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Synoptic Intertidal and Subtidal Monitoring of Kakanui Estuary

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For the People
Mō ngā tāngata

Synoptic Intertidal and Subtidal Monitoring of Kakanui Estuary

Prepared by

Keryn Roberts,

Leigh Stevens

and Barrie Forrest

for

Otago Regional Council

June 2021

keryn@saltecology.co.nz, +64 (0)21 0294 8546

www.saltecology.co.nz

For the environment
Mō te taiao

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GLOSSARY

aRPD	Apparent Redox Potential Discontinuity
CSR	Current Sedimentation Rate
ETI	Estuarine Trophic Index
HEC	High Enrichment Conditions (HECs) comprise mud-dominated sediments (>50% mud content) with macroalgal cover >50% that is entrained (growing >30mm deep) within the sediment, the combined presence of which may result in adverse ecological outcomes. HECs can also be present in non-algal areas where sediments have an elevated organic content (>1% total organic carbon) and low sediment oxygenation (apparent Redox Potential Discontinuity (aRPD) depth <10mm) as a consequence of algal degradation.
LCDB	Land Cover Data Base
MSL	Mean Sea Level
NSR	Natural Sedimentation Rate
NEMP	National Estuary Monitoring Protocol
ORC	Otago Regional Council
SOE	State of Environment (monitoring)
SSRTRE	Shallow Short-Residence Tidal River Estuary
Stratified	Fresh surface water overlying denser (heavier) seawater.

ACKNOWLEDGEMENTS

Many thanks to Sam Thomas (ORC) for reviewing the draft report.

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SUMMARY

BACKGROUND

Kakanui Estuary is an elongated and relatively narrow moderate-sized (~25ha) shallow short-residence tidal river estuary (SSRTRE), which discharges to the Otago coast 10km south of Oamaru. The estuary mouth is mobile and generally open to the sea; however, on occasion it constricts and closes due to the movement and build-up of gravel at the estuary entrance. The extent of seawater intrusion into the estuary is determined by the position and width of the estuary mouth. When the entrance is open, seawater can extend ~2.5km inland from the coast. The estuary is commonly stratified with fresh surface water overlying denser (heavier) seawater. A preliminary assessment of the estuary in 2009 indicated that it was in good health and only had minor fine sediment and nutrient issues. However, subsequent studies in 2013 and 2015 suggested that the state of the estuary had deteriorated, with the proliferation of macroalgae along the estuary margins and large mats of *Ulva* spp. in the lower estuary, likely stimulated by high nutrient concentrations in the Kakanui River and Waiareka Creek.

KEY FINDINGS

In January 2021, a survey was carried out after further anecdotal reports of fine sediment build-up and the proliferation of macroalgae in the estuary. The survey included broad scale habitat mapping of both intertidal and subtidal areas, and a synoptic water quality survey. The survey was carried out 2-weeks after a significant flood in the Kakanui River and results show the estuary had been well-flushed by that event, with considerable flood debris evident. The estuary substrate was scoured down to gravel, and nuisance macroalgae was absent. Water column stratification was observed ~2.5km upstream from the estuary mouth; however, there were no signs of significant or widespread eutrophication (e.g. low oxygen and high phytoplankton) in the water column. Relative to the earlier surveys and observations, the January 2021 results almost certainly reflect the timing of sampling (i.e. post flood) rather than the outcome of any improvements in the catchment. Flushing of excess sediments, nutrients and nuisance macroalgae from the estuary likely represents a period of short-term improvement in estuary condition that will return to a more degraded state if catchment inputs remain elevated. Hence, while Kakanui Estuary was in generally good health at the time of the survey, it remains under pressure and will likely continue to express eutrophic symptoms in future, particularly over the summer period when flushing is reduced.

RECOMMENDATIONS

Although the Kakanui Estuary was well-flushed at the time of sampling, significant eutrophic symptoms have been observed in previous surveys (e.g. macroalgae and phytoplankton). As such, it is recommended that ORC consider the following:

1. Undertake a repeat survey after a prolonged dry period (weeks to months) to determine the extent, if any, of subtidal eutrophication (e.g. low oxygen and phytoplankton) and identify whether profileration of macroalgae and fine sediment build-up reoccur.

2. Schedule regular ongoing monitoring (e.g. a 1-5 yearly cycle) focusing on intertidal and subtidal macroalgae, and water quality, in particular dissolved oxygen and phytoplankton impacts. A repeat of past 'fine scale' intertidal monitoring is not recommeded because the intertidal area is limited in extent, physically dynamic and in close proximity to the changeable entrance.

3. Assess catchment sources of nutrients and sediments to the estuary to determine whether changes to current land management practices are likely to significantly improve ecological condition and to guide council management priorities.

4. Use the Kakanui Estuary hydrodynamic model and the output of recommendation 3 to establish limits for catchment sediment and nutrient inputs that will protect the estuary from degradation.

1. INTRODUCTION

1.1 BACKGROUND

Estuary monitoring is undertaken by most councils in New Zealand as part of their State of the Environment (SOE) programmes. Monitoring is primarily designed to detect and understand changes in key estuaries over time and determine the effect of catchment influences, especially those due to the input of nutrients and muddy sediments.

The Otago Regional Council (ORC) programme includes synoptic surveys and/or routine monitoring in several smaller estuaries (e.g. Kaikorai, Taieri, Tokomairiro and Kakanui) that are classified as shallow short-residence tidal river estuaries (SSRTREs). These systems are river-dominated with a high flushing potential meaning they are less susceptible to nutrient enrichment impacts when compared to other estuary types. However, SSRTRE type estuaries can experience short periods (days to weeks) of restricted flushing when the estuary mouth undergoes partial or complete closure, increasing their susceptibility to nutrient loads during this time.

The National Estuary Monitoring Protocol (NEMP; Robertson et al. 2002a-c) is intended to provide resource managers with a scientifically defensible, cost-effective and standardised approach for monitoring the ecological status of estuaries in their region. Because SSRTREs commonly express symptoms of nutrient enrichment (eutrophication) and excessive sedimentation in the subtidal parts of the estuary (where sediment and nutrients concentrate), site-specific approaches beyond that described in the NEMP are needed for this type of system.

A synoptic subtidal assessment of SSRTRE type estuaries uses a series of cross-sectional transects, combined with assessment of broad and fine scale metrics which can be repeated over time and scaled up or down to address specific issues, as necessary.

Broad scale measures include synoptic mapping of estuary depth, benthic substrate, seagrass, and macroalgae, as well as delineating the spatial extent of phytoplankton blooms and any salinity or temperature stratification. Fine scale measures include *in situ* water and sediment quality measurements.

This approach has been previously shown to be a robust way to quickly describe estuary habitat and characterise trophic status (e.g. Stevens & Robertson 2012; Stevens et al. 2016, 2020; Stevens 2019).

The current report describes the methods and results of synoptic monitoring undertaken at Kakanui Estuary on 16 January 2021 (Fig. 1). Previous reports of deteriorating estuary state and the proliferation of macroalgae prompted the need for the current survey (Ozanne & Wilson 2013; Plew & Barr 2015). As such the primary purpose of the work was to characterise the presence and extent of macroalgae and fine sediments in addition to any subtidal stratification and water column eutrophication, and assess the overall trophic state of the estuary.

Kakanui Estuary entrance at high tide (top) and upper estuary (bottom)

1.2 BACKGROUND TO KAKANUI ESTUARY

Previous reports (e.g. Jellyman et al. 1997; ORC 2009, 2010; Plew & Barr 2015; Stewart & Bywater 2009) present background information on Kakanui Estuary, which is paraphrased (and expanded in places) below.

Kakanui Estuary is an elongated and relatively narrow moderate-sized (~25ha) SSRTRE type estuary, which discharges to the Otago coast 10km south of Oamaru. The estuary mouth is mobile and open to the sea; however, on occasion it constricts and closes due to the movement and build-up of gravel at the estuary entrance. The width and location of the mouth opening is determined by river flow in the Kakanui River (mean flow ~6.3 m^3/s) and Waiareka Creek (mean flow ~0.4 m^3/s; Fig. 1).

The extent of seawater intrusion into the estuary is determined by the position and width of the estuary mouth (see photos). Low flows in summer, exacerbated by water abstraction, mean mouth constriction is more likely to occur during this period. However, when the entrance is open seawater intrusion can extend approximately 2.5km inland from the coast. Under these conditions the estuary is commonly stratified in the upper reaches where fresh surface water is overlying denser (heavier) seawater. This denser seawater can become trapped in deep (2-4m) pools in the estuary with the potential for phytoplankton blooms to establish and oxygen to deplete after extended periods of poor flushing.

The width of the estuary mouth is an important determinant on water quality in the estuary. When the entrance is open there is greater exchange between the estuary and sea resulting in increased dilution of river water. Plew & Barr (2015) estimated that the dissolved inorganic nitrogen concentration in the estuary was 25 to 40% lower when the mouth was open compared to when the mouth was closed, owing to dilution of river water by seawater.

No intertidal seagrass has been observed in the Kakanui Estuary. Macroalgal growth, *Ulva intestinalis* and *Cladophora* sp., has been reported at nuisance levels on several occasions dominating the estuary margins (Ozanne & Wilson 2013; Plew & Barr 2015). Intertidal salt marsh is relatively sparse and restricted to narrow strips along the river margins and small islands. This reflects the limited extent of intertidal flats commonly associated with SSRTRE type estuaries, but in the case of the Kakanui Estuary is exacerbated by steep banks and artificial rock walls along the estuary margin. Almost all of the naturally vegetated terrestrial margin is modified. The surrounding catchment is dominated by high producing pasture (50%), low producing pasture (27%) and, in the upper catchment, tussock grassland (9%; see Fig. 2, Table 2).

The estuary has high cultural and spiritual values and is ecologically important because it is a feeding area for birds and an important habitat for fish. It is also frequented for recreational purposes.

Satellite imagery of the entrance closed (left), partial opening (middle left) and narrow opening (middle right). At the time of sampling the entrance was open (right). Imagery source for three left images Google Earth and right image L. Stevens.

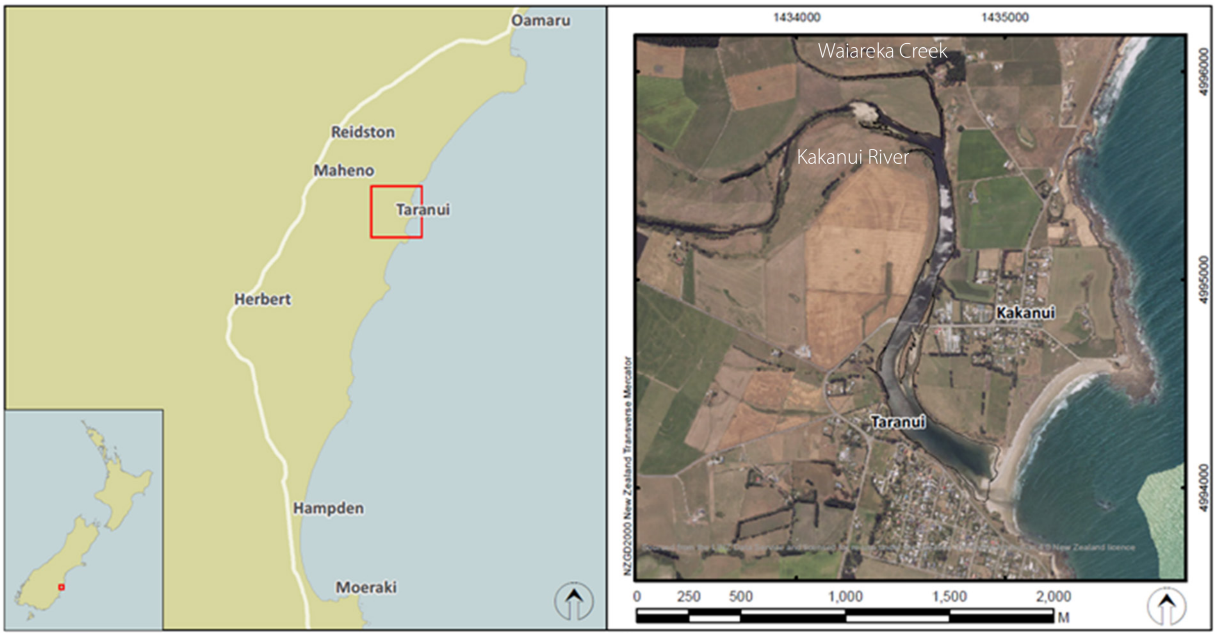


Fig. 1. Location of Kakanui Estuary, Otago.

Table 1. Summary of catchment land cover (LCDB 2017/18), Kakanui Estuary.

LCDB5 (2017/18) Catchment Land Cover		Ha	%
1	Built-up Area (settlement)	84.8	0.1
16	Gravel or Rock	159	0.2
20	Lake or Pond	77.2	0.1
21	River	191	0.2
30	Short-rotation Cropland	2722	3.0
33	Orchard, Vineyard, Perennial Crop	77.2	0.1
40	High Producing Exotic Grassland	45072	50.3
41	Low Producing Grassland	24169	27.0
43	Tall Tussock Grassland	8070	9.0
44	Depleted Grassland	52.9	0.1
51	Gorse and/or Broom	1124	1.3
52	Manuka and/or Kanuka	863	1.0
54	Broadleaved Indigenous Hardwoods	996	1.1
55	Sub Alpine Shrubland	303	0.3
56	Mixed Exotic Shrubland	303	0.3
58	Matagouri or Grey Scrub	607	0.7
64	Forest - Harvested	202	0.2
68	Deciduous Hardwoods	337	0.4
69	Indigenous Forest	351	0.4
71	Exotic Forest	3850	4.3
Grand Total		89669	100

Flood debris and scouring in the upper (top) and lower (bottom) estuary in Jan 2021, reflecting high flood-flows prior to the survey

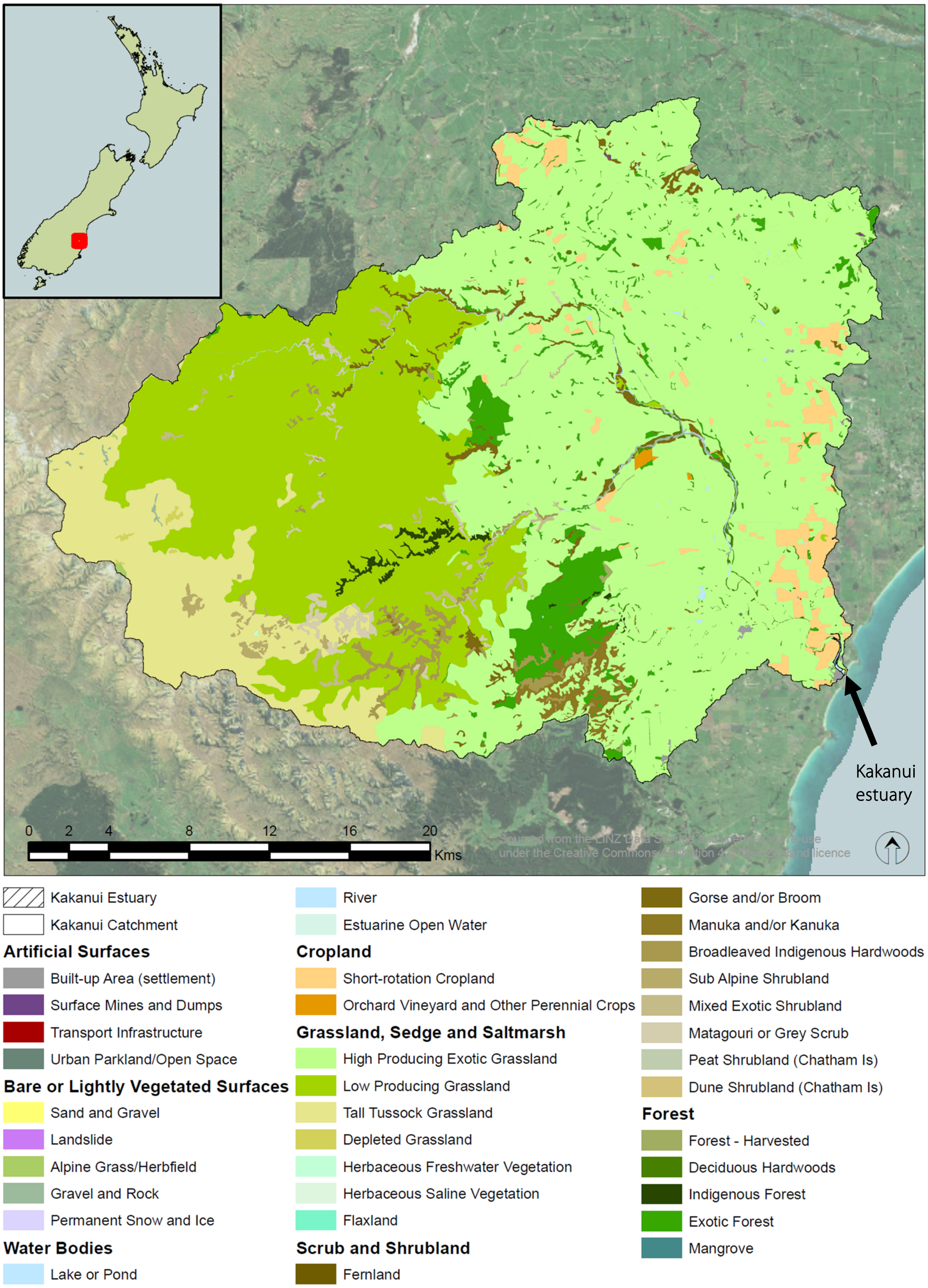


Fig. 2. Kakanui Estuary and surrounding catchment land use classifications from LCDB5 (2017/18) database.

2. METHODS

2.1 OVERVIEW

The focus of the current synoptic survey was to map the estuary's dominant intertidal and subtidal surface habitat features (substrate and vegetation) and characterise the ecological condition of the subtidal reaches. The current survey results were compared to a previous survey carried out in 2009 by Stewart & Bywater (2009).

2.2 BROAD SCALE MAPPING METHODS

2.2.1 General approach

The type, presence and extent of 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. As such, broad scale mapping provides time-integrated measures of prevailing environmental conditions that are generally less prone to small scale temporal variation associated with instantaneous water quality measures.

NEMP methods (Appendix 1) were used to map and categorise intertidal estuary substrate and vegetation. The mapping procedure combines the use of aerial photography, detailed ground truthing, and digital mapping using Geographic Information System (GIS) technology. Broad scale mapping was undertaken using 0.2m/pixel rural aerial photos flown in 2017 and sourced from ESRI online New Zealand imagery.

Ground truthing was undertaken by experienced scientists who assessed the estuary on foot and by boat to map the spatial extent of dominant vegetation and substrate. Subtidal areas were assessed using a combination of grab sampling, wading and underwater video, with water and sediment quality measurements also used to indicate the spatial extent of degraded sediments or bottom water.

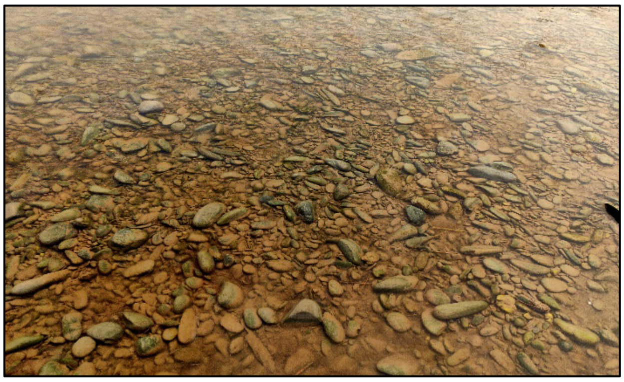
In the field, features were drawn directly onto laminated aerial photographs. The broad scale features were subsequently digitised into ArcMap 10.6 shapefiles using a Wacom Cintiq21UX drawing tablet and combined with field notes and georeferenced photographs. From this information, habitat maps were produced showing the dominant estuary features, e.g. salt marsh, and its underlying substrate type.

Assessment criteria, developed largely from previous broad scale mapping assessments, apply thresholds for helping to assess estuary condition. Additional details on specific broad scale measures are provided below.

Note seagrass has not been recorded in Kakanui Estuary and therefore mapping methods for this feature are not described here.

2.2.2 Substrate classification

Appendix 1 summarises the key NEMP classes used to define estuarine habitats in the current report. Substrate classification is based on the dominant surface substrate features present; e.g. rock, boulder, cobble, gravel, sand, mud. Sand and mud substrates were divided into sub-categories based on sediment 'muddiness', assessed according to a field-based assessment of textural and firmness characteristics. The primary indicator used to assess sediment mud prevalence is the area (horizontal extent) of mud-dominated sediment.



Gravel/ cobble substrate in the mid estuary

Sand substrate on lower intertidal flats

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2.2.3 Macroalgae

The NEMP provides no guidance on the assessment of macroalgae beyond recording its presence when it is a dominant surface feature. To improve on the NEMP approach, the mean percent cover of discrete macroalgal patches was visually assessed to the nearest 10% using the 6-category percent cover rating scale presented in Fig. 3 as a guide.

The New Zealand Estuary Trophic Index (ETI) (Robertson et al. 2016b) has adopted the use of the United Kingdom Water Framework Directive (WFD-UKTAG 2014) Opportunistic Macroalgal Blooming Tool (OMBT) for macroalgal assessment. The OMBT is a 5-part multi-metric index that produces an overall Ecological Quality Rating (EQR) ranging from 0 (major disturbance) to 1 (minimally disturbed) and which rates macroalgal condition within overall quality status threshold bands (bad, poor, good, moderate, high).

The integrated OMBT index provides a comprehensive measure of the combined influence of macroalgal growth and distribution in the estuary and is applied where macroalgal cover exceeds 5%.

2.2.4 Salt marsh

NEMP methods (Appendix 1) were used to map and categorise salt marsh, with two measures used to assess salt marsh condition: i) intertidal extent (percent cover) and ii) current extent compared to estimated historical extent.

2.2.5 Terrestrial margin

Broad-scale NEMP methods were used to map and categorise the 200m terrestrial margin using the dominant land cover classification codes described in the Landcare Research Land Cover Data Base (LCDB) detailed in Appendix 1.

2.3 SUBTIDAL SYNOPTIC SURVEY

Eleven subtidal sites were distributed relatively evenly throughout representative parts of the estuary (Fig. 4). Sampling was conducted on the low to incoming tide. The tidal range on the day of sampling was 1.5m (0.6-2.1m), reflecting spring tides, and was approximately 50% greater than the predicted neap tidal range of 0.9-1.9m (LINZ Hydrographic Tide Prediction). At all sites in the deepest part of the channel cross-section the subtidal habitat was assessed by either wading or by sampling from a boat, to measure the following variables (see descriptions on next page):

- Channel width (approximate)
- Water depth
- Secchi disk clarity
- Surface and bottom water quality variables: temperature, salinity, pH, dissolved oxygen, chlorophyll-a
- Halocline and thermocline depth (if present)
- Substrate type
- Depth in the sediment of the apparent Redox Potential Discontinuity (aRPD)

Boat used for subtidal sampling

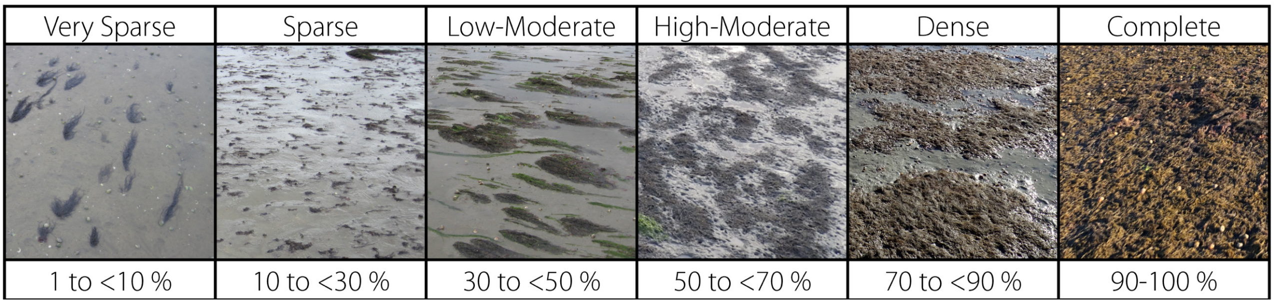


Fig. 3. Visual rating scale for percentage cover estimates for macroalgae. Modified from FGDC (2012).

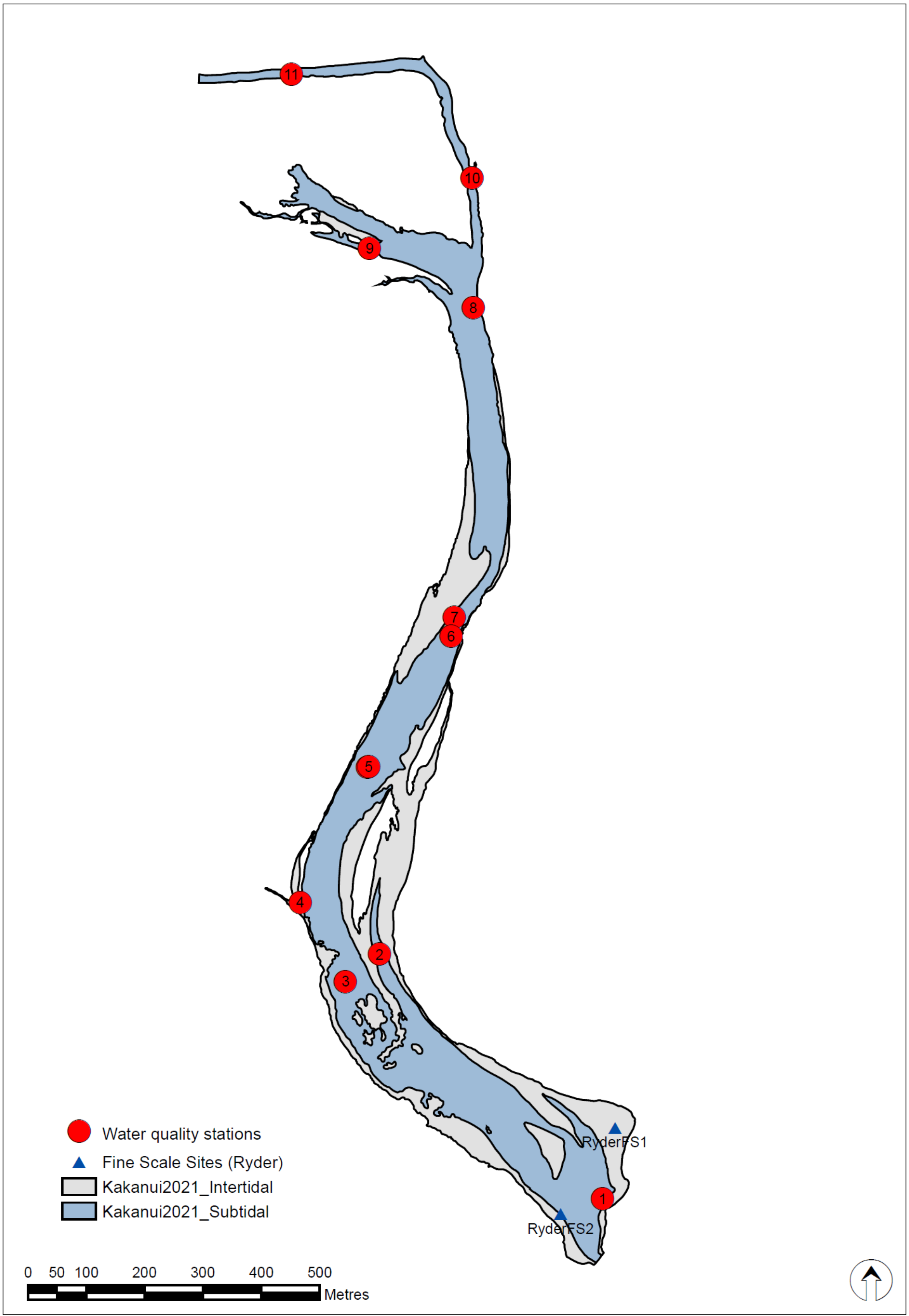


Fig. 4. Water quality sampling stations in Kakanui Estuary 16 January 2021. Sampling carried out on low to incoming tide. Also shown are 'fine scale' sites where detailed intertidal ecological sampling was undertaken in 2009 (Stewart & Bywater 2009).

2.3.1 Water column indicators

At the deepest point at each sampling location, water quality measures were taken from ~20cm below the water surface and ~20cm above the bottom sediment.

Water column measures of pH, salinity, dissolved oxygen (DO), temperature and chlorophyll-a (as an indicator of phytoplankton presence) were made using a YSI Pro10 meter and a Delrin Cyclops-7F fluorometer with chlorophyll optics and Databank datalogger. Care was taken not to disturb bottom sediments before sampling. A description of water column and sediment parameters is provided in Table 2.

Thermocline and halocline depths, where present, were recorded as the average depth of abrupt changes in temperature and salinity, respectively, recorded on the up- and down-cast meter deployments. A modified (pole-mounted) secchi disk was used to measure vertical water clarity to the nearest centimetre.

2.3.2 Sediment indicators

At each sampling location, a substrate sample was collected using a hoe. At the surface, sediment quality was assessed *in situ* for substrate type (as described in 2.2.2) and sediment oxygenation (see below). When a site was too deep for traditional methods, or a hard substrate was present, a camera attached to a surface monitor was slowly lowered to the estuary bed to visually assess substrate conditions.

2.3.3 Sediment oxygenation

The apparent Redox Potential Discontinuity (aRPD) was assessed at all soft-sediment locations from representative sediment samples. The depth of the visible transition between oxygenated surface sediments (typically brown in colour) and deeper less oxygenated sediments (typically dark grey or black in colour) was recorded.

Sediments were considered to have poor oxygenation if the aRPD was consistently shallower than 10mm deep and showed clear signs of organic enrichment indicated by a distinct colour change to grey or black in the sediments. Where the substrate was bedrock, cobble or gravel the aRPD was recorded as indeterminant.

Soft sediment collected with hoe sampler

Mapping the shallow subtidal areas and estuary margins

Example of water quality testing equipment

Example of underwater camera output, upper estuary

Table 2. Description of water column, sediment and habitat indicators used in Kakanui Estuary.

Water column	
Water Column parameters	Water column measures provide a useful tool for the synoptic appraisal of ecological condition in SSRTRE type estuaries. Salinity measures provide a simple way for determining the upstream extent of the estuary and indicate where stable areas of saline water may be trapped, with phytoplankton (algae) potentially able to grow and bloom in the retained water. Elevated nutrients can facilitate rapid algal growth but when algal blooms crash and die off, they deplete dissolved oxygen levels which can adversely impact both sediment-dwelling and water column communities.
Sediment	
Sediment oxygenation (aRPD)	The apparent Redox Potential Discontinuity (aRPD) depth is a subjective measure of the enrichment state of sediments. The aRPD depth provides a relatively stable measure of the sediment oxygenation conditions that infaunal communities are predominantly exposed to. An aRPD depth close to the sediment surface indicates oxygen is depleted, which can have a negative effect on infauna and alter nutrient cycling in the estuary (e.g. cause phosphorus release from sediments).
Substrate	Estuarine substrate can provide habitat for fish, shellfish and benthic fauna in addition to substrate for algae attachment. Estuaries experiencing poor sediment condition are prone to the deposition and build-up of fine sediments (or mud). In general terms, increased muddiness correlates to reduced sediment oxygenation due to limited diffusion among the tightly packed mud matrix. Increasing mud also causes a change in sediment animal communities, with sensitive species like pipi preferring low (<10%) mud environments, and communities becoming dominated by mud-tolerant organisms when mud levels exceed 25%.
Habitat	
Terrestrial margin vegetation	A densely vegetated terrestrial margin filters and assimilates sediment and nutrients, acts as an important buffer that protects against introduced grasses and weeds, is an important food source and habitat for a variety of species and, in waterway riparian zones, provides shade to help moderate stream temperature fluctuations, and improves estuary biodiversity.
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, acts as a buffer that protects against introduced grasses and weeds, and provides an important habitat for a variety of species including fish and birds.
Opportunistic macroalgae	Opportunistic macroalgae are a primary symptom of estuary eutrophication (nutrient enrichment). They are highly effective at utilising excess nitrogen, enabling them to out-compete other seaweed species and, at nuisance levels, can form mats on the estuary surface that adversely impact underlying sediments and fauna, other algae, fish, birds, seagrass (where present), and salt marsh.

2.4 DATA RECORDING AND QA/QC

Field water quality measurements were recorded electronically in templates that were custom-built using software available at www.fulcrumapp.com. Pre-specified constraints on data entry (e.g. with respect to data type, minimum or maximum values) ensured that the risk of erroneous data recording was minimised. Each sampling record created in Fulcrum generated a GPS position for that record (e.g. a sediment sample).

Broad scale maps were digitised as described in Section 2.2. Following digitising, in-house scripting tools were used to check for duplicated or overlapping GIS polygons, validate typology (field codes), and calculate areas and percentages used in summary tables.

2.5 ASSESSMENT OF ESTUARY CONDITION

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

The condition ratings used in the current report were derived primarily from the ETI (Robertson et al. 2016b) and subsequent revisions (Zeldis et al. 2017). The ETI provides screening guidance for assessing where an estuary is positioned on a eutrophication gradient. It includes site-specific thresholds for aRPD, dissolved oxygen, and phytoplankton concentrations, generally using spot measures from within the most degraded 10% of the estuary. We adopted the ETI thresholds for present purposes, except: (i) for aRPD we modified the ETI ratings based on the US Coastal and Marine Ecological Classification Standard Catalog of Units (FGDC 2012) and (ii) < and ≥ values were applied to CSR and NSR criteria in the ETI.

As many of the scoring categories in Table 3 are still provisional, they should be regarded only as a general guide to assist with interpretation of estuary health status. Accordingly, it is major spatio-temporal changes in the rating categories that are of most interest, rather than their subjective condition descriptors (e.g. 'poor' health status should be regarded more as a relative rather than absolute rating).

Table 3. Indicators used to assess results in the current report.

Indicator	Unit	Very good	Good	Fair	Poor
Broad scale Indicators					
Mud-dominated substrate[2]	% of intertidal area >50% mud	< 1	1 to 5	> 5 to 15	> 15
Macroalgae (OMBT)[1]	Ecological Quality Rating (EQR)	≥0.8 to 1.0	≥0.6 to <0.8	≥0.4 to <0.6	0.0 to <0.4
Salt marsh extent (current)[2]	% of intertidal area	> 20	> 10 to 20	> 5 to 10	0 to 5
Historical salt marsh extent[2]	% of historical remaining	≥ 80 to 100	≥ 60 to 80	≥ 40 to 60	< 40
200m terrestrial margin[2]	% densely vegetated	≥ 80 to 100	≥ 50 to 80	≥ 25 to 50	< 25
High Enrichment Conditions[1]	ha	< 0.5	≥ 0.5 to 5	≥ 5 to 20	≥ 20
High Enrichment Conditions[1]	% of estuary	< 1	≥ 1 to 5	≥ 5 to 10	≥ 10
Sedimentation rate[1,3]	CSR:NSR ratio	1 to 1.1 xNSR	1.1 to 2	2 to 5	> 5
Sediment quality					
aRPD depth[1]	mm	≥ 50	20 to < 50	10 to ≤ 20	≤ 10
Water quality					
Dissolved oxygen (DO)[1]	mg/L	≥ 5.5	≥ 5.0	≥ 4.0	< 4.0
Phytoplankton (chl-a)[1]	mg/m3	≤ 5	≥ 5 to < 10	≥ 10 to < 16	≥ 16

1. General indicator thresholds derived from a New Zealand Estuarine Tropic Index, with adjustments for aRPD as described in the main text. See text for further explanation of the origin or derivation of the different metrics.
2. Subjective indicator thresholds derived from previous broad scale mapping assessments.
3. CSR=Current Sedimentation Rate, NSR=Natural Sedimentation Rate (predicted from catchment modelling).

Firm sandy mud on top of cobble, mid-estuary margin

Lower estuary tidal flats

Cobble substrate in the lower estuary

Bedrock visible at the surface in the lower estuary

3. RESULTS

3.1 BROAD SCALE HABITAT MAPPING

3.1.1 Substrate

Table 4 and Fig. 5 show intertidal substrate in the Kakanui Estuary comprised a mapped area of 8.4ha, and was dominated by cobble (5.0ha, 60.3% of the intertidal area) and gravel (1.0ha, 11.4% intertidal area). Mud-dominated (>50% mud; 0.63ha, 7.7% intertidal area) sediments were primarily located on the channel margins in the mid estuary, above the bend and the lower estuary close to the 2009 Ryder NEMP fine scale site (Fig. 4 and Fig. 5).

Table 4. Summary of dominant intertidal substrate, Kakanui Estuary 2021.

Substrate Class	Feature	Ha	%
Artificial	Boulder field	0.1	0.9
Bedrock	Rock field	1.2	14.6
Boulder/Cobble/ Gravel	Cobble field	5.0	60.3
	Gravel field	1.0	11.4
Sand (0-10% mud)	Firm sand	0.4	5.2
Sandy Mud (>50-90% mud)	Firm sandy mud	0.03	0.3
	Soft sandy mud	0.5	5.8
	Very soft sandy mud	0.1	1.6
Total		8.4	100

The subtidal mapped area was 16.7h and, like the intertidal, was also dominated by cobble (7.5ha, 45.0% of the subtidal area) and gravel (14.8ha, 29.1% subtidal area; Table 5; Fig. 5). Bedrock made up 19.2% of the subtidal area. Subtidal mud-dominated sediments were localised to the lower Waiareka Creek in the upper estuary. This situation likely reflects the very low flow in the Creek, making it less prone to scouring (than Kakanui River) and enabling fine sediments to settle out of the water column in areas where freshwater mixes with seawater.

Table 5. Summary of dominant subtidal substrate, Kakanui Estuary 2021.

Substrate Class	Feature	Ha	%
Bedrock	Rock field	3.2	19.2
Boulder/Cobble/ Gravel	Cobble field	7.5	45.0
	Gravel field	4.8	29.1
Sand (0-10% mud)	Firm sand	0.0	0.1
Sandy Mud (>50-90% mud)	Firm sandy mud	1.0	6.2
	Soft sandy mud	0.1	0.4
Total		16.7	100

The relatively low incidence of mud in the subtidal estuary likely reflects a flushing event 2 weeks prior to sampling, where high flows have scoured the estuary substrate down to a cobble and gravel base (see Fig. 11).

Within the vegetated areas, substrate among herbfields comprised firm sand and firm sandy mud, while substrate among sedgeland was cobble and sand.

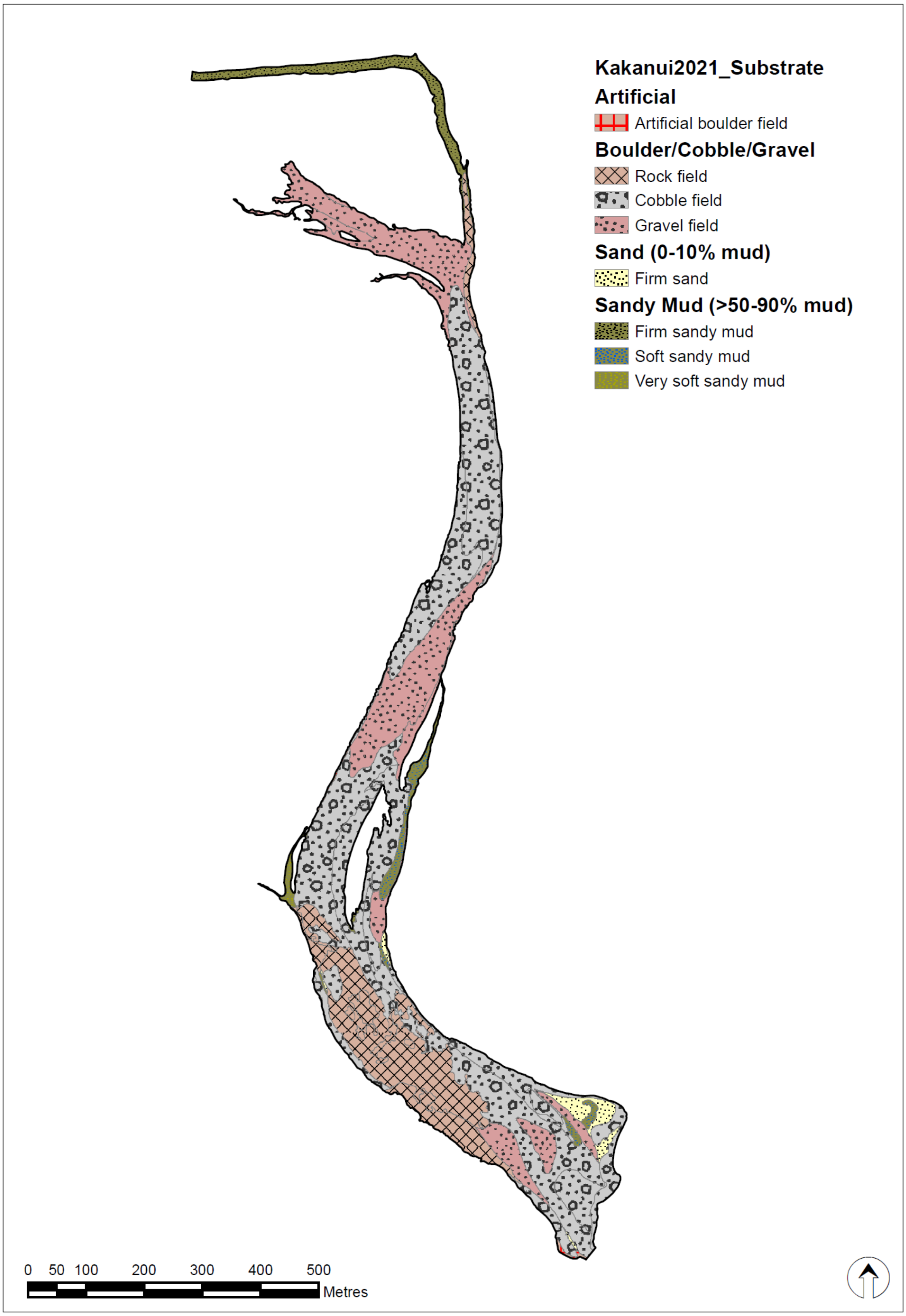


Fig. 5. Dominant substrate types in the intertidal and subtidal zones, Kakanui Estuary 2021.

3.1.2 Macroalgae

During summer months, previous studies have reported large mats of opportunistic macroalgae, *Ulva intestinalis*, on the estuary bed (Plew & Barr 2015). In the present survey no opportunistic macroalgae was recorded. The only algae present in the estuary were a few small areas of a filamentous green species (<5m^2 patches) attached to cobbles that appeared to have been recently scoured.

Attached filamentous green algae in small patches

3.1.3 Salt marsh

Table 6 and Fig. 6 show the small area of remaining salt marsh (0.04ha; 0.5% of the intertidal area) in the Kakanui Estuary.

The dominant herbfield species was *Cotula coronopifolia* (Bachelor's button; see photo), with sub-dominant species being *Selliera radicans* (Remuremu) and *Samolus repens* (Primrose). Herbfield covered a small area of 0.03ha or 0.35% of the intertidal area. The same species were present in 2009, however they were recorded across 0.06ha of the estuary and closer toward the Kakanui Bridge.

Cotula coronopifolia (Bachelor's button; top), and sub dominant species *Samolus repens* (Primrose; left) and *Selliera radicans* (Remuremu; right)

Schoenoplectus pungens (Three square; see photo below) was the only sedgeland species, recorded in two small patches (0.01ha; 0.1% of the intertidal area) on the true right bank. The 2021 results were consistent with the 2009 survey, where sedgeland was also rare. The small patch closer to the bridge is in the same location as described in the 2009 survey (Fig. 6; Stewart & Bywater 2009).

Small patch of *Schoenoplectus pungens* (Three square sedge)

Table 6. Summary of dominant salt marsh cover, Kakanui Estuary.

Subclass	Dominant species	Sub-dominant species	Ha	%
Sedgeland	*Schoenoplectus pungens* (Three square)		0.008	19.5
Herbfield	*Cotula coronopifolia* (Bachelor's button)		0.026	64.5
	Cotula coronopifolia (Bachelor's button)	*Selliera radicans* (Remuremu) *Samolus repens* (Primrose)	0.007	16.0
Grand Total			0.041	100

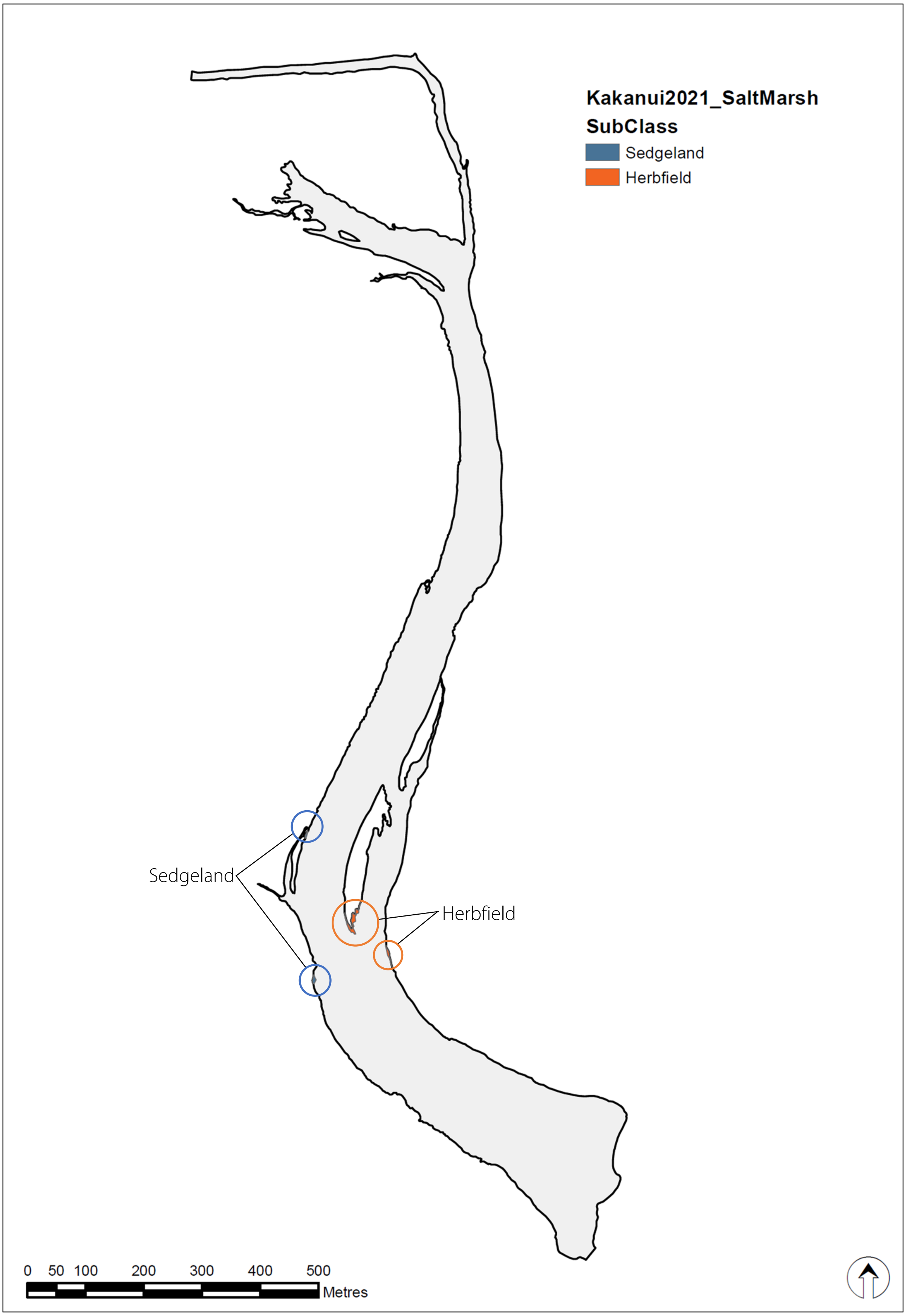


Fig. 6. Map of salt marsh extent, Kakanui Estuary 2021.

Since the 2009 assessment there has been an apparent decrease in saltmarsh habitat. In 2021, no estuarine shrubland was recorded representing a 0.1ha decrease or 100% loss since 2009 (Stewart & Bywater 2009). This change is attributed to the inclusion of terrestrial plants in 2009 that were not classified as estuarine salt marsh in 2021. Herbfield has also apparently decreased by 45% since 2009 while sedgeland has remained stable. Because there are only very small areas of salt marsh present, the changes since 2009 are considered negligible and most likely due to differences in mapping precision.

The historical extent of salt marsh in the estuary is unknown; however, the area of suitable habitat is limited due to the landform around the estuary. SSRTRE type estuaries typically have small intertidal areas and in the Kakanui Estuary this is exacerbated by steep banks and artificial rock walls along the lower estuary margin, meaning there are few areas of suitable habitat for salt marsh to grow.

3.1.4 Terrestrial margin

The results of the 200m terrestrial margin mapping are presented in Table 7 and Fig. 7. Most of the terrestrial margin has been modified and predominantly consists of the Kakanui settlement (15.8% of the terrestrial margin) and pasture (72.4% of the terrestrial margin; see photos). The area of margin meeting the definition of 'densely vegetated' (LCDB classes 45-71) was only 8.3%. This included relatively extensive restoration plantings on the true left bank of the lower estuary.

Table 7. Summary of 200m terrestrial margin land cover, Kakanui Estuary 2021

LCDB Class		Ha	%
1	Built-up Area (settlement)	19.6	15.8
2	Urban Parkland/Open Space	0.9	0.7
5	Transport Infrastructure	1.6	1.3
16	Gravel and Rock	0.9	0.7
21	River	1.0	0.8
40	High Producing Exotic Grassland	73.5	59.2
41	Low Producing Grassland	16.3	13.2
45	Herbaceous Freshwater Vegetation	0.2	0.1
47	Flaxland	0.1	0.1
51	Gorse and/or Broom	1.7	1.3
54	Broadleaved Indigenous Hardwoods	1.4	1.1
68	Deciduous Hardwoods	3.0	2.4
71	Exotic Forest	3.9	3.2
Grand Total		124.3	100
Total dense vegetated margin (LCDB classes 45-71)		10.3	8.3

As noted in Section 1.2, land cover in the wider catchment is dominated by high producing pasture (50%) and low producing pasture (27%), and in the upper catchment tussock grassland (9.0%; see Fig. 2, Table 2). Most fine sediments inputs to the estuary likely originate from the lower catchment where the land has been developed for pasture.

Kakanui settlement, rock wall providing erosion protection

Gorse lined walkway and pasture, upper estuary

Mixed grassland, gorse and pine in the lower estuary

Pine tree and exotic weeds on the estuary margin

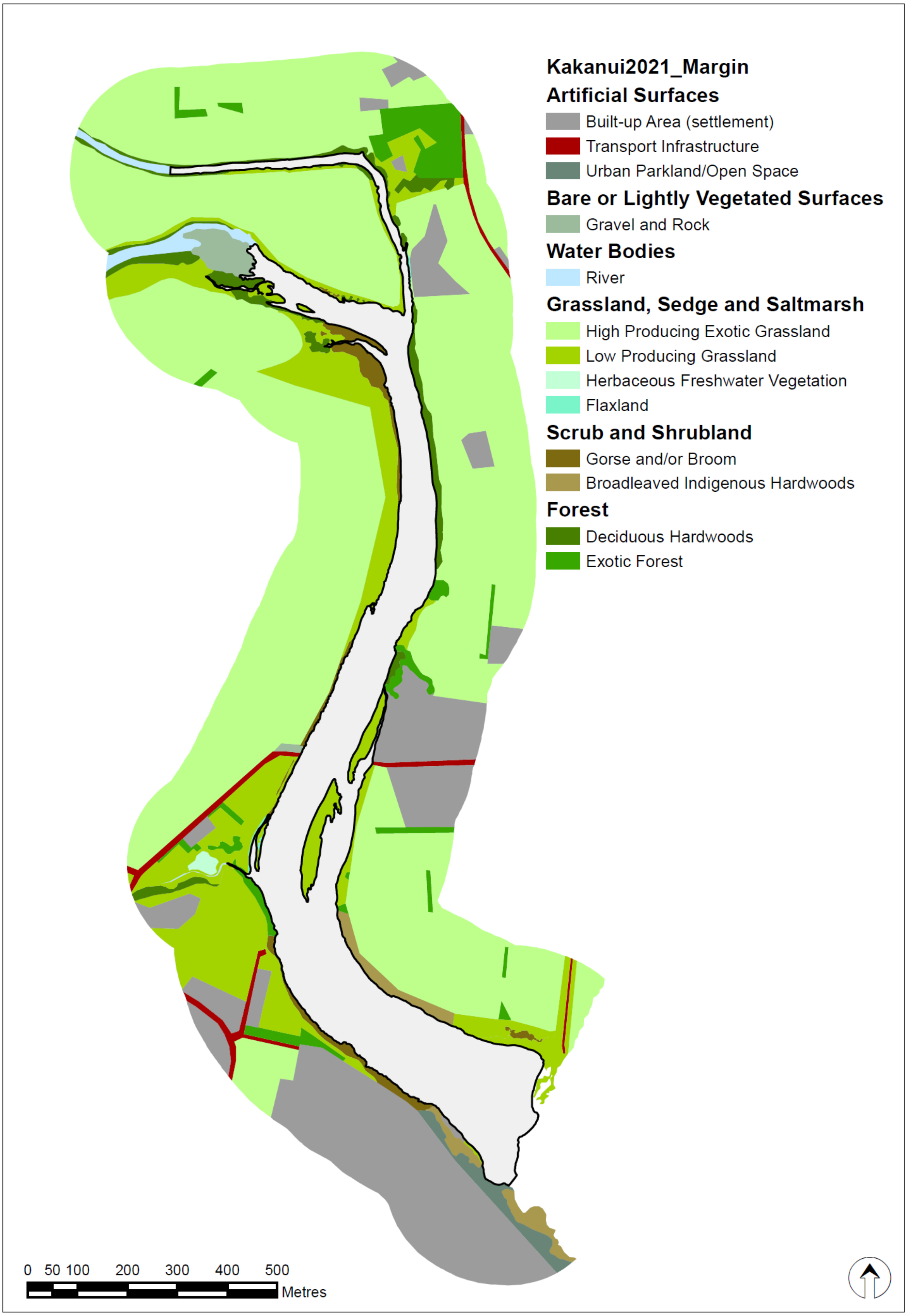


Fig. 7. Map of 200m terrestrial margin land cover, Kakanui Estuary (LCDB5 2017/18).

3.2 SUBTIDAL SYNOPTIC ASSESSMENT

3.2.1 Water Quality

The estuary entrance was open at the time of sampling (see photo in Section 1.2), undoubtedly reflecting the effect of the prior flood event. The estuary was stratified, with salinity ranging from 0.09 to 7.48ppt in the surface and 0.18 to 37.21ppt in the bottom waters (Table 8). To explain salinity stratification at the time of sampling, the conceptual diagram in Fig. 8 is referred to throughout the discussion below. The conceptual diagram is based on the supporting water quality data and bathymetry measured in the estuary in 2015 (Plew & Barr 2015; Fig. 9).

Two deep holes in the mid (T7) and upper (T8) estuary (Fig. 9) explain two pockets of salinity stratification upstream of the well-mixed water column at site T5. Denser (heavier) seawater was trapped in the bottom waters at sites T7 and T8, and remained in the estuary on the outgoing tide (Fig. 8, Fig. 10).

The deep hole on the true left bank at Site T8 occurs at the confluence of the Kakanui River and Waiareka Creek. The steep bedrock bank combined with the river flows have created the deep hole in this area. The shallow halocline depth (1.7m; max depth 5.5m; Table 8) and seawater intrusion further upstream into Waiareka Creek confirm that this area of the estuary is poorly flushed and prone to stratification.

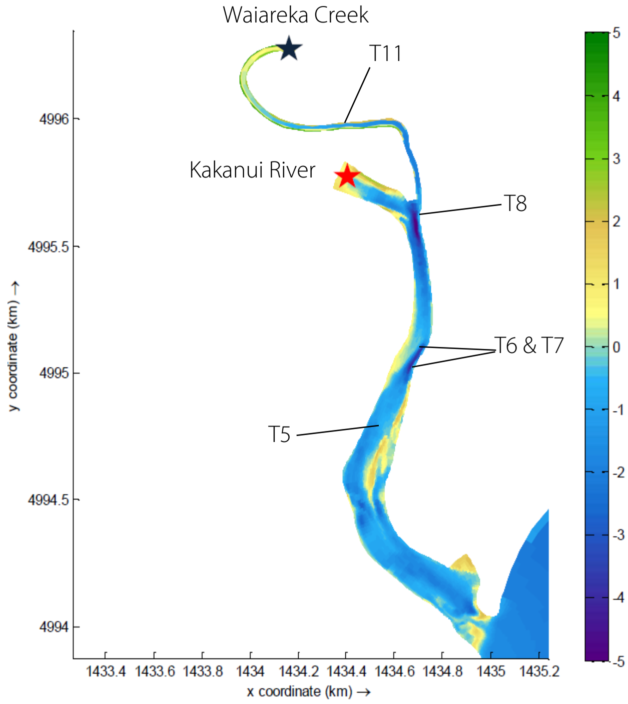


Fig. 9. Bathymetry within Kakanui Estuary. The scale represents metres from MSL (0m), darker blue represents deeper parts of the estuary, Source: Figure 4-2 in Plew & Barr (2015).

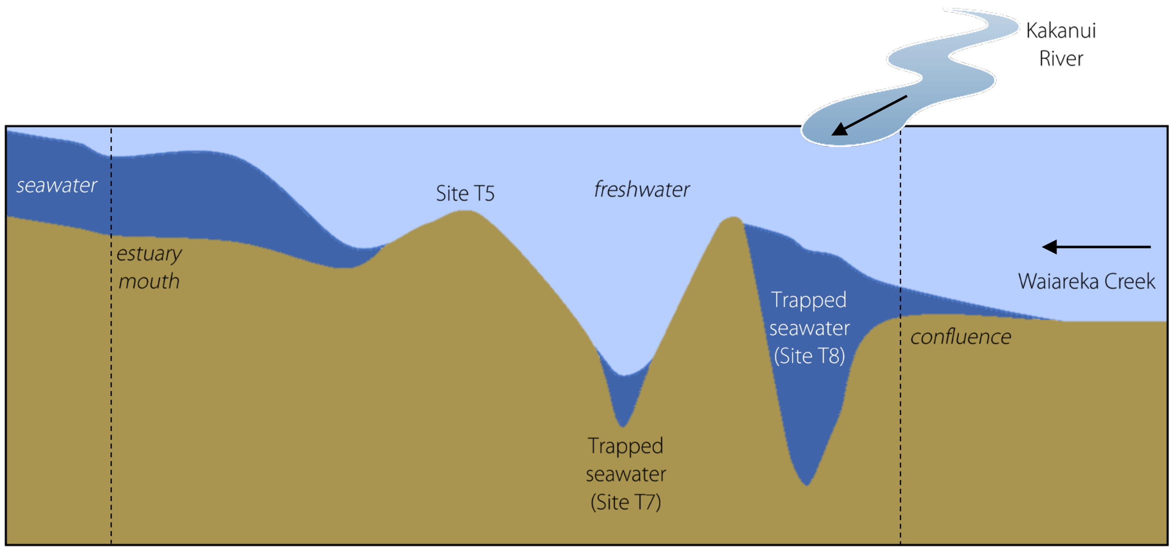


Fig. 8. Conceptual diagram depicting salinity stratification in the Kakanui Estuary at the time of sampling in January 2021. The conceptual diagram interprets the water quality data in the context of bathymetry collected in 2015 (Plew & Barr 2015).

Table 8. Summary of water quality measurements in the Kakanui Estuary, January 2021. Colours represent condition ratings for dissolved oxygen and phytoplankton (chlorophyll-a) in Table 3. nd = no data, ind = indeterminate.

Station	T1	T2	T3	T4	T5	T6	T7	T8	Kaik- 9	Wair-10	Wair-11
NZTM East	1434921	1434539	1434481	1434451	1434568	1434710	1434754	1434748	1434571	1434735	1434436
NZTM North	4994229	4994649	4994601	4992886	4993118	4993341	4993419	4993907	4994007	4994147	4994306
Distance from mouth (m)	80	665	675	790	1030	1300	1390	1870	2090[1]	2070[1]	2550[1]
Surface Measurement											
Measurement depth (m)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Temperature (°C)	20.6	22.3	21.8	21.8	21.8	21.9	22	21.3	21.4	21.5	21.4
DO saturation (%)	105.8	121.9	117.9	124.5	109.6	112.8	105.6	88.5	94.6	92.5	84.8
DO conc (g/m^3)#	9.3	10.1	9.9	10.3	9.3	9.7	8.9	8.1	8.4	8.1	7.4
Salinity	7.5	7.5	5.6	7.0	4.0	3.9	2.9	3.8	0.1	0.7	1.9
pH	8.04	8.31	8.53	7.11	8.3	8.12	8.05	8.31	8.28	8.07	7.58
Chlorophyll-a (mg/m^3) #	1.9	2.9	3.4	3.4	3.2	3.6	2.6	1.9	2.1	2.2	2.6
Stratified	yes	yes	yes	no	no	no	yes	yes	no	yes	no
Halocline depth (m)	0.5	0.5	1.8				3.8	1.7		2.4	
Thermocline depth (m)	0.5	0.5	1.8				3.8	1.7		2.4	
Bottom Measurement											
Measurement depth (m)	1.7	1.8	2.75		1.5	3.0	4.6	5.5	1.9	2.9	2.9
Temperature (°C)	16.9	17.3	16.8		22.0	21.9	20.2	17.5	21.1	18.2	21.3
DO saturation (%)	98.5	nd	101.1		123.5	114.8	76.0	82.8	90.3	47.3	78.8
DO conc (g/m^3) #	7.8	nd	7.8		10.5	9.9	6.7	6.5	8.0	3.8	6.9
Salinity	36.3	35.5	37.2		4.8	3.9	15.6	32.1	0.2	22.4	2.1
pH	7.95	7.96	8.09		8.28	8.15	7.73	7.85	8.26	7.09	7.57
Chlorophyll-a (mg/m^3) #	6.0	6.3	10		4.3	4.0	3.8	7.0	2.3	2.5	3.2
Other Measurements											
Secchi depth (m)	1.2	1.45	1.5	0.4	1.4	1.75	2.05	1.9	1.9	2.2	2.4
Max depth (m)	1.7	2.1	2.9	0.4	1.4	3.2	4.6	5.5	1.9	3.0	3.0
Channel width (m)	60	10	50	80	100	40	60	55	40	15	15
Sediment texture	firm	firm	firm	very soft	firm	firm	firm	firm	firm	firm	firm
Sediment type	CF	CF	CF	SM50_90	CF	GF	GF	GF	GF	RF	M90_100
aRPD depth (mm)	ind	ind	ind	ind	ind	ind	ind	ind	ind	ind	ind

[1] The three sites >2km from the Kakanui River mouth represent sites upstream of the confluence of Kakanui River and Waiareka Creek.

Looking upstream from Kakanui River confluence

Looking upstream of Waiareka Creek confluence

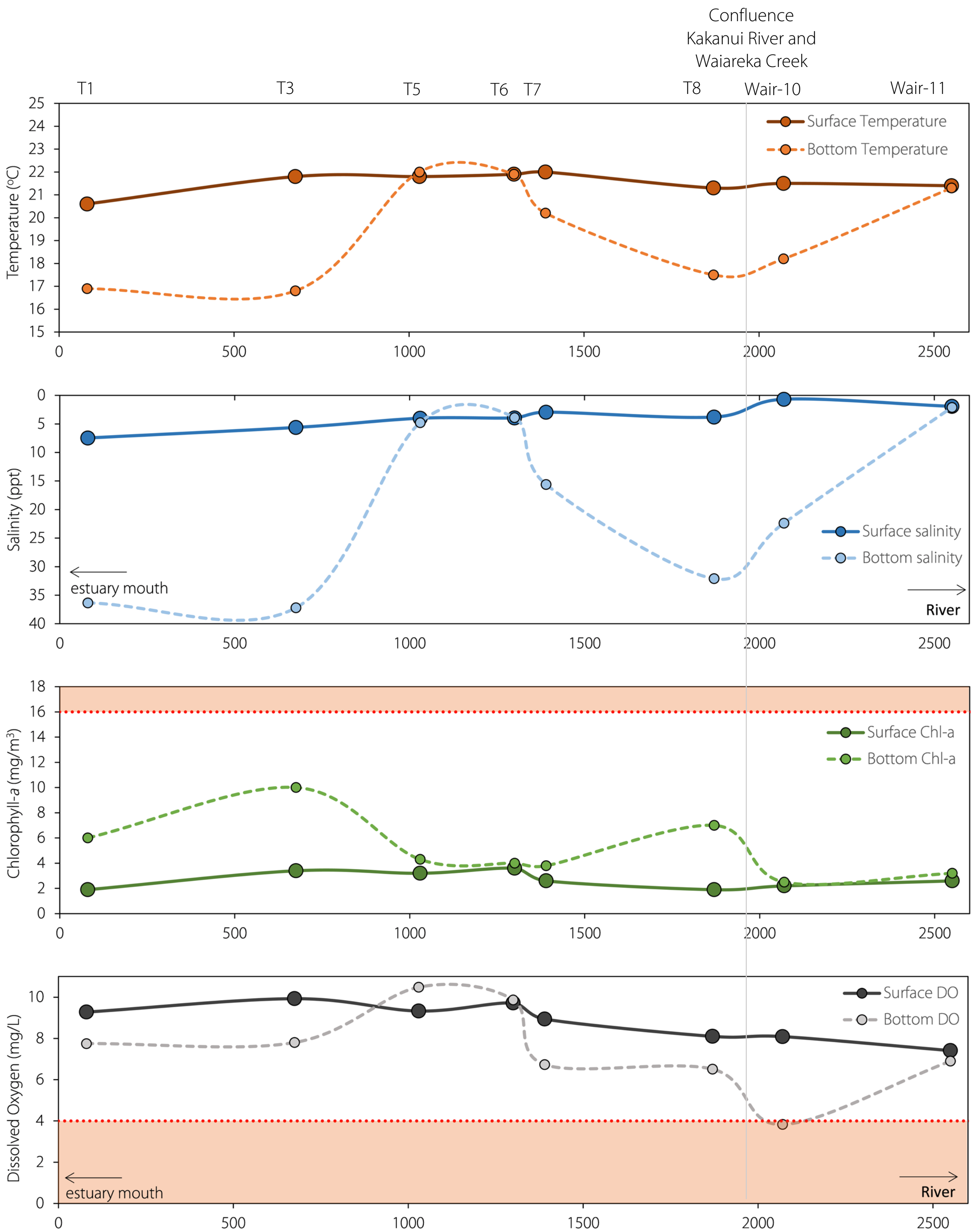


Fig. 10. Kakanui Estuary water quality results, 16 January 2021. a) Temperature (°C), b) Salinity (ppt), c) Chlorophyll-a (mg/m^3) and d) DO (mg/L), in relation to distance (m) from the estuary mouth.

*The red-dotted line and shading indicate the "poor" threshold and banding for chlorophyll-a and dissolved oxygen (see Table 3). Raw data are presented in Table 8. The vertical line at ~2000m represents the confluence of Kakanui River and Waiareka Creek. The sites presented above the confluence are data points from the lower estuarine section of the Waiareka Creek. Sites T2 and T4 are not graphically presented because they were not in the main channel of the estuary and represent back waters.

The upper extent of saltwater intrusion at the time of sampling was ~2.5km from the estuary mouth (Site T11; Waiareka Creek; Fig. 10). Waiareka Creek is deep and has a low gradient (Plew & Barr 2015; Fig. 9) therefore seawater intrudes further upstream than in Kakanui River, which shallows near the confluence with the estuary. River dominance is also greater in the Kakanui River due to its relatively high flows.

Seawater trapped in the bottom waters will be flushed from the estuary during high flow events. This conclusion is supported by the substrate type at T8 comprising gravel and bedrock (i.e. fine sediment has been scoured from the area). To illustrate the recent flushing event, Fig. 11 summarises freshwater flow measured at Kakanui River at McCones, an Otago Regional Council (ORC) water quality monitoring site ~4km upstream of the estuary entrance. Results show there was a large flood event (3/01/2021 flow 214m^3/s; Fig. 11) prior to the 16 January 2021 sampling, coinciding with above-normal rainfall recorded in the lower South Island (NIWA climate summary). These data confirm observations made on site, where flood debris was visible on the channel margins and the substrate was scoured down to cobble and gravel (see photos p. 3).

Water quality data summarised in Fig. 10 show post-flood, no eutrophic symptoms were observed in the water column (e.g. low dissolved oxygen and phytoplankton) in the main body of the estuary (Sites T1 – T8). In January 2021, phytoplankton (chlorophyll-a) concentrations in the estuary were low in the surface waters (≤4mg/m^3; Fig. 10) and moderate to low in the bottom waters (≤10mg/m^3;). A condition rating of 'very good' and 'fair' to 'very good', respectively (Table 3 and Table 8). The highest concentration of chlorophyll-a was recorded near the estuary entrance in the bottom waters and likely represents a marine source of phytoplankton rather than growth in the estuary. A typical salinity and phytoplankton profile recorded in Kakanui Estuary is shown in Fig. 12, where phytoplankton concentration abruptly increases with increasing salinity at the halocline.

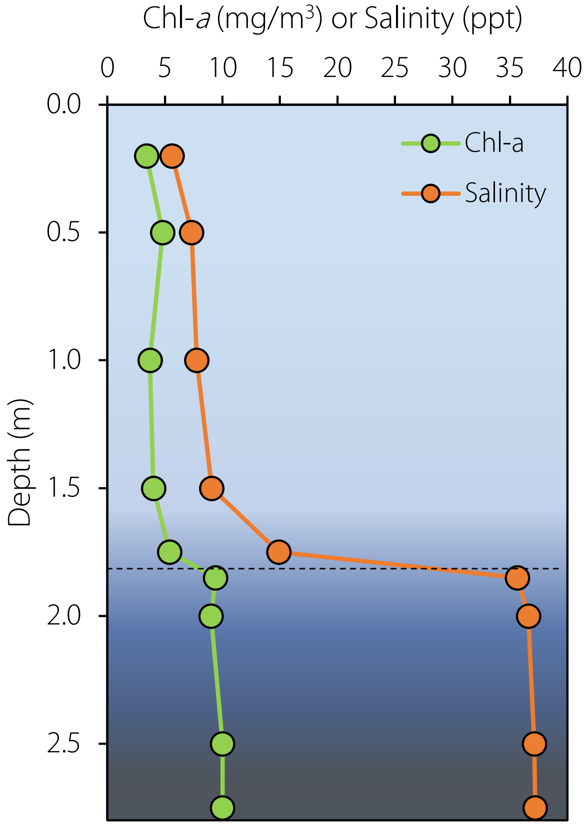


Fig. 12. Phytoplankton (Chl-a; mg/m^3) and Salinity (ppt) at site T3; ~0.7km upstream. from the estuary mouth. The dashed line represents the halocline.

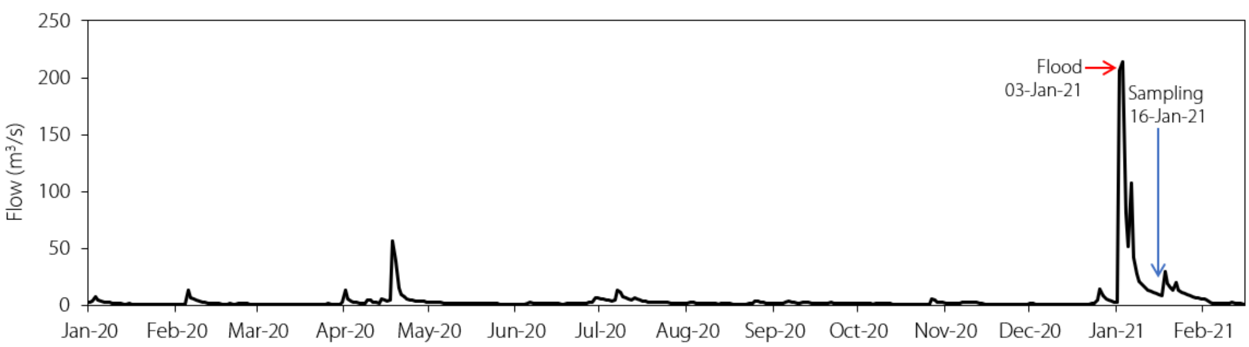


Fig. 11. Provisional flow data from ORC for Kakanui at McCones upstream of the estuary, showing daily river flow in the year prior to sampling.

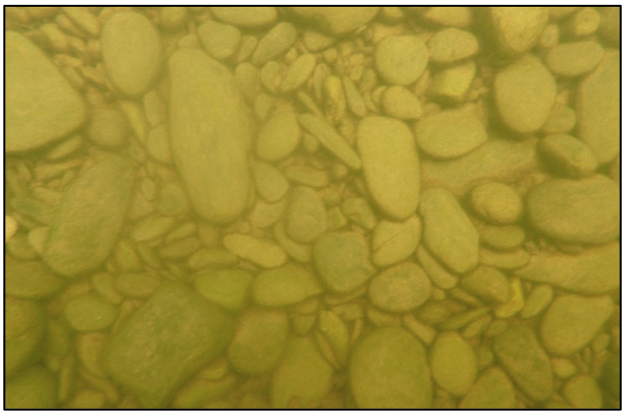
In the main body of the estuary (Sites T1-T8), surface waters were over-saturated with oxygen (>100% oxygen), resulting in a condition rating of 'very good'. The exception was the bottom waters at Site Wair-10 (the confluence of Waiareka Creek with the estuary and upper extent seawater), where the dissolved oxygen concentration dropped to 3.8mg/L; a condition rating of 'poor'.

The temperature ranged from 20.6 to 21.9°C in the fresh surface waters and 16.9 to 22.0°C in the bottom waters (Fig. 10; Table 8). In general, bottom waters with higher salinity had lower water temperatures.

Firm mud viewed using the underwater camera, Wair-11

3.2.2 Sediment quality

In addition to the broad scale mapping of surface substrate, sediment vertical profiles and oxygenation were assessed at each water quality location. Sediment oxygenation was indeterminate at all sites monitored (Table 8) because aRPD cannot be determined for bedrock, cobble and gravel substrates. At the two sites where muddy sediments were recorded, Site T4 and Wair-11 aRPD was recorded as indeterminant. At Site T4 there was no distinct colour difference in the sample and Wair-11 was too deep to collect a sediment sample (see photos). Because aRPD was indeterminant it cannot be assessed against the condition ratings in Table 3.



Cobble and gravel substrate in the Kakanui Estuary

Bedrock in lower Kakanui Estuary

Sandy mud site T4, with no distinct aRPD and large burrows visible

4. KEY FINDINGS

4.1 BROAD SCALE HABITAT MAPPING

The dominant features assessed as part of broad scale habitat mapping of Kakanui Estuary undertaken on 16 January 2021 are summarised in Table 9. Key broad scale indicator results and ratings are presented in Table 10, and additional supporting data used to assess estuary condition are in Table 11. Data from 2009, sourced from Stewart & Bywater (2009) are summarised Appendix 4.

Table 9. Summary of dominant broad scale features, Kakanui Estuary 2021.

a. Area Summary	Ha	% Estuary*
Intertidal area	8.4	33.5
Subtidal area	16.7	66.5
Total estuary area	25.1	100

b. Key estuary features	Ha	% Estuary*
Salt marsh	0.04	0.16
Seagrass (>50% cover)	0	0
Macroalgae (>50% cover)	0	0
Mud-dominated sediment (%)	1.7	6.8

c. Terrestrial margin (200m)	Ha	% Margin
200m densely vegetated margin	10.3	8.3
Total area of terrestrial margin	124.3	-

*% Estuary reflects the total area of the estuary including both subtidal and intertidal area

With regard to preliminary rating criteria for assessing estuary health, the extent of salt marsh and the percentage of densely vegetated 200m terrestrial margin were rated 'poor'. Past modification along the estuary margin has constricted available habitat for salt marsh, and will also prevent migration of salt marsh species with predicted sea level rise. This will likely result in further losses of salt marsh over time.

The area of mud dominated sediments was rated 'fair' and other eutrophic indicators (macroalgae and high enrichment conditions) were rated 'very good' (Table 10).

Previously, the most significant issues identified in the Kakanui Estuary has been the proliferation of algae and macroalgae during summer months (see photos below), and a build-up of fine muddy sediment. By contrast, in January 2021 the amount of macroalgae in the estuary was negligible, and sediments were primarily clean hard substrates. These changes almost certainly reflect the post-flood timing of sampling, rather than the outcome of any improvements in the catchment. Flood debris was still evident at the time of the survey.

Proliferation of algae in Kakanui Estuary March 2020 (top; source Sam Thomas), January 2015 (bottom left; Plew & Barr 2015) and February 2012 (bottom right; Ozanne & Wilson 2013)

Table 10. Comparison of key broad scale indicator results against Table 3 rating criteria.

Broad scale Indicators	Unit	Value	2021	Change since 2009
Mud-dominated substrate	% of intertidal area >50% mud	7.7#	Fair	-
Macroalgae (OMBT)	Ecological Quality Rating (EQR)	1.0*	Very Good	-
Salt marsh extent (current)	% of intertidal area	0.5	Poor	76% decrease
Historical salt marsh extent	% of historical remaining	-	-	-
200m terrestrial margin	% densely vegetated	8.3	Poor	-
High Enrichment Conditions	ha	0	Very Good	-
High Enrichment Conditions	% of estuary	0	Very Good	-

Dash represents no data. Colour bandings are reported in Table 3. OMBT = Opportunistic Macroalgal Blooming Tool. #reflects % of intertidal area *Estimated Value

Kakanui Estuary margin, artificial rock walls in the lower and mid estuary (top) and natural steep banks (bottom)

NIWA's national estuary sediment load estimator (Hicks et al., 2019) was used to predict sediment inputs and retention, and calculate a net deposition rate for the estuary. Assuming that there would be 50% wetland attenuation under natural conditions, the current sedimentation rate (CSR) is estimated to be 3.6 times the natural sedimentation rate (NSR). This equates to ~77mm/y of estuary infilling (Hicks et al. 2019; Table 11). The condition rating for the ratio of CSR:NSR is a condition rating of 'fair'. These estimates indicate that in the absence of physical scouring due to flooding the estuary will likely infill with fine sediments.

The pressure on the estuary reflects that the catchments of the lower Kakanui River and Waiareka Creek are dominated by a mixture of beef, sheep, deer, cropping and dairying, with irrigation also common (Ozanne & Wilson 2013). Conversion of land to pasture and clearing of native vegetation is a common feature in the New Zealand landscape. It reduces habitat connectivity, filtering of contaminants (sediment and nutrients) and erosion control, often leading to poor outcomes in rivers and estuaries.

Ozanne & Wilson (2013) linked deteriorating water quality in the Kakanui River and Waiareka Creek to land use in the catchment and poor outcomes in the estuary. Nutrient loads in the Kakanui River and Waiareka Creek exceed the proposed threshold at which macroalgal problems occur, which were derived from a modelling study on the Kakanui Estuary (Plew & Barr 2015). While no significant eutrophic symptoms were observed in the estuary at the time of sampling, given there have been no significant improvements in the catchment, the proliferation of algae, as well as fine sediment build-up, is likely to re-establish over time.

Table 11. Supporting data used to assess estuary ecological condition.

Supporting Condition Measure	Kakanui River
Mean freshwater flow (m^3/s)[1]	6.3
Catchment Area (Ha)[1]	89671
Catchment nitrogen load (TN/yr)[2]	200.1
Catchment phosphorus load (TP/yr)[2]	41.4
Catchment sediment load (KT/yr)[1]	66.5
Estimated N areal load in estuary ($mg/m^2/d$)[2]	2284
Estimated P areal load in estuary ($mg/m^2/d$)[2]	473
CSR:NSR ratio[1]	1.8
CSR:NSR with 50% natural wetland attenuation	3.6
Trap efficiency (sediment retained in estuary)[1]	42%
Estimated rate of sed. trapped in estuary (mm/yr)[1]	77.1

[1]Hicks et al. 2019.
[2]CLUES version 10.3, Run date: May 2021.

Margin vegetation; gorse (top), exotic trees (middle) and pasture (bottom)

4.2 SYNOPTIC SUBTIDAL ASSESSMENT

Complementary to the broad scale indicators, the results from the synoptic subtidal survey identified no widespread eutrophic symptoms in the water column or sediment in the Kakanui Estuary. As above, this result will reflect the flushing during heavy rainfall two weeks prior to sampling.

Building on the conceptual diagram in Fig. 8, the stratification scenarios likely to develop on different states of river flow and tide are illustrated in Fig. 13. A high flow event, such as occurred 2-weeks prior to sampling, may lead to complete flushing of the estuary with freshwater (Fig. 13a), removing excess nutrients, sediments, and trapped seawater.

Like other river dominated estuaries, the Kakanui Estuary is highly dynamic, with flushing influenced by the extent of estuary mouth constriction as well as tidal state. When the entrance is open to the sea, the estuary will stratify as tidal water flows in, and denser (heavier) seawater will become trapped in the deeper pools (Fig. 13b, c). This situation illustrates the estuary at the time of sampling on 16 January 2021.

This stratified scenario potentially enables phytoplankton blooms to establish and oxygen to become depleted (i.e. eutrophication symptoms). This phenomenon was partially evident at upper estuary Site Wair-10 at the time of sampling, with bottom water oxygen depletion evident but no phytoplankton bloom. Further downstream, two deep pools of entrapped seawater were recorded at T7 and T8, but no eutrophication symptoms were evident.

Based on our experience elsewhere (e.g. Stevens 2019; Roberts et al. 2021), we suggest that there was probably insufficient time post-flooding for symptoms of eutrophication to develop, but that the estuary may be prone to this outcome during extended periods of poor flushing.

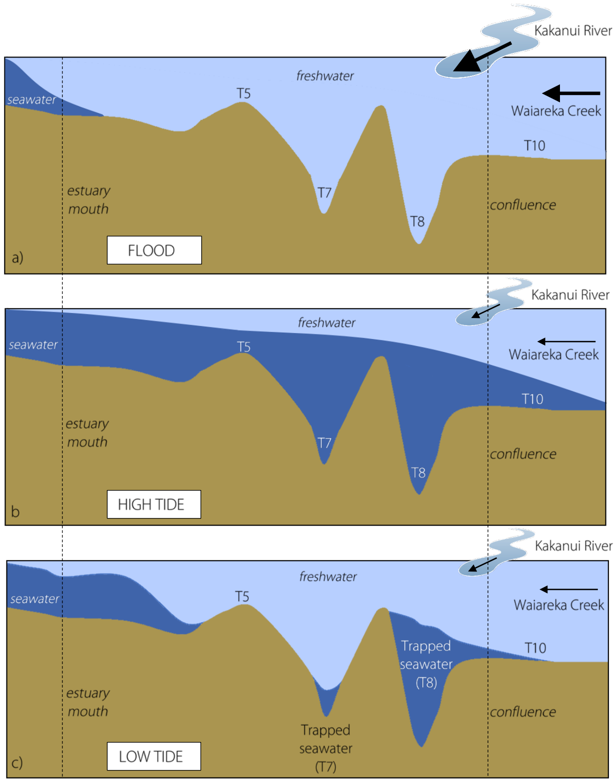


Fig. 13. Conceptual diagram of Kakanui Estuary under three scenarios. a) Predicted flushing during a flood event with the deeper sections flushed with freshwater (two weeks prior to sampling; Plew & Barr 2015), b) predicted high tide stratification (16 January 2021) and c) measured low tide stratification on 16 January 2021.

Both physical and biological processes control the depletion of oxygen in bottom waters. While physical processes such as stratification and isolation of the bottom waters promote oxygen depletion (i.e. through lack of mixing and re-aeration), biological processes such as high mineralisation rates during

Table 12. Summary of sediment and water quality indicators reflecting the most impacted 10% of the estuary. Ratings based in ETI criteria for water quality.

Indicator	Unit	Value	2021	Source of data
Sediment Quality				-
aRPD depth	mm	ind	na	All sites indeterminant aRPD
Water Quality				
Dissolved Oxygen (DO)	mg/L	3.8	Poor	Site Wair-10
Phytoplankton (chl-a)	mg/m^3	10	Fair	Site T3

na represents not applicable. ind represents indeterminant. Colour bandings are reported in Table 3.

summer, increased oxygen demand as a result of high nutrient loading and the breakdown of organic matter from phytoplankton blooms, can lead to further decreases in oxygen concentration. Diurnal fluctuations in oxygen production (photosynthesis) and consumption (respiration) also have a very strong influence on bottom water oxygen concentration.

Low oxygen events can significantly alter biogeochemical processes, including the cessation of nitrogen pathways (e.g. nitrification) and the release of sediment-bound nitrogen and phosphorus into the water column, further exacerbating nutrient related issues (e.g. phytoplankton growth) in estuaries.

Moreover, severe ecological effects can be observed, particularly in fish, below 4mg/L of dissolved oxygen (see Franklin 2014; Fig. 10). In a study by Otago Regional Council, diadromous fish (migratory fish that move between fresh and salt water) were recorded in the main riverine inputs to the Kakanui Estuary, including but not limited to; shortfin eel and longfin eel, redfin bully, lamprey and banded kōkopu (Ozanne & Wilson 2013). These species spend at least part of their life cycle at sea migrating through the estuary at different life stages. Low oxygen events during prolonged periods of poor flushing could inhibit or reduce the migration success of native fish species moving through the estuary.

Mid-lower estuary, spoonbills roosting

4.3 SUMMARY OF KEY FINDINGS

In January 2021, Kakanui Estuary was not expressing any significant symptoms of nutrient enrichment (eutrophication), such as excess phytoplankton, low oxygen, enriched sediments, or nuisance macroalgae growths. While this differs to previous surveys where these types of symptoms had been reported (Ozanne & Wilson 2013; Plew & Barr 2015; Stewart & Bywater 2009) this report shows that the estuary was well-flushed by a flood event in the 2-weeks prior to the survey, in which the Kakanui River exceeded its mean flow by more than 30 times. As such, the January 2021 results almost certainly reflect the timing of sampling (i.e. post-flood) rather than the outcome of any improvements in the catchment. The flushing of excess sediments, nutrients, and nuisance macroalgae from the estuary likely represents a period of short-term improvement in estuary condition that will return to a more degraded state if catchment sediment and nutrient inputs remain elevated.

5. RECOMMENDATIONS

Although the Kakanui Estuary was well-flushed at the time of sampling, significant eutrophic symptoms have been observed in previous surveys (e.g. macroalgae and phytoplankton). As such, it is recommended that ORC consider the following:

1. Undertake a repeat survey after a prolonged dry period (weeks to months) to determine the extent, if any, of subtidal eutrophication (e.g. low oxygen and phytoplankton) and identify whether profileration of macroalgae and fine sediment build-up reoccur.

2. Schedule regular ongoing monitoring (e.g. a 1-5 yearly cycle) focusing on intertidal and subtidal macroalgae, and water quality, in particular dissolved oxygen and phytoplankton impacts. A repeat of past 'fine scale' intertidal monitoring is not recommeded because the intertidal area is limited in extent, physically dynamic and in close proximity to the changeable entrance.

3. Assess catchment sources of nutrients and sediments to the estuary to determine whether changes to current land management practices are likely to significantly improve ecological condition and to guide council management priorities.

4. Use the Kakanui Estuary hydrodynamic model and the output of recommendation 3 to establish limits for catchment sediment and nutrient inputs that will protect the estuary from degradation.

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APPENDICES

Appendix 1. Broad Scale Habitat Classification Definitions

Estuary vegetation was classified using an interpretation of the Atkinson (1985) system described in the NEMP (Robertson et al. 2002) with minor modifications as listed. Revised substrate classes were developed by Salt Ecology to more accurately classify fine unconsolidated substrate. Terrestrial margin vegetation was classified using the field codes included in the Landcare Research Land Cover Database (LCDB5) - see following page.

VEGETATION (mapped separately to the substrates they overlie and ordered where commonly found from the upper to lower tidal range).

Estuarine shrubland: Cover of estuarine shrubs in the canopy is 20-80%. Shrubs are woody plants <10 cm dbh (density at breast height).

Tussockland: Tussock cover is 20-100% and exceeds that of any other growth form or bare ground. Tussock includes all grasses, sedges, rushes, and other herbaceous plants with linear leaves (or linear non-woody stems) that are densely clumped and >100 cm height. Examples occur in all species of *Cortaderia, Gahnia*, and *Phormium*, and in some species of *Chionochloa, Poa, Festuca, Rytidosperma, Cyperus, Carex, Uncinia, Juncus, Astelia, Aciphylla*, and *Celmisia*.

Sedgeland: Sedge cover (excluding tussock-sedges and reed-forming sedges) is 20-100% and exceeds that of any other growth form or bare ground. "Sedges have edges". If the stem is clearly triangular, it's a sedge. If the stem is flat or rounded, it's probably a grass or a reed. Sedges include many species of *Carex, Uncinia*, and *Scirpus*.

Grassland[1]: Grass cover (excluding tussock-grasses) is 20-100% and exceeds that of any other growth form or bare ground.

Introduced weeds[1]: Introduced weed cover is 20-100% and exceeds that of any other growth form or bare ground.

Reedland: Reed cover is 20-100% and exceeds that of any other growth form or open water. Reeds are herbaceous plants growing in standing or slowly- running water that have tall, slender, erect, unbranched leaves or culms that are either round and hollow – somewhat like a soda straw, or have a very spongy pith. Unlike grasses or sedges, reed flowers will each bear six tiny petal-like structures. Examples include *Typha, Bolboschoenus, Scirpus lacutris*, *Eleocharis sphacelata*, and *Baumea articulata*.

Lichenfield: Lichen cover is 20-100% and exceeds that of any other growth form or bare ground.

Cushionfield: Cushion plant cover is 20-100% and exceeds that of any other growth form or bare ground. Cushion plants include herbaceous, semi- woody and woody plants with short densely packed branches and closely spaced leaves that together form dense hemispherical cushions.

Rushland: Rush cover (excluding tussock-rushes) is 20-100% and exceeds that of any other growth form or bare ground. A tall grass-like, often hollow-stemmed plant. Includes some species of *Juncus* and all species of *Apodasmia (Leptocarpus)*.

Herbfield: Herb cover is 20-100% and exceeds that of any other growth form or bare ground. Herbs include all herbaceous and low-growing semi-woody plants that are not separated as ferns, tussocks, grasses, sedges, rushes, reeds, cushion plants, mosses or lichens.

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

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

Note NEMP classes of Forest and Scrub are considered terrestrial and have been included in the terrestrial Land Cover Data Base (LCDB) classifications.

[1]Additions to the NEMP classification.

SUBSTRATE (physical and zoogenic habitat)

Sediment texture is subjectively classified as: firm if you sink 0-2 cm, soft if you sink 2-5cm, very soft if you sink >5cm, or mobile - characterised by a rippled surface layer.

Artificial substrate: Introduced natural or man-made materials that modify the environment. Includes rip-rap, rock walls, wharf piles, bridge supports, walkways, boat ramps, sand replenishment, groynes, flood control banks, stopgates. Commonly sub-grouped into artificial: substrates (seawalls, bunds etc), boulder, cobble, gravel, or sand.

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

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

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

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

Sand: Granular beach sand with a low mud content 0-10%. No conspicuous fines evident when sediment is disturbed.

Sand/Shell: Granular beach sand and shell with a low mud content 0-10%. No conspicuous fines evident.

Muddy sand (Moderate mud content): Sand/mud mixture dominated by sand, but has an elevated mud fraction (i.e. >10-25%). Granular when rubbed between the fingers, but with a smoother consistency than sand with a low mud fraction. Generally firm to walk on.

Muddy sand (HIgh mud content): Sand/mud mixture dominated by sand, but has an elevated mud fraction (i.e. >25-50%). Granular when rubbed between the fingers, but with a much smoother consistency than muddy sand with a moderate mud fraction. Often soft to walk on.

Sandy mud (Very high mud content): Mud/sand mixture dominated by mud (i.e. >50%-90% mud). Sediment rubbed between the fingers is primarily smooth/silken but retains a granular component. Sediments generally very soft and only firm if dried out or another component, e.g. gravel, prevents sinking.

Mud (>90% mud content): Mud dominated substrate (i.e. >90% mud). Smooth/silken when rubbed between the fingers. Sediments generally only firm if dried out or another component, e.g. gravel, prevents sinking.

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

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

Shell bank: Area that is dominated by dead shells

Table of modified NEMP substrate classes and list of Landcare Land Cover Database (LCDB5) classes.

Consolidated substrate			Code
Bedrock		Rock field "solid bedrock"	RF
Coarse Unconsolidated Substrate (>2mm)			
Boulder/ Cobble/ Gravel	>256mm to 4.096m	Boulder field "bigger than your head"	BF
	64 to <256mm	Cobble field "hand to head sized"	CF
	2 to <64mm	Gravel field "smaller than palm of hand"	GF
	2 to <64mm	Shell "smaller than palm of hand"	Shel
Fine Unconsolidated Substrate (<2mm)			
Sand (S)	Low mud (0-10%)	Firm shell/sand	fSS
		Mobile sand	mS
		Firm sand	fS
		Soft sand	sS
Muddy Sand (MS)	Moderate mud (>10-25%)	Firm muddy shell/sand	fSS10
		Mobile muddy sand	mMS10
		Firm muddy sand	fMS10
		Soft muddy sand	sMS10
	High mud (>25-50%)	Firm muddy shell/sand	fSS25
		Mobile muddy sand	mMS25
		Firm muddy sand	fMS25
		Soft muddy sand	sMS25
Sandy Mud (SM)	Very high mud (>50-90%)	Firm sandy mud	fSM
		Soft sandy mud	sSM
		Very soft sandy mud	vsSM
Mud (M)	Mud (>90%)	Firm mud	fM90
		Soft or very soft mud	sM90
Zootic (living)			
		Cocklebed	CKLE
		Mussel reef	MUSS
		Oyster reef	OYST
		Sabellid field	TUBE
Artifical Substrate			
		Substrate (brg, bund, ramp, walk, wall, whf)	aS
		Boulder field	aBF
		Cobble field	aCF
		Gravel field	aGF
		Sand field	aSF

Artificial Surfaces
1 Built-up Area (settlement)
2 Urban ParklandOpen Space
5 Transport Infrastructure
6 Surface Mines and Dumps

Bare or Lightly Vegetated Surfaces
10 Sand and Gravel
12 Landslide
14 Permanent Snow and Ice
15 Alpine Grass/Herbfield
16 Gravel and Rock

Water Bodies
20 Lake or Pond
21 River

Cropland
30 Short-rotation Cropland
33 Orchard Vineyard & Other Perennial Crops

Grassland, Sedge and Saltmarsh
40 High Producing Exotic Grassland
41 Low Producing Grassland
43 Tall-Tussock Grassland
44 Depleted Grassland
45 Herbaceous Freshwater Vegetation
46 Herbaceous Saline Vegetation

Scrub and Shrubland
47 Flaxland
50 Fernland
51 Gorse and/or Broom
52 Manuka and/or Kanuka
54 Broadleaved Indigenous Hardwoods
55 Sub Alpine Shrubland
56 Mixed Exotic Shrubland
58 Matagouri or Grey Scrub

Forest
64 Forest - Harvested
68 Deciduous Hardwoods
69 Indigenous Forest
71 Exotic Forest

Appendix 2. Information supporting ratings in the report

Sediment Mud Content

Sediments with mud contents of <25% are generally relatively firm to walk on. When mud contents increase above ~25%, sediments start to become softer, more sticky and cohesive, and are associated with a significant shift in the macroinvertebrate assemblage to a lower diversity community tolerant of muds. This is particularly pronounced if elevated mud contents are contiguous with elevated total organic carbon, and sediment bound nutrients and heavy metals whose concentrations typically increase with increasing mud content. Consequently, muddy sediments are often poorly oxygenated, nutrient rich, can have elevated heavy metal concentrations and, on intertidal flats of estuaries, can be overlain with dense opportunistic macroalgal blooms. High mud contents also contribute to poor water clarity through ready re-suspension of fine muds, impacting on seagrass, birds, fish and aesthetic values. Such conditions indicate changes in land management may be needed.

Apparent Redox Potential Discontinuity (aRPD)

aRPD depth, the visually apparent transition between oxygenated sediments near the surface and deeper more anoxic sediments, is a primary estuary condition indicator as it is a direct measure of time integrated sediment oxygenation. Knowing if the aRPD is close to the surface is important for three main reasons:

The closer to the surface anoxic sediments are, the less habitat there is available for most sensitive macroinvertebrate species. The tendency for sediments to become anoxic is much greater if the sediments are muddy. Anoxic sediments contain toxic sulphides and support very little aquatic life. As sediments transition from oxic to anoxic, a "tipping point" is reached where nutrients bound to sediment under oxic conditions, becomes released under anoxic conditions to potentially fuel algal blooms that can degrade estuary quality.

In sandy porous sediments, the aRPD layer is usually relatively deep (greater than 3cm) and is maintained primarily by current or wave action that pumps oxygenated water into the sediments. In finer silt/clay sediments, physical diffusion limits oxygen penetration to less than 1cm (Jørgensen & Revsbech 1985) unless bioturbation by infauna oxygenates the sediments.

Opportunistic Macroalgae

The presence of opportunistic macroalgae is a primary indicator of estuary eutrophication, and when combined with high mud and low oxygen conditions (see previous) can cause significant adverse ecological impacts that are very difficult to reverse. Thresholds used to assess this indicator are derived from the OMBT (see WFD-UKTAG (Water Framework Directive – United Kingdom Technical Advisory Group), 2014; Robertson et al 2016a,b; Zeldis et al. 2017), with results combined with those of other indicators to determine overall condition.

Seagrass

Seagrass (*Zostera muelleri*) grows in soft sediments in most NZ estuaries. It is widely acknowledged that the presence of healthy seagrass beds enhances estuary biodiversity and particularly improves benthic ecology (Nelson 2009). Though tolerant of a wide range of conditions, it is seldom found above mean sea level (MSL), and is vulnerable to fine sediments in the water column and sediment quality (particularly if there is a lack of oxygen and production of sulphide), rapid sediment deposition, excessive macroalgal growth, high nutrient concentrations, and reclamation. Decreases in seagrass extent are likely to indicate an increase in these types of pressures. The assessment metric used is the percent change from baseline measurements.

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Appendix 3. Ground truthing Kakanui Estuary January 2021

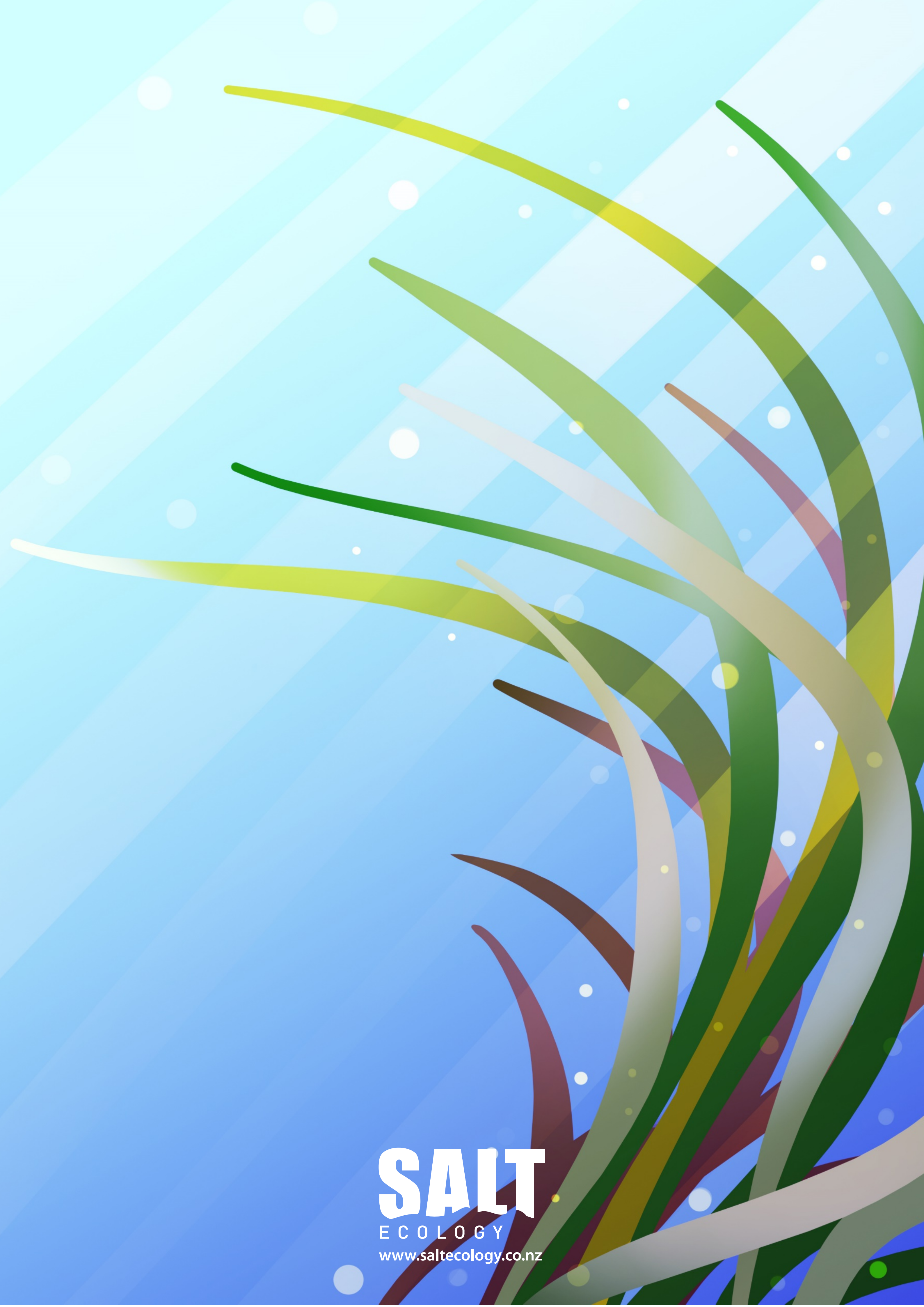
Ground-truthing extent and location of field photos in January 2021

Appendix 4. Comparison 2021 and 2009 broad scale mapping data

Summary of key broad scale indicator results and ratings

	2021		2009	
Broad scale Indicators	ha	%	Value	2021
Intertidal area	8.4	33.5	-	-
Subtidal area	16.7	66.5	-	-
Total Estuary Area	25.1	100	24.6	100
Saltmarsh[1]				
Estuarine Shrub	0	0	0.1	-
Sedgeland	0.01	0.1	0.01	-
Herbfield	0.03	0.4	0.06	-
Macroalgae (OMBT)	1.0*	-	-	-
Macroalgae beds (>50% cover)	0	0	0.04[3]	-
Mud-dominated sediment[2] (intertidal)	0.6	7.7	-	-
Mud-dominated sediment[2] (subtidal)	1.1	6.6	-	-
High Enrichment Conditions	0	0	0	-
Densely vegetated 200m terrestrial margin	10.3	8.3	-	-

[1]Percentage of intertidal area
[2]Mud dominated sediment > 50% mud
[3]Only recorded as macroalgae no % cover was recorded. However, it is noted in the report no nuisance macroalgae was present.
Dash represents no data



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