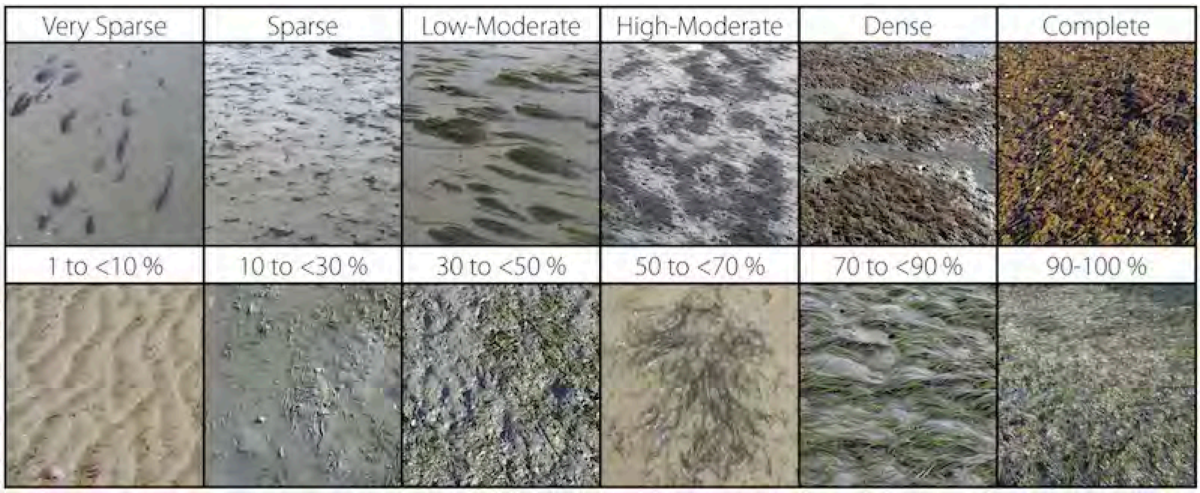

Fig. A1. Visual rating scale for percentage cover estimates. Macroalgae (top), seagrass (bottom). Modified from FGDC (2012).

The state of seagrass is assessed by the change in spatial cover as a percentage of the measured 'baseline'. which generally represents the earliest available ground-truthed broad scale survey. In the absence of ground-truthed broad scale surveys historic imagery, supported by anecdotal reports of seagrass presence, can be georeferenced in ArcMap (v10.8) and visible seagrass digitised. It is difficult to reliably map seagrass areas of <50% cover, and to distinguish boundaries between subtidal and intertidal areas, solely from historic imagery (i.e., no ground-truthing). Therefore, comparisons of broad scale data captured from aerial imagery alone can generally only be reliably made for percent cover categories >50%, with the estuary-wide area of seagrass >50% cover typically compared across years. Notwithstanding that seagrass extent derived from historic imagery may be less reliable than that derived from ground-truthed surveys, it remains a useful metric to understanding the narrative of seagrass change, including its natural variability.

A1.6 Estuary macroalgae assessment

The NEMP provides no guidance on the assessment of macroalgae beyond recording its presence when it is a dominant surface feature, hence, improved methods are used by Salt Ecology. These are based on the New Zealand Estuary Trophic Index (Robertson et al. 2016a), which adopts the United Kingdom Water Framework Directive (WFD-UKTAG 2014) Opportunistic Macroalgal Blooming Tool (OMBT). The OMBT, described in detail in previous reports (e.g., Stevens et al. 2022; Roberts et al. 2022), is a five-part multi-metric index that provides a comprehensive measure of the combined influence of macroalgal growth and distribution in an estuary. It produces an overall Ecological Quality Rating (EQR) ranging from 0 (major disturbance) to 1 (minimally disturbed), and rates estuarine condition in relation to macroalgal status within five overall quality status threshold bands (bad, poor, good, moderate, high). The individual metrics that are used to calculate the EQR include:

- *Percentage cover of opportunistic macroalgae:* The spatial extent and surface cover of algae present in intertidal soft sediment habitat in an estuary provides an early warning of potential eutrophication issues.
- *Macroalgal biomass:* Biomass provides a direct measure of macroalgal growth (wet weight biomass). Measurements and estimates of mean biomass are made within areas affected by macroalgal growth, as well as across the total estuary intertidal area.
- *Extent of algal entrainment into the sediment matrix:* Macroalgae is defined as entrained when growing in stable beds or with roots deep (e.g., >30mm) within the sediments, which indicates that persistent macroalgal growths have established.

If an estuary supports <5% opportunistic macroalgal cover within the Available Intertidal Habitat (AIH), then the overall quality status using the OMBT method is reported as 'high' (EQR score ≥ 0.8 to 1.0) with no further sampling required. In this situation a numeric EQR score, which is based directly on the measured opportunistic macroalgal percent cover in the AIH, is calculated for the 'high' band using the approach described in Stevens et al. (2022). Using the OMBT, opportunistic macroalgae patches are mapped during field ground-truthing using a 6-category rating scale (modified from FGDC 2012) as a percentage cover guide (Fig. A1). Within these percent cover categories, representative patches of comparable macroalgal growth are identified and the biomass and the extent of macroalgal entrainment in sediment is measured. Biomass is measured by collecting algae growing on the surface of the sediment from within a defined area (e.g., 25x25cm quadrat) and placing it in a sieve bag. The algal material is then rinsed to remove sediment. Any non-algal material including stones, shells and large invertebrate fauna (e.g., crabs, shellfish) are also removed. Remaining algae are then hand squeezed or spun until water stops running, and the wet weight is recorded to the nearest 10g using 1kg Pesola light-line spring scales. When sufficient representative patches have been measured to enable biomass to be reliably estimated, biomass estimates are then made following the OMBT method.

Macroalgae patches are digitised in ArcMAP (v10.8) as described in Section 1.1 with each patch containing data on the species present, percent cover, biomass and entrainment status. Each macroalgal patch is given a unique 'Patch ID' up to a maximum of 100 patches per estuary (i.e., the maximum the OMBT excel calculator can calculate). If more than 100 patches are present, comparable patches are grouped (i.e., patches with the same species, percent cover, biomass and entrainment). The raw data is exported from ArcMap (v10.8) into excel using a scripting tool. The OMBT Microsoft Excel template (i.e., WFD-UKTAG Excel template) is used to calculate an OMBT EQR, with OMBT biomass thresholds (Table A3) updated to reflect conditions in New Zealand estuaries as described in Plew et al. (2020). The scores are then categorised on the five-point scale adopted by the method as outlined in Table A3.

Table A3. Thresholds used to calculate the OMBT-EQR in the current report.

ECOLOGICAL QUALITY RATING (EQR)	High[1]	Good	Moderate	Poor	Bad
	≥0.8 - 1.0	≥0.6 - <0.8	≥0.4 - <0.6	≥0.2 - <0.4	0.0 - <0.2
% cover on Available Intertidal Habitat (AIH)	0 - ≤5	>5 - ≤15	>15 -≤25	>25 - ≤75	>75 - 100
Affected Area (AA) [>5% macroalgae] (ha)[2]	≥0 - 10	≥10 - 50	≥50 - 100	≥100 - 250	≥250
AA/AIH (%)*	≥0 - 5	≥5 - 15	≥15 - 50	≥50 - 75	≥75 - 100
Average biomass ($g.m^{-2}$) of AIH[3]	≥0 - 100	≥100 - 200	≥200 - 500	≥500 - 1450	≥1450
Average biomass ($g.m^{-2}$) of AA[3]	≥0 - 100	≥100 - 200	≥200 - 500	≥500 - 1450	≥1450
% algae entrained >3cm deep	≥0 - 1	≥1 - 5	≥5 - 20	≥20 - 50	≥50 - 100

[1] Where ≤5%,cover AIH EQR was calculated as described in Section A1.6.

[2] Only the lower EQR of the 2 metrics, AA or AA/AIH, should be used in the final EQR calculation (WFD-UKTAG (2014).

[3] Updated thresholds for New Zealand estuaries described in Plew et al. (2020).

A1.7 Broad scale data recording, QA/QC and analysis

Broad scale mapping provides a rapid overview of estuary substrate, macroalgae, seagrass and salt marsh condition. The ability to correctly identify and map features is primarily determined by the resolution of available aerial imagery, the extent of ground-truthing undertaken to validate features visible on photographs, and the experience of those undertaking the mapping. In most instances features with readily defined edges can be mapped at a scale of ~1:2000 to within 1-2m of their boundaries. The greatest scope for error occurs where boundaries are not readily visible on imagery, e.g., sparse seagrass or macroalgal beds. Extensive mapping experience has shown that transitional boundaries can be mapped to within ±10m where they have been thoroughly ground-truthed, but when relying on imagery alone (i.e., no ground-truthing), accuracy is unlikely to be better than ±20-50m, and generally limited to vegetation features with a percent cover >50%.

There are many potential sources of error that can occur during the digitising and GIS data collation process that may affect the accuracy of the metrics derived from broad scale mapping, and undermine the assessment of temporal change. To minimise this risk, Salt Ecology has developed in-house scripting tools in Phyton to create a customised GIS toolbox for broad scale mapping outputs. The scripting tools sequentially run through a QA/QC checklist to check for duplicated or overlapping GIS polygons and to identify gaps or slivers and validate typology (field codes). Following rectification of any errors, the customised toolbox is used to create maps with consistent symbology, generate standardised summary tables for reporting, and to add metadata to final GIS packages.

Additional to the annotation of field information onto aerial imagery during ground-truthing, electronic templates (custom-built using Fulcrum app software - www.fulcrumapp.com) are used to record substrate validation locations and measurements of sediment aRPD, texture and sediment type, as well as macroalgal data (i.e., biomass and cover measurements, entrainment). Each sampling record created in Fulcrum generates a GPS position, which is exported to ArcMap, with pre-specified data entry constraints (e.g., with minimum or maximum values for each data type) minimising the risk of erroneous data recording. Scripting tools are then used within ArcMap to upload data.

B. SEDIMENT QUALITY AND BIOTA METHODS

B1.1 Overview

Mapping the main habitats in an estuary using the NEMP broad scale approach provides a basis for identifying representative areas to sample sediment quality and associated biota. Samples are typically collected from sufficient sites to characterise the range of conditions in estuary soft sediments, from the seaward extent to upper estuary areas, including areas in the vicinity of any potentially strong catchment influences (e.g., river mouths, stormwater point sources). A summary of sediment and biota indicators, the rationale for their use, and field sampling methods, is provided in the main body of the report (i.e., Table 2). The sampling methods generally adhere to the NEMP 'fine scale' sampling protocol, except where noted.

B1.2 Sediment quality sampling and laboratory analyses

At each site, a composite sediment sample (~500g) is pooled from three sub-samples (to 20mm depth). Samples are stored on ice and sent to RJ Hill Laboratories for analysis of: particle grain size in three categories (%mud <63μm, sand <2mm to ≥63μm, gravel ≥2mm); organic matter (total organic carbon, TOC); nutrients (total nitrogen, TN; total phosphorus, TP); and trace contaminants (arsenic, As; cadmium, Cd; chromium, Cr; copper, Cu; mercury, Hg; lead, Pb; nickel, Ni; zinc, Zn). Details of laboratory methods and detection limits are provided in Table B1.

Table B1. Hill Labs methods and detection limits.

Sample Type: Sediment		
Test	**Method Description**	**Default Detection Limit**
Individual Tests		
Environmental Solids Sample Drying*	Air dried at 35°C Used for sample preparation. May contain a residual moisture content of 2-5%.	-
Environmental Solids Sample Preparation	Air dried at 35°C and sieved, <2mm fraction. Used for sample preparation May contain a residual moisture content of 2-5%.	-
Dry Matter for Grainsize samples (sieved as received)*	Drying for 16 hours at 103°C, gravimetry (Free water removed before analysis).	0.10 g/100g as rcvd
Total Recoverable digestion	Nitric / hydrochloric acid digestion. US EPA 200.2.	-
Total Recoverable Phosphorus	Dried sample, sieved as specified (if required). Nitric/Hydrochloric acid digestion, ICP-MS, screen level. US EPA 200.2.	40 mg/kg dry wt
Total Sulphur*	LECO S144 Sulphur Determinator, high temperature furnace, infra-red detector. Subcontracted to SGS, Waihi. ASTM 4239.	0.010 g/100g dry wt
Total Nitrogen*	Catalytic Combustion (900°C, O2), separation, Thermal Conductivity Detector [Elementar Analyser].	0.05 g/100g dry wt
Total Organic Carbon*	Acid pretreatment to remove carbonates present followed by Catalytic Combustion (900°C, O2), separation, Thermal Conductivity Detector [Elementar Analyser].	0.05 g/100g dry wt
Heavy metals, trace As,Cd,Cr,Cu,Ni,Pb,Zn,Hg	Dried sample, <2mm fraction. Nitric/Hydrochloric acid digestion, ICP-MS, trace level.	0.010 - 0.8 mg/kg dry wt
3 Grain Sizes Profile as received		
Fraction >/= 2 mm*	Wet sieving with dispersant, as received, 2.00 mm sieve, gravimetry.	0.1 g/100g dry wt
Fraction < 2 mm, >/= 63 μm*	Wet sieving using dispersant, as received, 2.00 mm and 63 μm sieves, gravimetry (calculation by difference).	0.1 g/100g dry wt
Fraction < 63 μm*	Wet sieving with dispersant, as received, 63 μm sieve, gravimetry (calculation by difference).	0.1 g/100g dry wt

B1.3 Field sediment oxygenation assessment

The apparent Redox Potential Discontinuity (aRPD) depth is used to assess the trophic status (i.e., extent of excessive organic or nutrient enrichment) of soft sediment. The aRPD depth is the visible transition between oxygenated surface sediments (typically brown in colour) and deeper less oxygenated sediments (typically dark grey or black in colour). The aRPD provides an easily measured, time-integrated, and relatively stable indicator of sediment enrichment and oxygenation conditions (Rosenberg et al. 2001; Gerwing et al. 2013). Sediments are considered to have poor oxygenation if the aRPD is consistently <10mm deep and shows clear signs of organic enrichment, indicated by a distinct colour change to grey or black in the sediments.

Example of distinct aRPD colour change with brown oxygenated sediments from the surface down to ~40mm

B1.4 Biological sampling: sediment-dwelling macrofauna

To sample sediment-dwelling macrofauna, duplicate large (130mm diameter) sediment cores (see Table 2 in main body of the report) are collected, and placed in separate 0.5mm mesh sieve bags, which are gently washed in seawater to remove fine sediment. The retained animals are preserved in a mixture of ~75% isopropyl alcohol and 25% seawater for later sorting and taxonomic identification by a skilled taxonomic laboratory (e.g., NIWA). The types of animals present in each sample, as well as the range of different species (i.e., richness) and their abundance, are well-established indicators of ecological health in estuarine and marine soft sediments.

B1.5 Biological sampling: surface-dwelling epibiota

In addition to macrofaunal core sampling, epibiota (macroalgae and conspicuous surface-dwelling animals nominally >5mm body size) visible on the sediment surface at each site are semi-quantitatively categorised using 'SACFOR' abundance (animals) or percentage cover (macroalgae) ratings shown in Table B2. These ratings represent a scoring scheme simplified from established monitoring methods (MNCR 1990; Blyth-Skyrme et al. 2008).

The SACFOR method is ideally suited to characterise intertidal epibiota with patchy or clumped distributions. It was conducted as an alternative to the quantitative quadrat sampling specified in the NEMP, which is known to poorly characterise scarce or clumped species. Note that our epibiota assessment does not include infaunal species that may be visible on the sediment surface, but whose abundance cannot be reliably determined from surface observation (e.g., cockles). Nor does it include very small organisms such as the estuarine snail *Potamopyrgus* spp.

Table B2. SACFOR ratings for site-scale abundance, and percent cover of epibiota and algae, respectively.

SACFOR category	Code	Density per m^2	Percent cover
Super abundant	S	> 1000	> 50
Abundant	A	100 - 999	20 - 50
Common	C	10 - 99	10 - 19
Frequent	F	2 - 9	5 - 9
Occasional	O	0.1 - 1	1 - 4
Rare	R	< 0.1	< 1

B1.6 Sediment quality and biota data recording, QA/QC and analysis

All sediment and macrofaunal samples sent to analytical laboratories were tracked using standard Chain of Custody forms, and results were transferred electronically from the laboratory to avoid transcription errors. Field measurements (e.g., aRPD) and site metadata were recorded electronically in templates (custom-built using Fulcrum app software - www.fulcrumapp.com), with pre-specified data entry constraints (e.g., with minimum or maximum values for each data type) minimising the risk of erroneous data recording.

Excel sheets were imported into the software R 4.2.3 (R Core Team 2023) and assigned sample identification codes. All summaries of univariate responses (e.g., sediment analyte concentrations, macrofauna abundances) were produced in R, including tabulated or graphical representations of the data. Where results for sediment quality parameters were below analytical detection limits, half of the detection limit value was used, according to convention.

Before sediment-dwelling macrofaunal analyses, the data were screened to remove species that were not regarded as a true part of the macrofaunal assemblage; these were planktonic life-stages and non-marine organisms (e.g., freshwater drift). To facilitate comparisons with any future surveys, and other estuaries, cross-checks were made to ensure consistent naming of species and higher taxa. For this purpose, the adopted name was that accepted by the World Register of Marine Species (WoRMS, www.marinespecies.org/).

Macrofaunal response variables included richness and abundance by species and higher taxonomic groupings. In addition, scores for the biotic health index AMBI (Borja et al. 2000; Borja et al. 2019) were derived. AMBI scores reflect the proportion of taxa falling into one of five eco-groups (EG) that reflect sensitivity to pollution, ranging from relatively sensitive (EG-I) to relatively resilient (EG-V).

To meet the criteria for AMBI calculation, macrofauna data were reduced to a subset that included only adult 'infauna' (those organisms living within the sediment matrix), which involved removing surface dwelling epibiota and any juvenile organisms. AMBI scores were calculated based on standard international eco-group classifications where possible (http://ambi.azti.es). However, to reduce the number of taxa with unassigned eco-groups, international data were supplemented with more recent eco-group classifications for New Zealand (Keeley et al. 2012; Robertson et al. 2015; Robertson et al. 2016c; Robertson 2018). Note that AMBI scores were not calculated for macrofaunal cores that did not meet operational limits defined by Borja et al. (2012), in terms of the percentage of unassigned taxa (>20%), or low sample richness (<3 taxa) or abundances (<6 individuals).

Where helpful in understanding estuary health, multivariate analyses of macrofaunal community data are undertaken, mainly using the software package Primer v7.0.13 (Clarke et al. 2014). Patterns in site similarity as a function of macrofaunal composition and abundance are assessed using an 'unconstrained' non-metric multidimensional scaling (nMDS) ordination plot, based on pairwise Bray-Curtis similarity index scores among samples.

Prior to the multivariate analysis, macrofaunal abundance data are transformed (e.g., square root) to down-weight the influence on the ordination pattern of the dominant species or higher taxa. The procedure PERMANOVA may be used to test for compositional differences among samples. Overlay vectors and bubble plots on the nMDS are used to visualise relationships between multivariate biological patterns and sediment quality data (the latter may need to be transformed (e.g., log x+1) and normalised to a standard scale. The Primer procedure Bio-Env is typically used to evaluate the suite of sediment quality variables that best explain the macrofauna ordination pattern.

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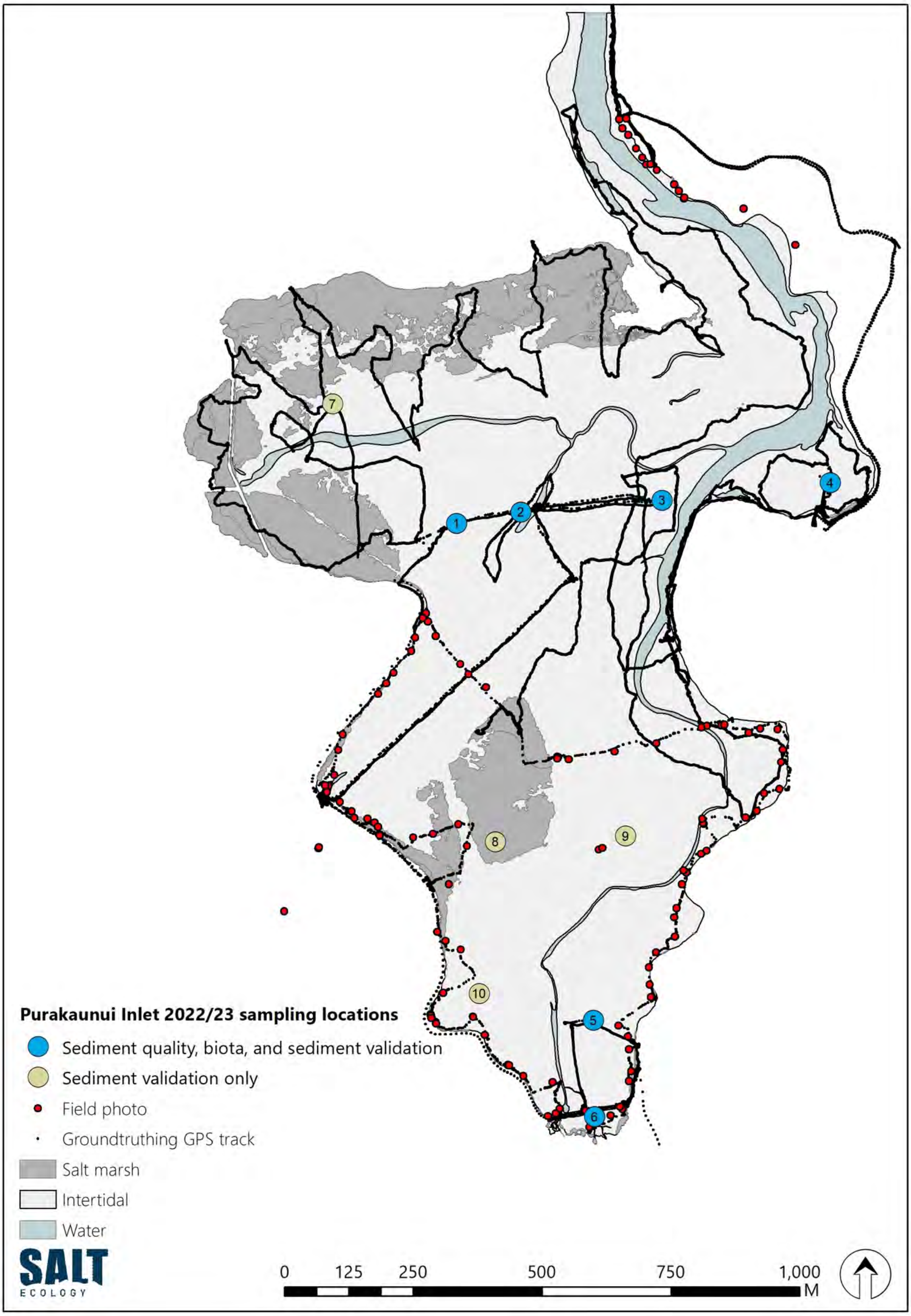
APPENDIX 2. GROUND-TRUTHING



APPENDIX 3. RAW DATA ON DOMINANT SALT MARSH SPECIES

SubClass	Dominant species	Sub-dominant species 1	Sub-dominant species 2	Ha	%
Estuarine Shrub					
	Plagianthus divaricatus (Salt marsh ribbonwood)			0.02	0.08
		Selliera radicans (Remuremu)	*Samolus repens* (Primrose)	0.03	0.13
Rushland					
	Apodasmia similis (Jointed wirerush)			0.09	0.38
		Juncus kraussii (Searush)	*Atriplex prostrata* (Orache, Creeping saltbush)	0.62	2.63
		Plagianthus divaricatus (Salt marsh ribbonwood)		0	0.01
	Juncus kraussii (Searush)			2.75	11.66
		Apodasmia similis (Jointed wirerush)		0.73	3.1
		Plagianthus divaricatus (Salt marsh ribbonwood)		0.01	0.02
		Plagianthus divaricatus (Salt marsh ribbonwood)	*Apodasmia similis* (Jointed wirerush)	0.02	0.09
		Selliera radicans (Remuremu)	*Sarcocornia quinqueflora* (Glasswort)	1	4.23
Herbfield					
	Leptinella dioica	*Cotula coronopifolia* (Bachelor's button)		0	0.01
	Samolus repens (Primrose)			0.01	0.03
		Cotula coronopifolia (Bachelor's button)		0	0.02
		Isolepis cernua (Slender clubrush)	*Carex litorosa* (Sea sedge)	0	0
		Sarcocornia quinqueflora (Glasswort)		0.01	0.03
		Selliera radicans (Remuremu)	*Sarcocornia quinqueflora* (Glasswort)	0.02	0.08
		Suaeda novaezelandiae (Sea blite)	*Isolepis cernua* (Slender clubrush)	0.01	0.05
	Sarcocornia quinqueflora (Glasswort)			9.64	40.83
		Festuca arundinacea (Tall fescue)	*Leptinella dioica*	0.01	0.05
		Puccinella stricta (Salt grass)	*Samolus repens* (Primrose)	0.47	1.98
		Samolus repens (Primrose)		0.09	0.38
		Samolus repens (Primrose)	*Cotula coronopifolia* (Bachelor's button)	0.04	0.17
		Samolus repens (Primrose)	*Selliera radicans* (Remuremu)	0.84	3.54
		Selliera radicans (Remuremu)		2.65	11.22
		Selliera radicans (Remuremu)	*Juncus kraussii* (Searush)	0	0.01
		Selliera radicans (Remuremu)	*Samolus repens* (Primrose)	2.2	9.3
		Suaeda novaezelandiae (Sea blite)		0.12	0.5
		Suaeda novaezelandiae (Sea blite)	*Samolus repens* (Primrose)	0	0.02
	Selliera radicans (Remuremu)	*Isolepis cernua* (Slender clubrush)		0	0
		Samolus repens (Primrose)		0.01	0.02
		Sarcocornia quinqueflora (Glasswort)	*Carex litorosa* (Sea sedge)	0.01	0.05
		Sarcocornia quinqueflora (Glasswort)	*Isolepis cernua* (Slender clubrush)	1.39	5.88
		Sarcocornia quinqueflora (Glasswort)	*Samolus repens* (Primrose)	0.49	2.08
		Sarcocornia quinqueflora (Glasswort)	*Thyridia repens* (New Zealand musk)	0.33	1.39
	Suaeda novaezelandiae (Sea blite)	*Sarcocornia quinqueflora* (Glasswort)		0.01	0.04
Total				23.62	100

Note; Zero values indicate species present but covering <0.1ha.

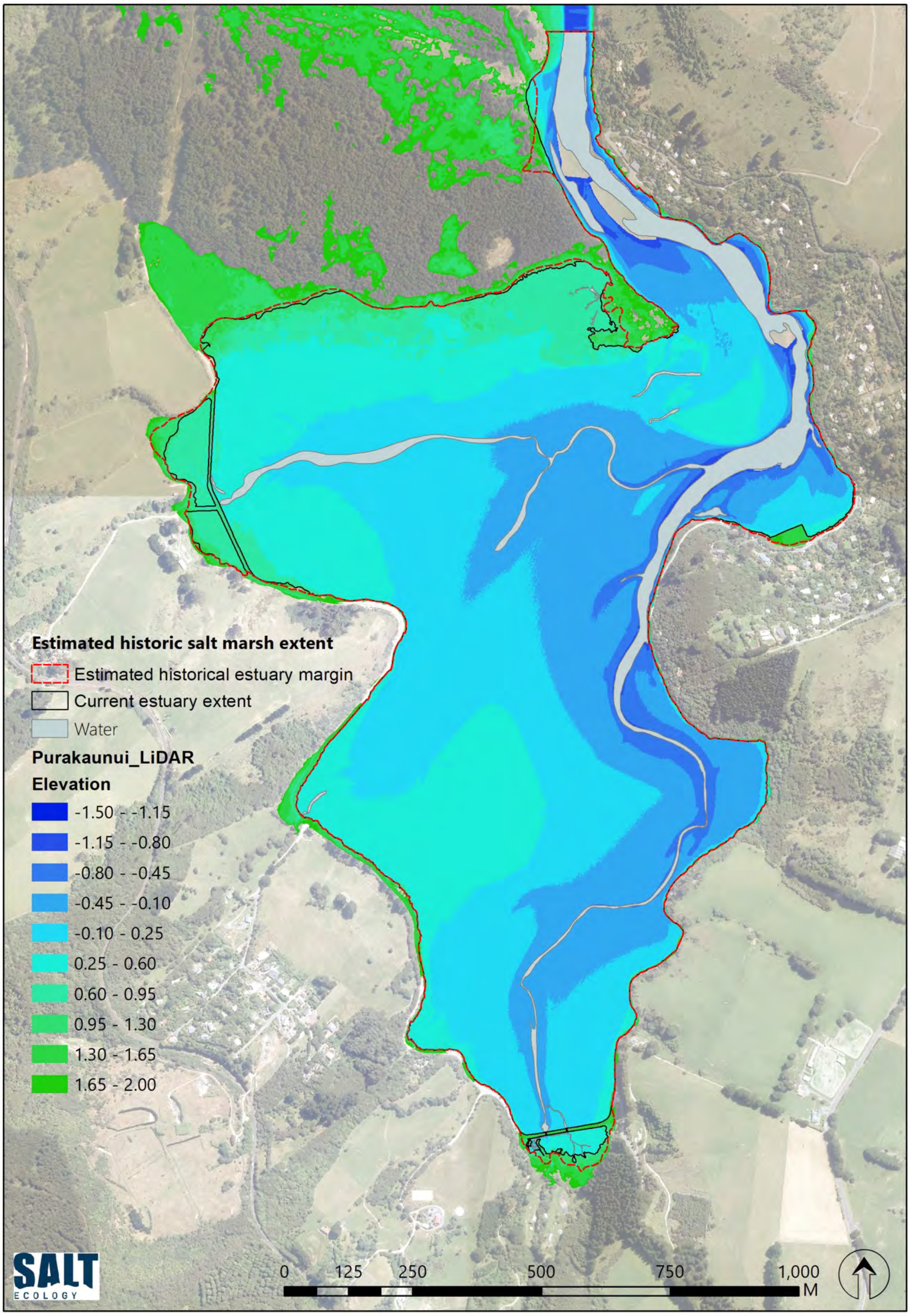
APPENDIX 4. RAW DATA ON SUBSTRATE

Total intertidal area, Available Intertidal Habitat (AIH; total less salt marsh), and substrate within salt marsh, seagrass and macroalgae.

Substrate Class	Features	Total intertidal area		AIH*		Salt marsh		Seagrass		Macroalgae	
		Ha	%	Ha	%	Ha	%	Ha	%	Ha	%
Bedrock	Rock field	0.3	0.3	0.3	0.4	0.0	-	0.0	-	0.0	-
Coarse substrate (>2mm)	Boulder field	0.3	0.3	0.3	0.3	0.0	-	0.0	-	0.0	-
	Artificial Boulder field	0.1	0.1	0.1	0.1	0.0	-	0.0	-	0.0	-
	Cobble field	1.5	1.2	1.5	1.5	0.0	0.1	0.0	-	0.0	-
	Gravel field	0.7	0.6	0.5	0.5	0.1	0.6	0.0	-	0.0	-
	Shell bank	0.3	0.3	0.3	0.3	0.0	-	0.0	-	0.0	-
Sand (0-10% mud)	Firm shell/sand	5	4.1	5.0	5.1	0.0	-	0.0	-	0.0	-
	Mobile sand	8.5	7	8.5	8.7	0.0	-	0.0	-	0.0	-
	Firm sand	42.8	35.3	42.5	43.5	0.3	1.4	0.0	-	1.4	73.8
Muddy Sand (>10-25% mud)	Firm muddy shell/sand	0.9	0.7	0.9	0.9	0.0	-	0.0	-	0.0	-
	Firm muddy sand	37.7	31.1	35.0	35.9	2.6	11.1	0.0	-	0.5	26.2
Muddy Sand (>25-50% mud)	Firm muddy sand	12.8	10.6	1.1	1.1	11.7	49.6	0.0	-	0.0	-
	Soft muddy sand	7	5.8	0.7	0.7	6.3	26.9	0.0	-	0.0	-
Sandy Mud (>50-90% mud)	Soft sandy mud	2.5	2.1	0.1	0.1	2.4	10.4	0.0	-	0.0	-
	Very soft sandy mud	0.8	0.6	0.8	0.8	0.0	-	0.0	-	0.0	-
Total		121	100	97.5	100	23.6	100	0.0	-	1.8	100

*AIH - Available Intertidal Habitat (excludes salt marsh)

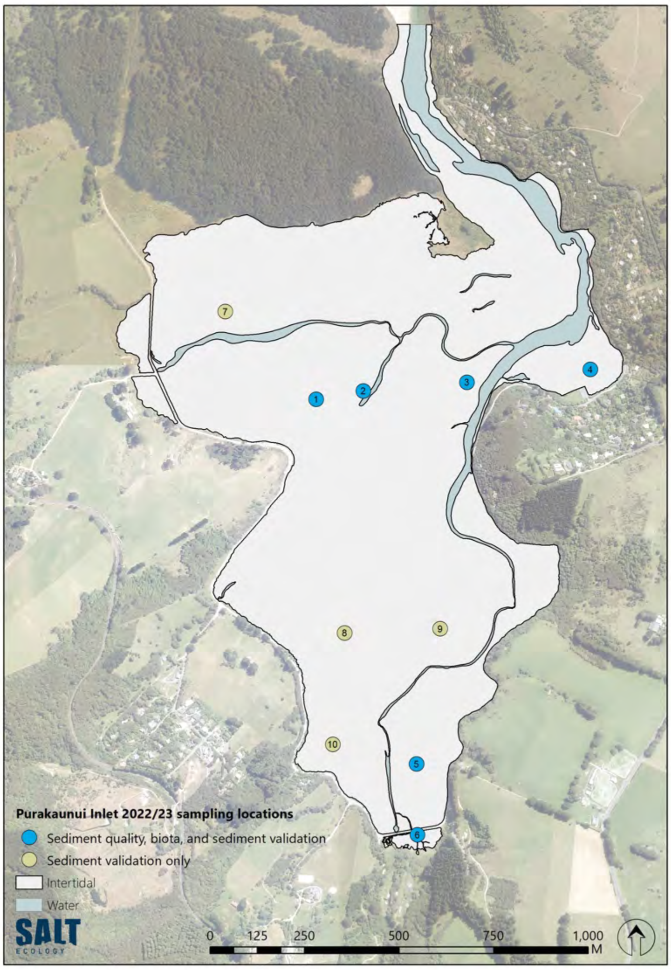
APPENDIX 5. LIDAR ELEVATIONS



APPENDIX 6. SEDIMENT VALIDATION

Sampling was undertaken at 10 sites (see map below) to validate subjective field estimates of sediment type (with respect to mud content) against laboratory grain size analysis of mud content. There was a match for 8 of the 10 samples. The two differences are shown in red in the Table below. In these cases, the laboratory result was within the 5% mud content tolerance of the subjective threshold boundary adopted for this method. As such, no adjustments to field classifications were made.

Site	NZTM_E	NZTM_N	Field code	Sed firmness	Assessed % mud	Mud (%)	Sand (%)	Gravel (%)
1	1415139	4930710	fS	firm	0-10	4.8	94.7	0.5
2	1415264	4930732	fMS10	firm	10-25	6.0	93.8	0.2
3	1415539	4930755	fS	firm	0-10	3.5	94.2	2.3
4	1415865	4930789	fMS10	firm	10-25	19.2	80.8	< 0.1
5	1415405	4929745	fMS10	firm	10-25	10.7	89.3	< 0.1
6	1415408	4929557	vsSM	very soft	50-90	78.3	21.6	< 0.1
7	1414898	4930942	fS	firm	0-10	9.0	91.0	< 0.1
8	1415214	4930092	sMS25	soft	25-50	24.1	75.7	0.2
9	1415468	4930103	fS	firm	0-10	4.8	95.1	0.1
10	1415183	4929797	fS	firm	0-10	9.0	85.4	5.6




Site 7


Site 8

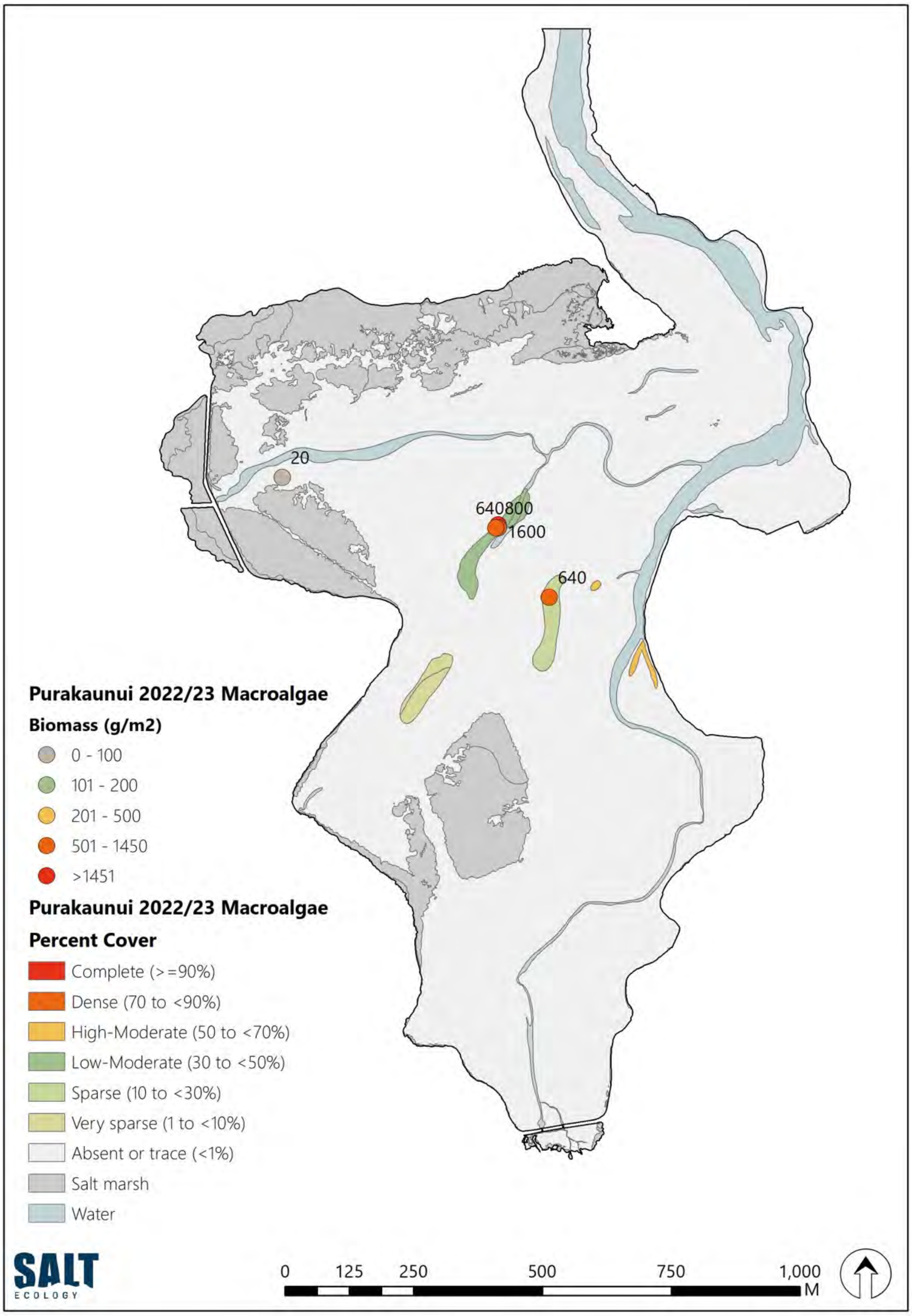

Site 9


Site 10

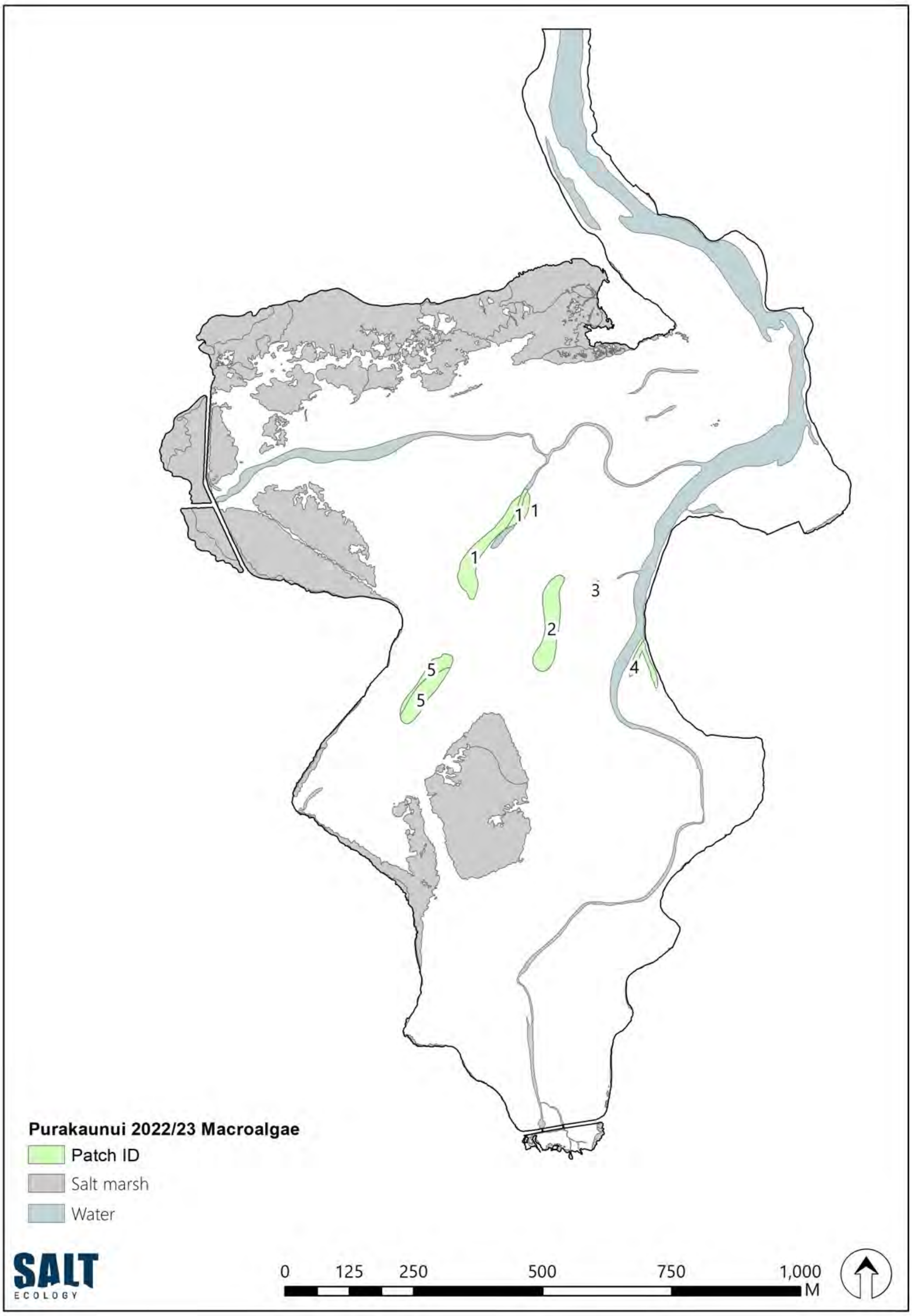
Photos of Sites 1-6 presented in main report.

APPENDIX 7. MACROALGAE COVER, BIOMASS AND PATCH INFORMATION

A. Cover and biomass



B. Macroalgae patch information



PatchID	Dominant species	Sub-dominant species	% Cover	Percent Cover Category	Biomass(g/m2)	Biomass Category	Entrained	Substrate	Ha
1	Agarophyton spp. (Agar weed)	Unspecified Macroalgae	40	Low-Moderate (30 to <50%)	1013	High (>500 - 1450)	1	fS	0.56
2	Agarophyton spp. (Agar weed)	Unspecified Macroalgae	16	Sparse (10 to <30%)	640	High (>500 - 1450)	1	fS	0.57
3	Agarophyton spp. (Agar weed)		50	High-Moderate (50 to <70%)	200	Low (>100 - 200)	0	fS	0.03
4	Agarophyton spp. (Agar weed)		60	High-Moderate (50 to <70%)	150	Low (>100 - 200)	0	fMS10	0.13
5	Agarophyton spp. (Agar weed)		1	Very sparse (1 to <10%)	10	Very low (1 - 100)	0	fMS10	0.35
5	Agarophyton spp. (Agar weed)		1	Very sparse (1 to <10%)	10	Very low (1 - 100)	0	fS	0.19

APPENDIX 8. MACROFAUNA RAW DATA

Main group	Taxa	Habitat	EG	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b
Amphipoda	*Paracalliope novizealandiae*	Infauna	I	19	11	295	239	1	2	-	-	2	-	-	1
Amphipoda	*Paramoera chevreuxi*	Infauna	II	-	-	-	-	2	-	-	-	-	-	-	-
Amphipoda	*Parawaldeckia kidderi*	Infauna	II	-	-	34	20	-	-	-	-	-	-	-	-
Amphipoda	*Torridoharpinia hurleyi*	Infauna	I	5	4	2	5	-	-	-	-	8	3	-	-
Anthozoa	*Edwardsia* sp.	Epibiota	II	1	2	2	-	-	-	1	-	1	1	-	-
Bivalvia	*Arthritica* sp. 5	Infauna	III	-	-	15	7	-	-	-	-	-	-	9	27
Bivalvia	*Austrovenus stutchburyi*	Infauna	II	2	3	9	7	25	26	15	21	-	-	-	-
Bivalvia	*Lasaea parengaensis*	Infauna	II	4	4	13	21	-	-	2	4	-	-	-	-
Bivalvia	*Macomona liliana*	Infauna	II	-	-	1	1	-	1	3	2	-	-	-	-
Bivalvia	*Nucula nitidula*	Infauna	I	1	1	31	16	-	-	22	25	-	-	-	-
Chironomidae	Chironomidae	Infauna	III	2	-	-	-	-	-	-	-	-	-	-	-
Cirripedia	*Austrominius modestus*	Epibiota	II	-	-	-	-	22	13	-	-	-	-	-	-
Copepoda	*Copepoda*	Infauna	II	-	-	-	-	-	-	-	-	-	1	-	-
Cumacea	*Colurostylis lemurum*	Infauna	II	1	-	-	-	3	4	4	1	1	-	-	-
Decapoda	*Halicarcinus whitei*	Infauna	III	-	-	3	4	1	-	-	-	2	-	-	-
Decapoda	*Hemiplax hirtipes*	Infauna	III	1	-	2	7	-	1	1	-	-	-	2	-
Gastropoda	*Amphibola crenata*	Epibiota	III	1	-	-	-	-	-	-	-	1	-	1	-
Gastropoda	*Cominella glandiformis*	Epibiota	III	-	1	-	-	-	1	1	3	-	-	-	-
Gastropoda	*Diloma subrostratum*	Epibiota	II	-	-	1	-	-	-	-	-	-	-	-	-
Gastropoda	*Micrelenchus huttonii*	Epibiota	-	-	-	1	3	3	6	-	1	-	-	-	-
Gastropoda	*Notoacmea scapha*	Epibiota	II	-	-	6	3	9	9	-	-	-	-	-	-
Gastropoda	*Zeacumantus subcarinatus*	Epibiota	II	-	-	-	-	2	-	-	-	-	-	-	-
Isopoda	*Isocladus* sp.	Infauna	I	-	-	-	1	7	1	-	1	-	-	-	-
Nematoda	Nematoda	Infauna	III	-	-	-	-	-	-	1	-	-	-	-	-
Nemertea	Nemertea	Infauna	III	1	-	4	10	-	-	1	-	-	-	-	1
Oligochaeta	Naididae	Infauna	V	-	-	4	2	-	-	-	-	-	-	-	1
Ostracoda	Ostracoda	Infauna	I	-	-	6	8	-	-	-	-	-	-	-	-
Polychaeta	*?Thelepus* sp.	Infauna	II	-	-	7	1	-	-	-	-	-	-	-	-
Polychaeta	*Aglaophamus macroura*	Infauna	II	-	5	1	-	1	-	2	2	4	2	-	-
Polychaeta	*Aonides trifida*	Infauna	I	-	-	1	-	-	1	1	1	-	-	-	-
Polychaeta	*Aricidea* sp.	Infauna	I	-	-	1	-	-	-	-	-	-	-	-	1
Polychaeta	*Armandia maculata*	Infauna	III	-	-	-	1	-	2	-	-	-	-	-	-
Polychaeta	*Boccardia acus*	Infauna	IV	-	-	-	-	-	-	-	3	-	-	-	-
Polychaeta	*Boccardia syrtis*	Infauna	II	3	-	14	10	-	-	8	6	15	15	-	-
Polychaeta	*Capitella cf. capitata*	Infauna	V	-	-	-	2	-	-	1	-	-	-	-	-
Polychaeta	*Eulalia* sp.	Infauna	II	-	-	-	-	-	-	-	1	-	-	-	-
Polychaeta	*Exogoninae* sp. 1	Infauna	II	4	6	18	27	-	-	21	12	-	3	-	-
Polychaeta	*Exogoninae* spp.	Infauna	II	-	-	14	24	-	-	-	-	-	-	-	-
Polychaeta	*Glycera* sp.	Infauna	II	-	-	-	-	-	-	1	-	-	-	-	-
Polychaeta	*Heteromastus filiformis*	Infauna	IV	-	-	5	3	-	-	-	3	-	-	-	-
Polychaeta	*Macroclymenella stewartensis*	Infauna	II	19	17	19	28	-	-	28	23	54	31	-	-
Polychaeta	*Microspio maori*	Infauna	I	-	1	-	-	-	-	1	-	10	15	-	-
Polychaeta	*Naineris naineris-A*	Infauna	I	-	1	-	-	-	-	-	-	-	-	-	-
Polychaeta	*Nicon aestuariensis*	Infauna	III	-	1	-	-	-	-	-	-	-	-	1	1
Polychaeta	*Orbinia papillosa*	Infauna	I	-	-	-	-	1	-	-	-	-	-	-	-
Polychaeta	*Paradoneis lyra*	Infauna	III	138	92	111	166	-	-	-	-	100	69	-	-
Polychaeta	*Platynereis* sp.	Infauna	III	-	-	48	58	-	-	-	1	-	-	-	-
Polychaeta	*Prionospio aucklandica*	Infauna	III	-	-	4	8	-	-	7	11	-	-	-	-
Polychaeta	Sabellidae	Infauna	I	-	-	-	-	-	-	-	-	6	1	-	-
Polychaeta	*Scolecolepides benhami*	Infauna	IV	-	-	-	-	-	-	-	-	-	2	12	10
Polychaeta	*Scoloplos cylindrifer*	Infauna	I	-	-	3	3	-	-	1	-	-	-	-	-
Tanaidacea	Tanaidacea	Infauna	II	-	2	45	68	-	-	-	-	-	-	-	-
			Richness	15	15	31	29	12	12	20	18	12	11	5	7
			Abundance	202	151	720	753	77	67	122	121	204	143	25	42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