Wriggle coastalmanagement

Waimatuku Estuary 2018

Fine Scale Monitoring and Macrophyte Mapping

Prepared
for
Environment
Southland
June
2018

Cover Photo: Waimatuku Estuary, lower reaches facing west. Inside cover: Scientist assessing benthic condition near the estuary mouth.

Waimatuku Estuary 2018

Fine Scale Monitoring and Macrophyte Mapping

Prepared for
Environment Southland

By

Ben Robertson and Barry Robertson

Wriggle Limited, 027 823 8665, 0275 417 935, www.wriggle.co.nz

RECOMMENDED CITATION:

Robertson, B.P. and Robertson, B.M. 2018. Waimatuku Estuary: Fine Scale Monitoring and Macrophyte Mapping 2018. Report prepared by Wriggle Coastal Management for Environment Southland. 29p.

Contents

Waimatuku Estuary - Executive Summary vii
1. Introduction 1
2. Estuary Risk Indicator Ratings. 5
3. Methods 6
4. Results and Discussion 7
5. Summary and Conclusions 17
6. Monitoring and management. 19
7. Acknowledgements 19
8. References 19
Appendix 1. Details on Analytical Methods. 22
Appendix 2. 2017/18 Detailed Results 23
Appendix 3. Sonde Calibration Report 24
Appendix 4. Detailed Statistical Outputs 29

List of Tables

Table 1. Summary of the major environmental issues affecting most New Zealand estuaries. 2
Table 2. Summary of estuary condition risk indicator ratings used in the present report. 5
Table 3. Summary of water quality and bottom sediment, Waimatuku Estuary, 14 February 2018. 7

List of Figures

Figure 1. Sampling sites in the Waimatuku Estuary, February 2018. 4
Figure 2. Percent cover categories for aquatic vegetation. 6
Figure 3. Longitudinal profile (river to sea) of maximum water depth (at high water) and substrate type . . . 9
Figure 4. Nutrient concentrations in surface and bottom water (*n* = 1) at three mid-estuary channel sites . 11
Figure 5. Chlorophyll *a* and dissolved oxygen concentrations in surface and bottom water 11
Figure 6. Sediment mud content at three proximate mid-estuary transect stations 12
Figure 7. Sediment characteristics at three proximate mid-estuary transect stations 13
Figure 8. Percent cover of aquatic vegetation at 12 discrete Waimatuku estuary transects 2009-2012 and 2018. 14
Figure 9. Dominant macrophytes and macroalgae, Waimatuku Estuary.. 15
Figure 10. Site photos, Waimatuku Estuary, 14 February 2018. 16
Figure 11. Waimatuku Estuary - subtidal channel condition and trophic state 18

All photos by Wriggle except where noted otherwise.

WAIMATUKU ESTUARY - EXECUTIVE SUMMARY

Waimatuku Estuary is a small (20 ha), shallow (mean depth ~0.5-1 m at high water), often poorly-flushed tidal river type estuary. It has a single tidal opening that may occasionally be restricted, a central river channel, and a larger, sand-dominated basin in the lower estuary. The surrounding catchment is dominated by pasture. It is one of the key estuaries in Environment Southland's (ES's) long-term coastal monitoring programme. This report presents the results of the February 2018 synoptic estuary subtidal channel monitoring results, overall estuary condition and issues, and monitoring recommendations summarised below.

SYNOPTIC FINE SCALE SURVEY RESULTS

2018 Subtidal Habitat Results

- Opportunistic macroalgae, a primary indicator of eutrophication, was present at sites in the upper-middle estuary, while there was extensive benthic microalgae growing on lower estuary sands.
- Sediment mud content was low (7.4-11 % mud) at three established mid-estuary fine scale sites, with upper and lower estuary sediments dominated by mud and sand, respectively.
- Sediment oxygenation depth was moderate (aRPD 0.5-2 cm) at mid-estuary fine scale sites, deeper (aRPD >5 cm) in the sandy lower estuary, and poor (aRPD <0.5 cm) in the upper estuary muds.
- The benthic indicators of organic enrichment (total organic carbon) and nutrient enrichment (total nitrogen and phosphorus) were at low-moderate concentrations across the three fine scale sites.
- Surface and bottom waters in main estuary channel were non-stratified, and had very low chlorophyll *a* concentrations despite the presence of above threshold nutrient concentrations in surrounding waters.
- High value rooted aquatic macrophytes were present throughout the mid-upper estuary.

RISK INDICATOR RATINGS

(INDICATE RISK OF ADVERSE ECOLOGICAL IMPACTS)

🟦	Low	🟨	Moderate
⬜	Very Low	🟧	High

	Waimatuku Estuary	Site D (Upper middle)				Site E (Middle)				Site G (Lower middle)			
		2010	2011	2012	2018	2010	2011	2012	2018	2010	2011	2012	2018
Sediment	**Sediment Mud Content**	Moderate	Moderate	Low	Low	Low	Low	Low	Low	Very Low	Very Low	Very Low	Low
	Sediment Oxygenation (aRPD)	Unreliable	High	Unreliable	Moderate	Unreliable	Moderate	Unreliable	Moderate	Unreliable	Unreliable	Unreliable	Moderate
	Total Organic Carbon (TOC)	Moderate	Low	Low	Moderate	Low	Moderate	Low	Low	Very Low	Very Low	Very Low	Moderate
	Total Nitrogen (TN)	High	Moderate	Moderate	Moderate	Moderate	High	Low	Low	Low	Low	Low	Moderate
	Total Phosphorus (TP)	Ratings not developed											
Bottom Waters	**Chlorophyll *a* (Phytoplankton)**	Not measured			Very Low	Not measured			Very Low	Not measured			Very Low
	Dissolved Oxygen	Not measured			Very Low	Not measured			Very Low	Not measured			Very Low
	Macroalgae	Nuisance growths present				Nuisance growths present				Nuisance growths present			

Comparison with Baseline Results

Statistical comparison of the baseline (2010-2012) and 2018 results was possible for some indicators. Comparisons show that baseline benthic results were similar to those from nearby middle estuary sites in 2018, indicating that part of the estuary has not changed significantly ($P > 0.05$) in terms of sediment mud, TOC, TN and TP concentrations in the past decade. Shallow estuarine waters, often stratified (even at low tide) during baseline years, were highly brackish and non-stratified in 2018. Macroalgae was present throughout the mid-upper estuary but had reduced in extent since baseline years, with rooted macrophytes characterising a much greater extent of estuary area. This reduction in macroalgal coverage may reflect the increased cover of low salinity tolerant rooted macrophytes, which very effectively utilise surrounding nutrients, thereby preventing algal growth in the estuary. Seagrass (*Zostera capricornia*), present in 2011 and 2012, was not observed in the estuary in 2018. Intertidal and subtidal flats in lower estuary supported a benthic microalgal film also evident in 2011 and 2012.

Waimatuku Estuary - Executive Summary (continued)

ESTUARY CONDITION AND ISSUES

Sedimentation (muddiness)

Sediments were in relatively good condition with limited accumulation of muds and moderate sediment oxygenation in the middle-lower channel, but were in poorer condition (elevated muds and poorly oxygenated) at monitoring sites located in the upper channel. Mud content measured at three subtidal channel sites, chosen to represent the main middle estuary benthic habitat, were low. Ecologically, the low mud content at these sites indicates a *'minor stress on sensitive organisms, especially if nutrient loads are elevated'* (Robertson et al. 2016b) for that part of the estuary. Overall, the findings indicate excessive deposition of muds in Waimatuku Estuary is currently only a problem in the deeper, less well flushed upper estuary where substrata were dominated by muds.

Eutrophication

The NZ Estuary Trophic Index tool (NZ ETI; Robertson et al. 2016a,b) combines a range of broad and fine scale indicators to provide an overall assessment of eutrophic expression in an estuary, and is largely driven by nuisance-level macroalgae (and associated benthic degradation) occurring over >10 % of the estuary area. Although it was invalid to give an ETI score for the primary reason that the macroalgal component currently cannot be applied in subtidal situations, the presence of eutrophic symptoms in the upper-mid Waimatuku Estuary in February 2018 indicated that this threshold was exceeded for subtidal benthic macroalgae and sediment oxygenation. However, the water quality results indicated little evidence of eutrophication symptoms in overlying waters, as indicated by the low chlorophyll *a* (phytoplankton) concentrations, despite the presence of above threshold nutrient concentrations.

Taken as a whole, the available data indicates that on the day of sampling, elevated nutrients in the estuary were responsible for high levels of attached macrophyte/macroalgal production, but because of the short residence time for phytoplankton in the estuary (i.e. the estuary is well-flushed), localised phytoplankton blooms were absent from the water column habitat. However, given this was only one comprehensive sampling event and that there is the possibility of water column stratification occurring at other times during the growing season, there is potential for stratified bottom water phytoplankton blooms to occur, particularly if the flow at the estuary mouth becomes further constricted. Effects are compounded by the absence of an extensive vegetated margin to help buffer excess nutrients.

Overview

The combined 2018 synoptic survey results place the Waimatuku Estuary in a low-moderate state overall in relation to subtidal channel condition and trophic status, indicating conditions have deteriorated slightly since 2012. Given its above threshold catchment nutrient load coupled with potential further eastward mouth migration and consequent constriction, eutrophication (presently expressed as nuisance macroalgal production and reduced sediment oxygenation in the upper-middle estuary) and to a lesser extent sedimentation are expected to be ongoing issues in the estuary.

RECOMMENDED MONITORING AND MANAGEMENT

Continue fine scale monitoring every 5 years (next scheduled for February 2023). Because current fine scale Sites D, E and G only represent part of the estuary, it is recommended that future monitoring instead be undertaken at upper, mid and lower estuary Sites C, E and J. Also undertake annual cost effective (data only) indicator monitoring (next scheduled for February 2019) as follows: RPD (via ORP probe), water column chlorophyll a, DO, salinity, clarity, substrata type and vegetative % cover at Transects C, E and J combined with a coarse assessment of mouth status and vegetative cover elsewhere in the estuary.

The 2018 synoptic survey results underscore the need to manage nutrient and to a lesser extent fine sediment sources entering the estuary from the catchment. This involves three key steps:

1. Develop and assign catchment nutrient and sediment load guideline criteria to Waimatuku Estuary based on available catchment load/estuary response information from other relevant estuaries.
2. Estimate catchment nutrient and suspended sediment loads using available catchment models and stream monitoring data.
3. Determine the extent to which the estuary meets guideline catchment load criteria.
4. Develop management and/or restoration plans for the estuary as appropriate.

1. INTRODUCTION

Developing an understanding of the condition and risks to coastal and estuarine habitats is critical to the management of biological resources. In 2000, Environment Southland (ES) identified a number of estuaries in it's region as immediate priorities for long term monitoring and in 2002 began the monitoring programme in a staged manner. The estuaries currently included in the programme are New River, Jacobs River, Fortrose, Waikawa, Haldane, Waiau, Waituna, Waimatuku and Freshwater. Risk assessments have been undertaken for a number of other estuaries in order to establish priorities for their management. Risk assessments have also been undertaken to establish management priorities for a number of other estuaries (Robertson and Stevens 2007a,b,c). To evaluate the ongoing condition of Waimatuku Estuary, Wriggle Coastal Management was contracted by ES in 2017 to undertake routine monitoring of the estuary in February 2018.

Within NZ, the approach for monitoring estuary condition follows the National Estuary Monitoring Protocol (NEMP) (Robertson et al. 2002) and the NZ Estuary Trophic Index (ETI) (Robertson et al. 2016a and b). It consists of three components as follows:

1. **Ecological Vulnerability Assessment** of the estuary to major issues (Table 1) and appropriate monitoring design. This component has been completed for Waimatuku Estuary and is reported on in Robertson and Stevens (2008).
2. **Broad Scale Habitat Mapping** (NEMP approach). This component (see Table 1), which documents the key habitats within each estuary and changes to these habitats over time, is reported on in Robertson and Stevens (2008).
3. **Fine Scale Monitoring** (Synoptic survey and NEMP approach). Monitoring of selected biological, physical and chemical characteristics (water column nutrients, chlorophyll *a*, clarity, salinity, depth, sediment oxygenation, muddiness, presence of macrophytes and nuisance macroalgae). This component, which provides detailed information on the condition of the Waimatuku Estuary, began with a preliminary synoptic survey in February 2009 (Robertson and Stevens 2009) followed by repeat monitoring annually for three years (2010, 2011 and 2012) to establish a baseline. The current report describes the first post-baseline survey of the condition of the estuary's two main habitat types (water column and underlying benthic habitat) undertaken in February 2018.

WAIMATUKU ESTUARY

Waimatuku Estuary is a small (20 ha at high water), relatively long, moderately-highly flushed, shallow, short residence time tidal river estuary (SSRTRE; NZ ETI classification in Robertson et al. 2016a) that extends approximately 4.5 km inland (Figure 1). The estuary drains to the sea through a sand dominated barrier beach and modified marram grass duneland, and has relatively small intertidal flats (typical for tidal river estuaries it is dominated by a central channel), while the estuary mouth periodically constricts, naturally reducing salt intrusion.

The estuary also holds Kai Tahu cultural and spiritual values, and its estuarine values include intertidal flats used as feeding and roosting areas for birds and fish nursery habitat. The surrounding catchment (150 km^2) is dominated by sheep, beef and dairy farming, with much of the mid-upper estuary margin directly bordered by developed pasture and rural road.

Despite receiving a high nutrient load from both riverine and groundwater sources (estimated catchment N areal loading of 2877 mg N m^{-2} d^{-1} exceeds the guideline for low susceptibility SSRTRE estuaries of ~2000 mg N m^{-2} d^{-1}; Robertson et al. 2016), when its mouth is open for exchange with the sea, the Waimatuku has a relatively low susceptibility to eutrophication. This is primarily because of its highly flushed nature, given that it is strongly channelised with very few poorly flushed areas, and has high freshwater inflow. However, the assimilative capacity of the estuary with regard to nutrients is very quickly exceeded when the mouth is constricted (Stevens and Robertson 2012). Since monitoring began in 2008, the estuary mouth has been driven approximately 1 km to the east by long shore drift, potentially further constricting the mouth, restricting flushing, and therefore increasing the likelihood of eutrophication issues. Currently, nutrients retained in the estuary contribute to the growth of attached macrophytes and associated nuisance macroalgae, while the presence of elevated chlorophyll *a* concentrations at times may be attributable to phytoplankton blooms in saline bottom waters and from freshwater sources upstream of the estuary.

The estuary has relatively low vulnerability to muddiness issues based on the fact that most of the estuary is dominated by sands, particularly in lower and middle estuary reaches. Disease risk indicators on the Southland coast, including Waimatuku Estuary, are assessed separately in ES's recreational water quality monitoring programme, while heavy metal toxicity is considered to be at such a low risk it is not considered necessary to monitor (Robertson and Stevens 2008).

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

1. Sediment Changes

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

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

Recommended Key Indicators:

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

2. Eutrophication

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

Recommended Key Indicators:

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

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

3. Disease Risk

Runoff from farmland and human wastewater often carries a variety of disease-causing organisms or pathogens (including viruses, bacteria and protozoans) that, once discharged into the estuarine environment, can survive for some time (e.g. Stewart et al. 2008). Every time humans come into contact with seawater that has been contaminated with human and animal faeces, we expose ourselves to these organisms and risk getting sick. Human diseases linked to such organisms include gastroenteritis, salmonellosis, campylobacteriosis and hepatitis A (Wade et al. 2003; (Hsieh and Sulaiman 2018). Aside from serious health risks posed to humans through recreational contact and shellfish consumption, pathogen contamination can also cause economic losses due to closed commercial shellfish beds.

Recommended Key Indicators:

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

4. Toxic Contamination

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

Recommended Key Indicators:

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

5. Habitat Loss

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

Recommended Key Indicators:

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

1. Introduction (Continued)

Waimatuku Estuary 2018 Transect Locations

Transect		NZTM East	NZTM North
	A	1226984	4855992
Upper	B	1226805	4855507
	C	1226727	4855281
Middle	D	1226952	4855034
	E	1226895	4854934
	F	1227028	4854923
	G	1227176	4854864
	H	1227273	4854581
Lower	I	1227761	4854312
	J	1228167	4854051
	K	1228430	4853708
	L	1228582	4853552

Figure 1. Sampling sites in the Waimatuku Estuary, February 2018. Image source: Google Earth Pro (dated 13 January 2018). Note: Lower estuary sites I, J, K and L were relocated eastward in 2018 to account for estuary mouth migration since 2012.

2. ESTUARY RISK INDICATOR RATINGS

The estuary monitoring approach used by Wriggle has been established to provide a defensible, cost-effective way to help quickly identify the likely presence of the predominant issues affecting NZ estuaries (i.e. eutrophication, sedimentation, disease risk, toxicity and habitat change; Table 1), and to assess changes in the long term condition of estuarine systems. The design is based on the use of primary indicators that have a documented strong relationship with water or sediment quality.

In order to facilitate this assessment process, NZ ETI "risk indicator ratings" (Robertson et al. 2016b), which superseed the "interim condition ratings" used previously to evaluate the health of the Waimatuku Estuary (e.g. Stevens and Robertson 2012), have also been proposed that assign a relative level of risk (e.g. very low, low, moderate, high) of specific indicators adversely affecting intertidal estuary condition (see Table 2 below). Each risk indicator rating is designed to be used in combination with relevant information and other risk indicator ratings, and under expert guidance, to assess overall estuarine condition in relation to key issues, and make monitoring and management recommendations. When interpreting risk indicator results we emphasise:

- The importance of taking into account other relevant information and/or indicator results before making management decisions regarding the presence or significance of any estuary issue e.g. community aspirations, cost/benefit considerations.
- That rating and ranking systems can easily mask or oversimplify results. For instance, large changes can occur within the same risk category, but small changes near the edge of one risk category may shift the rating to the next risk level.
- Most issues will have a mix of primary and supporting indicators, primary indicators being given more weight in assessing the significance of results. It is noted that many supporting estuary indicators will be monitored under other programmes and can be used if primary indicators reflect a significant risk exists, or if risk profiles have changed over time.
- Ratings have been established in many cases using statistical measures based on NZ estuary data and presented in the NZ estuary Trophic Index (NZ ETI; Robertson et al. 2016a and 2016b). However, where such data is lacking, or has yet to be processed, ratings have been established using professional judgement, based on our experience from monitoring numerous NZ estuaries. Our hope is that where a high level of risk is identified, the following steps are taken:
    1. Statistical measures be used to refine indicator ratings where information is lacking.
    2. Issues identified as having a high likelihood of causing a significant change in ecological condition (either positive or negative), trigger intensive, targeted investigations to appropriately characterise the extent of the issue.
    3. The outputs stimulate discussion regarding what an acceptable level of risk is, and how it should best be managed.

The indicators and interim risk ratings used for the 2018 Waimatuku Estuary synoptic monitoring programme are summarised in Table 2. The basis underpinning most of the ratings is the observed correlation between an indicator and the presence of degraded estuary conditions from a range of tidal lagoon and tidal river estuaries throughout NZ. Work to refine and document these relationships is ongoing.

Table 2. Summary of estuary condition risk indicator ratings used in the present report. Note risk indicator ratings were not available for all parameters included in the present report (e.g. Total phosphorus in sediments).

RISK INDICATOR RATINGS / ETI BANDS (indicate risk of adverse ecological impacts)					
FINE SCALE INDICATORS		Very Low Band A	Low Band B	Moderate Band C	High Band D
Sediment	**Sediment Mud Content (%mud)***	<5 %	5 to 10 %	>10 to 25 %	>25 %
	Apparent Redox Potential Discontinuity (aRPD)***	Unreliable	Unreliable	0.5 to 2 cm	<0.5 cm
	Total Organic Carbon (TOC)*	<0.5 %	0.5 to <1 %	1 to <2 %	>2 %
	Total Nitrogen (TN)*	<250 mg kg^{-1}	250 to 1000 mg kg^{-1}	>1000 to 2000 mg kg^{-1}	>2000 mg kg^{-1}
	Total Phosphorus (TP)	Rating not developed			
Water column	**Chlorophyll *a* (phytoplankton)**	<5 ug l^{-1}	5 to <10 ug l^{-1}	10 to <16 ug l^{-1}	>16 ug l^{-1}
	Dissolved Oxygen (DO)	≥7.5 mg l^{-1}	≥5.0 mg l^{-1}	≥4.0 mg l^{-1}	<4.0 mg l^{-1}
	NZ ETI score*	0 to 0.25	0.25 to 0.50	0.50 to 0.75	0.75 to 1.0

*NZ ETI (Robertson et al. 2016b), **Hargrave et al. (2008), ***Robertson B.P. (PhD thesis - in press), Keeley et al. (2012). See NOTES in Appendix 2 for further information.

3. METHODS

Figure 2. Percent cover categories for aquatic vegetation.

To characterise conditions within the main estuary channel and thereby allow for comparisons between baseline and 2018 results, twelve previously established transect sampling sites in Waimatuku Estuary (Figure 1, Robertson and Stevens 2012), representing the range of different conditions present throughout the estuary, were visited by two scientists on 14 February 2018 when the lagoon was open to the sea, tidal influence was potentially moderate (i.e. neap tide), and the river was in a low-flow cycle (flow <1 m^3 s^{-1} for previous 7 days; ES's river flow database). At each site at high tide (i.e. when salinity intrusion and stratification effects are maximised), a YSI-EXO1 Sonde hand-held field meter (see calibration report in Appendix 3) was used to directly measure and log depth, [chlorophyll *a*], salinity, temperature, and [dissolved oxygen] in upper and lower 0.2 m of the water column. At the same locations water samples were also collected with a van dorn water sampler for laboratory analyses (chlorophyll *a*, total nitrogen (N), nitrate-N, ammonia-N, dissolved reactive P and total P concentrations).

In addition, at each site secchi disc (200 mm) clarity was measured and one benthic sediment sample was collected using either a remotely triggered van veen grab sampler or a custom built sediment sampling hoe with telescopic handle). Once at the surface the sediment apparent Redox Potential Discontinuity (aRPD) depth was measured and photographed, vegetation (species/% cover) noted (Figure 2 gives examples of % cover estimates for vegetation), and a sediment sub-sample (~500 g, representing 5 composite cross-channel subsamples of the top 20 mm of sediment) collected for subsequent chemical analysis for total organic carbon (TOC), grain size distribution (% mud, sand gravel), and total N (TN) and total phosphorus (TP).

- All samples were kept in a chilly bin in the field before dispatch to R.J. Hill Laboratories for chemical analysis (details of lab methods and detection limits in Appendix 1):
- Samples were tracked using standard Chain of Custody forms and results checked and transferred electronically to avoid transcription errors.

Analytical details are provided in Appendix 1. Note disease risk indicators on the Southland coast are assessed separately in ES's recreational water quality monitoring programme, while heavy metal toxicity was considered to be at such a low risk it was not considered necessary to monitor (Robertson and Stevens 2008).

Note lower estuary sites I, J, K and L were relocated eastward in 2018 to account fot estuary mouth migration since 2012 (as noted in Figure 1).

A visual examination of the whole estuary was also undertaken to assess the extent of aquatic vegetation occurring outside of the chosen transects. Appendix 2 presents the 2018 field measurements. Results of the 2010, 2011 and 2012 monitoring are reported in Robertson and Stevens (2010, 2011 and 2012).

Finally, one-way ANOVA was used to investigate differences in benthic fine scale parameters (sediment mud, TOC, TN and TP contents) between the 2018 and baseline datasets (see Appendix 4 for detailed output). Data were log-transformed if this improved homogeneity of variance, as tested by Levene's test. Post-hoc comparisons of the means were based on Tukey's HSD test using a significance level (α) of 0.05. All statistical analyses were undertaken using R statistical software (Development core team, 2015—3.0.3 GUI 1.63 Snow Leopard build 6660).

4. RESULTS AND DISCUSSION

A summary of the results of the 2017/18 synoptic subtidal channel monitoring of the Waimatuku Estuary is presented in Table 3 below, with detailed results in Appendix 2. Also included are the summary results of the baseline (2010-2012) synoptic benthic monitoring (bottom table).

Table 3. Summary of water quality and bottom sediment (composite sample, *n* = 1) results, Waimatuku Estuary, 14 February 2018. **NA = site not assessed in 2018. *bottom sample only where site depth <0.5 m. **based on in situ values obtained using a YSI-EXO1 Sonde. **fine scale sites.**

Water Column 2018	Position	Site Depth (m)	Sample Depth (m)	Temp (ºC)	Salinity (ppt)	Diss. Oxygen (mg l^{-1})	Chlorophyll a (ug l^{-1})***	Total N (g m^{-3})	Total Ammoniacal-N (g m^{-3})	Nitrate-N (g m^{-3})	Dissolved Reactive P (g m^{-3})	Total P (g m^{-3})
Transect A*	Surface		-	-	-	-	-	-	-	-	-	-
	Bottom	0.4	0.2	19.7	0.1	11.1	3.1	-	-	-	-	-
Transect B	Surface		0.2	18.8	0.2	12.1	4.2	-	-	-	-	-
	Bottom	2.0	1.8	18.3	0.2	12.5	4.3	-	-	-	-	-
Transect C	Surface		0.2	19.5	0.2	16.3	5.2	-	-	-	-	-
	Bottom	1.0	0.8	18.1	0.2	13.4	4	-	-	-	-	-
Transect D**	Surface		0.2	18.2	0.2	10.6	4.6	1.5	0.01	1.1	0.05	0.07
	Bottom	1.0	0.8	18.0	0.2	10.0	4.5	1.5	0.01	1.1	0.04	0.07
Transect E**	Surface		0.2	18.2	0.2	10.6	4.6	1.5	0.01	1.1	0.05	0.07
	Bottom	0.7	0.5	18.0	0.2	10.0	4.5	1.6	0.01	1.1	0.05	0.08
Transect F	Surface		NA	NA	NA	NA	NA	-	-	-	-	-
	Bottom	NA	NA	NA	NA	NA	NA	-	-	-	-	-
Transect G**	Surface		0.2	19.6	0.2	12.1	5.0	1.4	0.01	1.0	0.05	0.07
	Bottom	1.0	0.8	19.5	0.2	11.8	5.0	1.5	0.04	1.0	0.05	0.09
Transect H	Surface		0.2	20.3	0.2	12.2	3.7	-	-	-	-	-
	Bottom	0.7	0.5	20.3	0.2	12.2	4.4	-	-	-	-	-
Transect I*	Surface							-	-	-	-	-
	Bottom	0.5	0.2	20.8	0.3	11.7	3.0	-	-	-	-	-
Transect J	Surface		0.2	22.3	0.3	10.3	2.1	-	-	-	-	-
	Bottom	1.0	0.8	21.1	0.4	10.2	5.0	-	-	-	-	-
Transect K	Surface		0.2	22.5	0.3	10.5	5.1	-	-	-	-	-
	Bottom	1.0	0.8	22.6	0.3	10.6	2.8	-	-	-	-	-
Transect L	Surface		0.2	22.7	0.4	10.5	5.2	-	-	-	-	-
	Bottom	1.2	1.0	22.8	0.3	10.7	2.2	-	-	-	-	-

	Bottom Sediment	aRPD (cm)	TOC (%)	Mud (%)	Sand (%)	Gravel (%)	TN (mg kg^{-1})	TP (mg kg^{-1})
2010	Transect D	>5	1.80	25.3	55.8	18.9	2400	820
	Transect E	>5	0.76	9.8	90.2	<0.1	1400	850
	Transect G	>5	0.24	2.6	97.2	0.2	<500	770
2011	Transect D	0-1	0.90	15.9	50.8	33.2	1300	660
	Transect E	0-3	1.82	12.8	32.8	54.4	2200	660
	Transect G	>10	0.28	3.7	96.0	0.4	<500	560
2012	Transect D	3-5	0.65	5.3	51.6	43.1	1200	490
	Transect E	3-5	0.56	4.9	66.9	28.1	900	650
	Transect G	3-5	0.27	3.1	81.5	15.4	600	640
2018	Transect D	1-3	1.0	7.4	92.1	0.4	1190	803
	Transect E	1-3	0.8	9.5	90.1	0.4	860	648
	Transect G	1-3	1.1	11.0	88.9	0.1	1220	888

As general background, between 2008-2012 longshore drift had pushed the estuary mouth approximately 600 m to the east, and since 2012, the mouth has shifted a further 500-600 m to the east. The estuary had similar water depths (predominantly <1.5 m, and the deepest area (~2 m) at Transect B and shallowest (~0.6 m) at lower Transects J, K and L), compared to the previous surveys in 2009-2012. Longitudinal profiles indicate some deposition and erosion of sediments across the estuary between 2012 and 2018, while differences in cross sectional depths at each site were negligible (Table 3, Figure 3, Appendix 2).

Analysis and discussion of the baseline and 2018 results are presented as two main steps; firstly, the main channel water column habitat condition (Section 4.1) and secondly, the main channel benthic habitat condition (Section 4.2). The synoptic assessment is undertaken with a focus on the key estuarine issues of muddiness (or sedimentation) and eutrophication. Statistical differences between 2018 and baseline datasets are investigated wherever appropriate.

4.1 WATER COLUMN HABITAT CONDITION

4.1.1 EUTROPHICATION

BACKGROUND

In shallow tidal river type estuaries the rapid flushing time (<3 days for these estuaries) means water column phytoplankton cannot reach high concentrations before they are flushed to the sea. However, the Waimatuku can experience elevated concentrations in parts of the main estuary channel during low flow-baseflow periods when inflowing freshwater flows over more saline tidal water and results in a dense isolated layer of saline bottom water that neither freshwater or tidal inflow currents are strong enough to flush out. Such isolated (or stratified) bottom water (often situated in the 1-2 m depth range) is susceptible to phytoplankton blooms, low dissolved oxygen, elevated nutrient concentrations and flocculation-driven accumulation of fine sediment. In these situations, which vary between marine and close to freshwater salinities, a co-limiting situation between nitrogen (N) and phosphorus (P) is expected, and as a consequence any assessment of nutrient impacts should include both N and P.
Since both N and P are continually cycling between all of their major nutrient forms, an assessment of total N (TN), dissolved inorganic N (DIN) and total P (TP) is needed in order to gauge the level of N and P within an estuary and therefore its potential nutrient related health. Reliance on a single N or P fraction, e.g. inorganic N, results in inaccurate assessments, since even in a large algal bloom inorganic concentrations may be low due to the uptake by the plants (Howes et al. 2003). Based on the following literature, a TN, DIN and TP threshold concentration of approximately 0.4 mg TN l^{-1}, 0.096 mg DIN l^{-1} and 0.025 mg TP l^{-1} for the appearance of eutrophic conditions can be identified (see inset).

Literature supporting water column TN, DIN and TP thresholds

- In Horsen's Estuary, Denmark, research indicates a mean growing season threshold value of 0.398 mg TN l^{-1} to meet good ecological status (Hinsby et al. 2012). This research also identified a threshold for inorganic nutrients as 0.021 mg DIN l^{-1} and 0.007 mg DIP l^{-1}.
- Similarly, ECan Avon-Heathcote Estuary data from 2010-2014 suggests the appearance of eutrophic conditions may be unlikely below a TN concentration around 0.4 mg TN l^{-1} (John Zeldis pers. comm. 2016).
- In the US, EPA Region 1 has considered total N threshold concentrations for estuaries and coastal waters of 0.45 mg TN l^{-1} as protective of DO standards and 0.34 mg TN l^{-1} as protective for eelgrass (Latimer and Rego 2010, State of New Hampshire 2009, Benson et al. 2009).
- As concentrations at inner Massachusetts estuaries rose to levels above 0.40 mg TN l^{-1}, with the entry of a wastewater nitrogen plume, eelgrass beds began declining and localized macro-algal accumulations were reported (Howes et al. 2003).
- In Waituna Lagoon, a coastal lagoon in Southland, thresholds of 0.33 mg N l^{-1} and 0.02 mg P l^{-1} have been identified to maintain a healthy rooted aquatic plant community (particularly key species like *Ruppia* spp.) (Robertson et al. 2013; Burns et al. 2000; Schallenburg et al. 2017).
- In Kakanui Estuary, a coastal lagoon in Otago, DIN thresholds of 0.07 mg DIN l^{-1} when the mouth is closed and 0.096 mg DIN l^{-1} when open have been proposed to limit nuisance level production of the opportunistic macroalga *Ulva* sp. (Plew and Barr 2015).

4. Results and Discussion (Continued)

RESULTS

Water Column Stratification

Salinity measurements showed that on 14 February 2018, all estuary transects (A to L) were freshwater-dominated (salinity range: 0.1 - 0.4 ppt) and non-stratified during low flow and high tide conditions (Figure 3, Table 3). Comparisons with baseline results when stratification was present in the estuary, suggested that saline intrusion into the estuary now likely extends for a shorter length than in previous years when the mouth was located further to the west. This lessened salinity intrusion has likely manifested for some time given the predominance of freshwater aquatic plant life in the mid-upper estuary (further discussed in Section 4.2 of this report). Water temperature (range: 18.1-22.8 °C) was also similar throughout the estuary, and there was negligible difference between surface and bottom temperatures (Table 3).

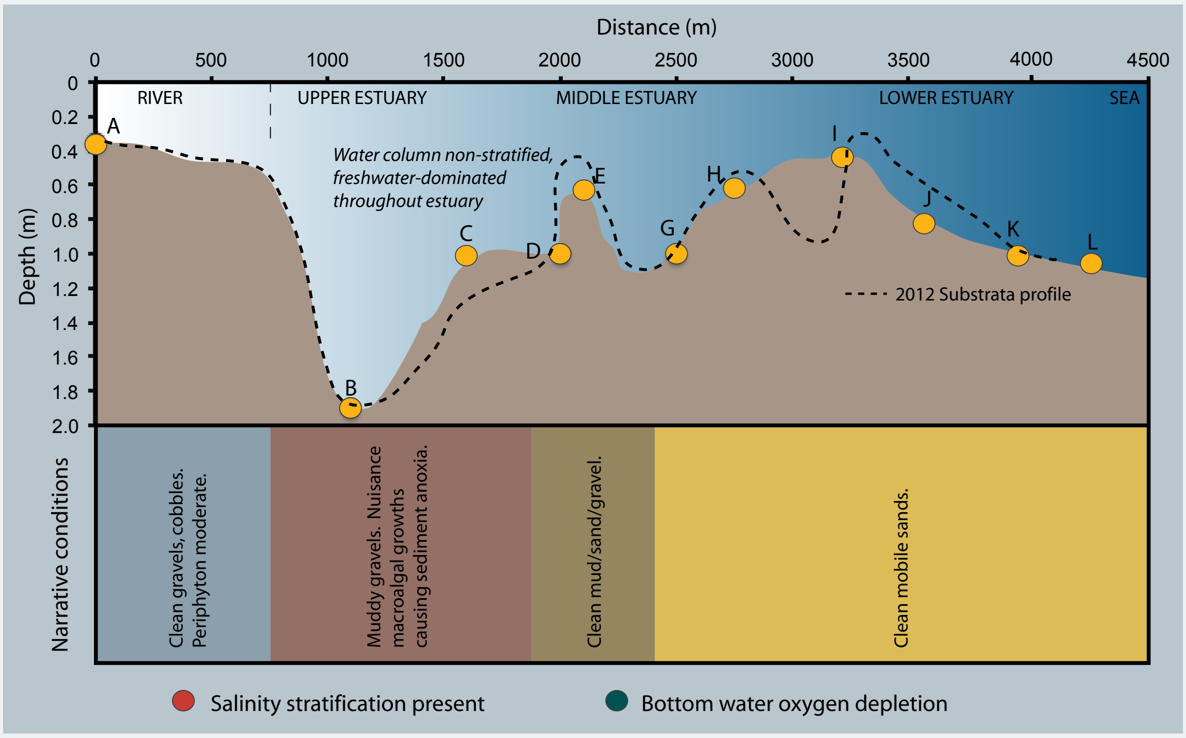


Figure 3. Longitudinal profile (river to sea) of maximum water depth (at high water) and substrate type, 14 February 2018. 2012 substrata profile superimposed to allow for temporal comparison.

4. Results and Discussion (Continued)

Susceptibility to eutrophication based on water column TN, DIN, TP, chlorophyll *a* and dissolved oxygen concentrations

Total nitrogen (TN), dissolved inorganic nitrogen (DIN) and total phosphorus (TP) concentrations in both the surface and bottom waters at all three middle estuary sites exceeded the eutrophication threshold levels of 0.4 mg TN l^{-1} and 0.096 mg DIN l^{-1}, and 0.025 mg P l^{-1} for all samples (Figure 4 overleaf). These plots show that bottom water TP concentrations subtly increased with distance inland, but otherwise middle estuary nutrient concentrations were relatively similar across sites.

Despite the above threshold TN, DIN and TP concentrations in surface and bottom waters, chlorophyll *a* concentrations were low* in these same waters across all three sites (<10 µg l^{-1}) (Figure 5). The likely explanation for this difference is that on the day of sampling in 2018 the water and associated nutrients and phytoplankton were being flushed from the estuary at such a rate that phytoplankton production (i.e. chlorophyll *a*) was limited to the low levels measured. The same sites had supersaturated dissolved oxygen concentrations in bottom water during daylight (>10 mg DO l^{-1}) (Figure 5), mostly likely associated with macrophyte photosynthesis, and indicating a potential for depression to low levels during the night. Taken together, these results indicate a low expression of eutrophication symptoms in the water column habitat (e.g. high chlorophyll *a* concentrations) on the day of sampling.

However, a note of caution is required when extrapolating data for one discrete sampling event (i.e. the 2018 results) into the likely situation for other times of the year. In particular, if the flow at the estuary mouth becomes constricted, high salinity bottom water could become trapped and result in ideal conditions for prolonged periods of bottom water eutrophication.

*** The NZ ETI threshold for chlorophyll *a* (the primary indicator of water column eutrophication) is expressed as the 90th percentile of monthly measures collected during the growing season, and for dissolved oxygen (the main eutrophication supporting indicator), a 7 day mean. Consequently the one-off measures collected on 14 February 2018 can only be used as an indication of current condition.**

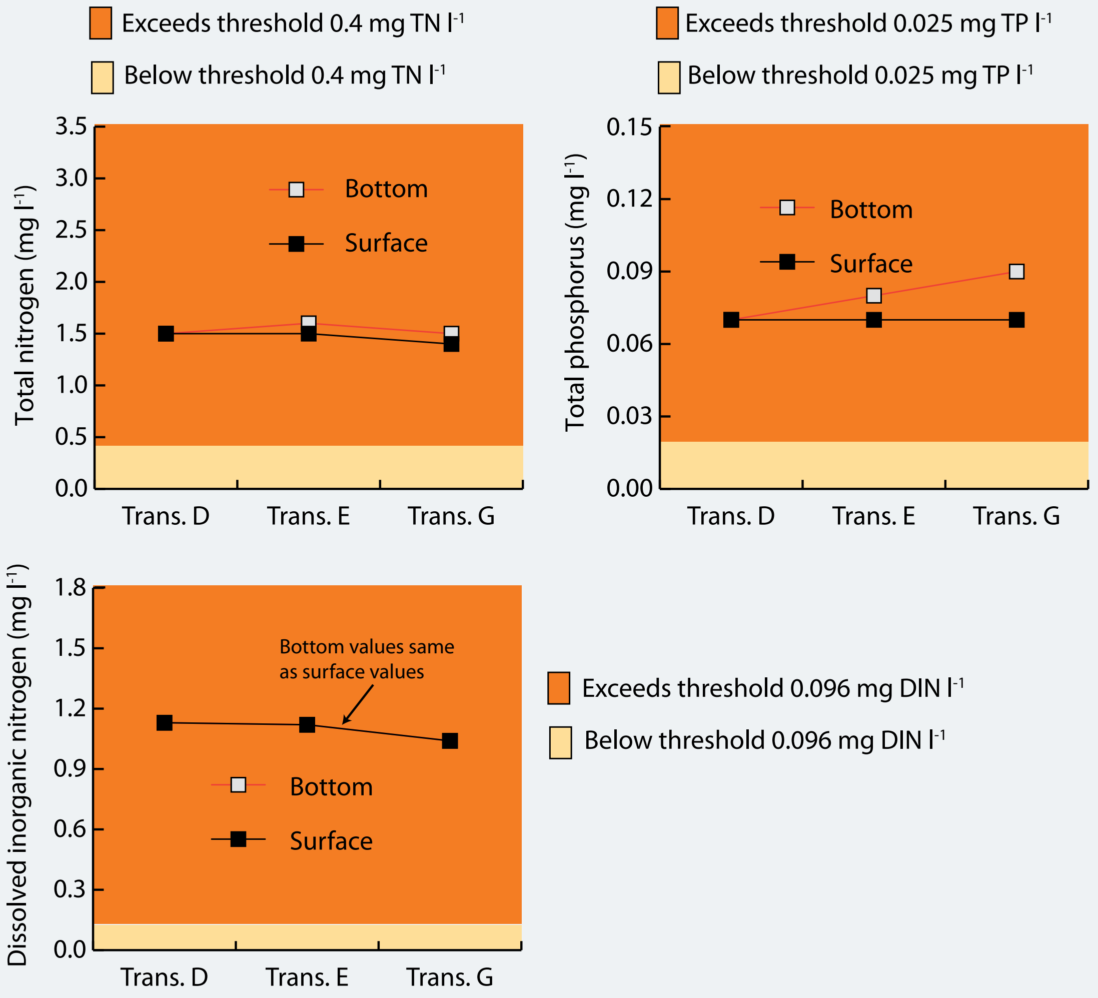


Figure 4. Total nitrogen, dissolved inorganic nitrogen and total phosphorus concentrations in surface and bottom water (*n* = 1) at three mid-estuary channel sites, Waimatuku Estuary, 14 February 2018.

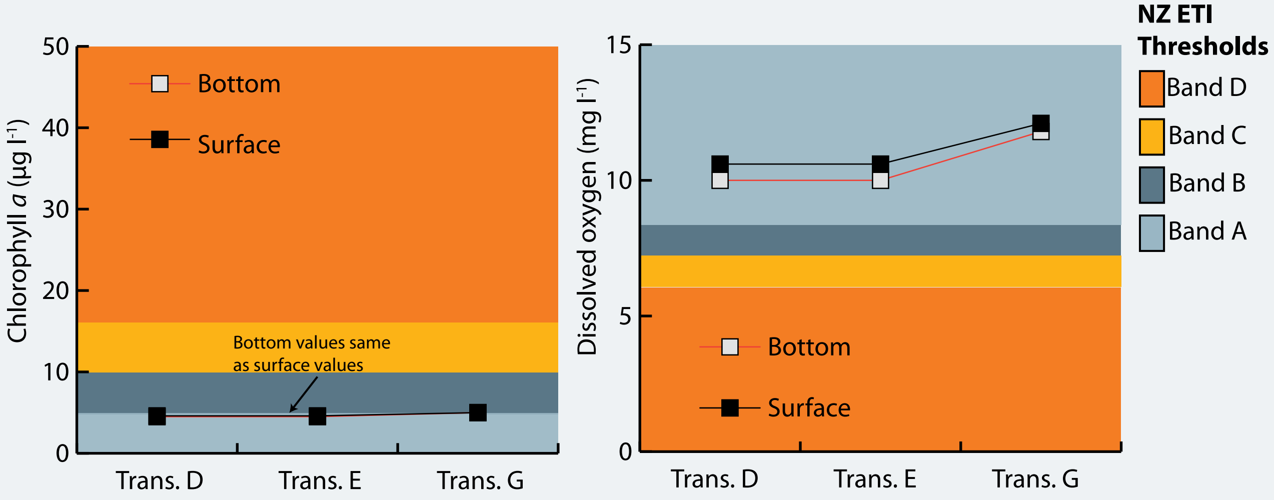


Figure 5. Chlorophyll *a* and dissolved oxygen concentrations in surface and bottom water (*n* = 1) at three subtidal channel sites, Waimatuku Estuary, 14 February 2018.

4.2 BENTHIC SUBTIDAL HABITAT CONDITION

4.2.1 SEDIMENTATION

Where sediment contribution from the catchment exceeds the assimilative capacity of an estuary, adverse estuary impacts are expected. Multiple studies have shown estuarine biological communities to be adversely affected by mud accumulation, both through direct and indirect mechanisms including: declining sediment oxygenation, smothering, and compromisation of feeding habits (e.g. see Mannino and Montagna 1997; Rakocinski et al. 1997; Peeters et al. 2000; Norkko et al. 2002; Ellis et al. 2002; Thrush et al. 2003; Lohrer et al. 2004; Sakamaki and Nishimura 2009; Wehkamp and Fischer 2012; Robertson 2013; Robertson et al. 2015, 2016; B.P Robertson 2018 - PhD thesis in press).

Because of such consequences, three key measures are commonly used to assess muddiness problems:

i. **Horizontal extent** (area of soft mud) - broad scale indicator (see rating in Table 2);
ii. **Vertical buildup** (sedimentation rate) - fine scale assessment using sediment plates (or retrospectively through historical coring). Ratings are currently under development as part of national ANZECC guidelines;
iii. **Sediment mud content** - fine scale indicator - recommended guideline is no increase from established baseline. This measure was used to assess muddiness issues in the present report as follows:

Sediment Mud Content

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

Results showed the Waimatuku Estuary middle Transect Sites (D, E and G) in 2018 had low (7.4-11 %) sediment mud contents (Table 3, Figure 6), a risk rating of LOW, and indicated minimal change in mud content over time when proximate transect sites from 2018 were combined (*n* = 3) and compared to baseline levels (ANOVA $p > 0.05$; Appendix 4). The overall low mud content in the middle estuary, where mud deposition is expected to be encouraged, indicates excessive benthic muddiness in Waimatuku Estuary is not a significant ecological issue.

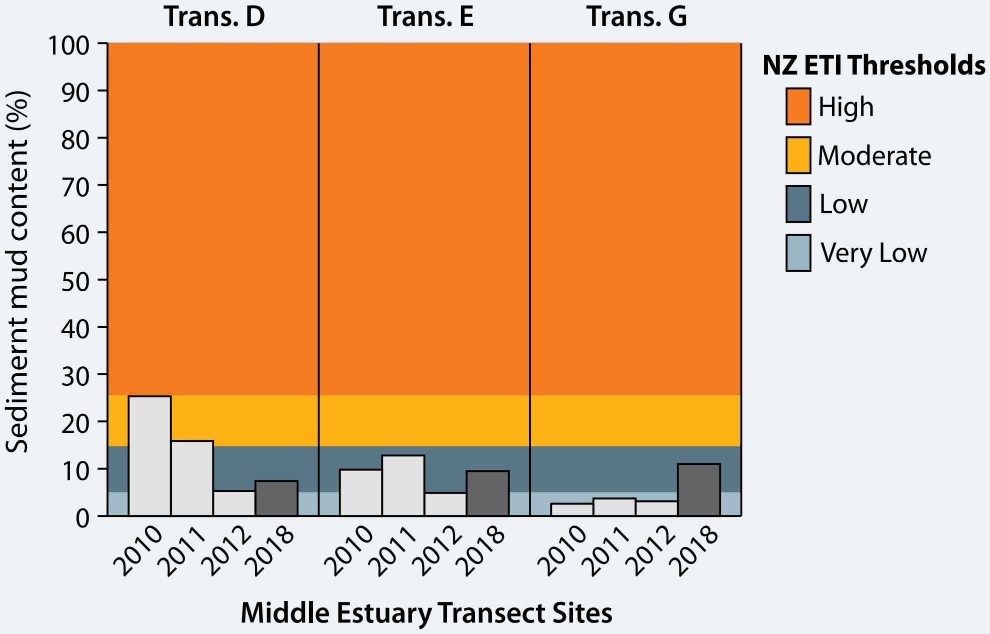


Figure 6. Sediment mud content at three proximate mid-estuary transect stations (composite sample, *n* = 1), Waimatuku Estuary, Feb 2010, 2011, Jan 2012 and Feb 2018.

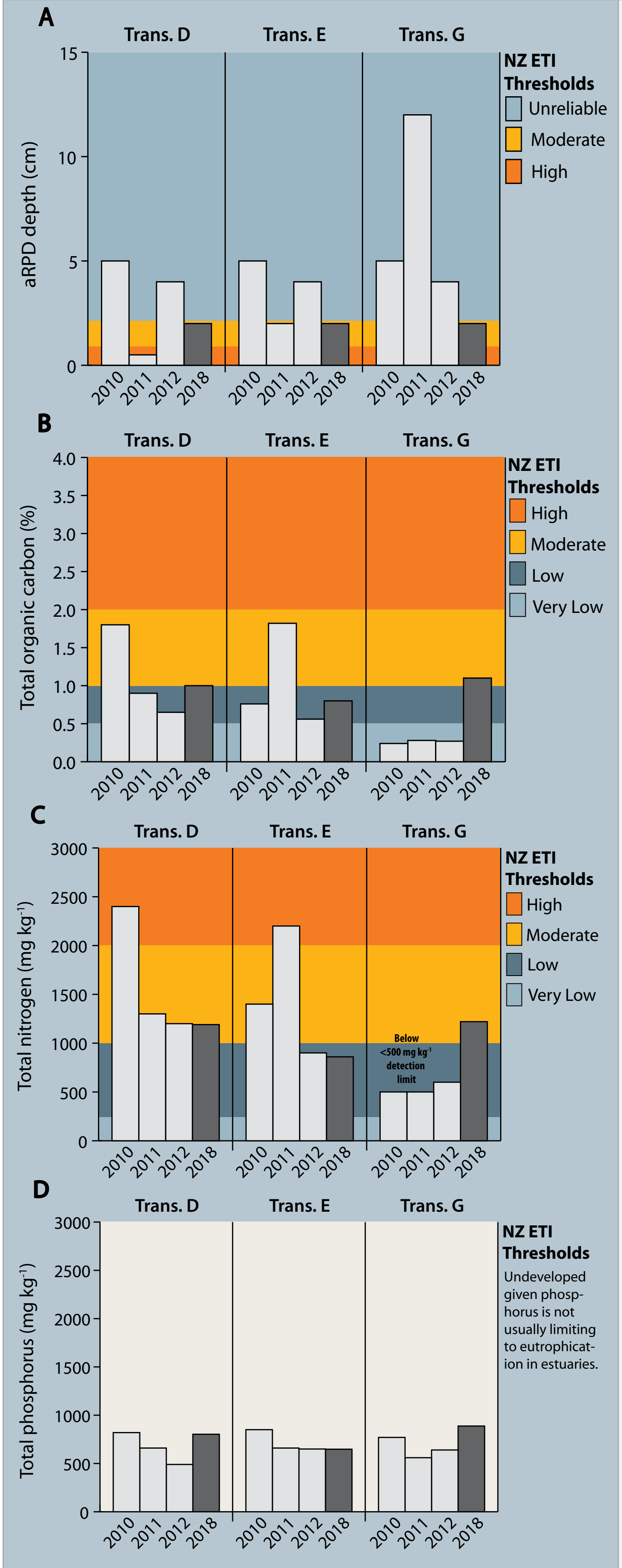


Figure 7. Sediment apparent Redox Potential Discontinuity (aRPD) (A), total organic carbon (B), total nitrogen (C), and total phosphorus (D) at three proximate mid-estuary transect stations (composite sample, $n = 1$), Waimatuku Estuary, Feb 2010, 2011, Jan 2012 and Feb 2018.

4.2.2 EUTROPHICATION

Excessive organic input, either from external sources or growing within the estuary in response to high nutrient loads, is a principal cause of physical and chemical degradation and associated biological change in estuarine environments. In tidal river estuaries, the sediments become deoxygenated, nuisance algal growth becomes abundant and the number of suspension-feeders (e.g. bivalves and certain polychaetes) declines and deposit-feeders (e.g. opportunistic polychaetes) increase as organic input to the sediment increases (Pearson and Rosenberg 1978). The primary variables indicating benthic eutrophication impacts are sediment mud content (discussed in the previous sediment section and is not repeated here), oxygenation (aRPD depth), and organic carbon, nitrogen and phosphorus concentrations, and aquatic plant and algal growth.

Apparent Redox Potential Discontinuity (aRPD) The depth of the aRPD zone provides a coarse indication of the level of sediment oxygenation. The results (Figure 7A, Table 3), showed that the 2018 aRPD depth at the Waimatuku sites was ~1-3 cm at all sites, and therefore the sediments in the mid-estuary were likely to be moderately oxygenated. Although variable through time, there was no significant difference between 2018 aRPD ratings and those measured in previous baseline years (ANOVA $p > 0.05$; Appendix 4). Such temporal variability in aRPD values indicate the changeable conditions often experienced in tidal river estuaries where both river flow and tidal intrusion have a major influence on estuary condition. As a result, the benthic community in the middle estuary was likely to be transitional and dominated by organisms and plants tolerant of moderate organic enrichment.

Total Organic Carbon and Nutrients

The concentrations of sediment organic matter (TOC) and nutrients (TN and TP) provide valuable trophic state information. In particular, if concentrations are elevated and eutrophication symptoms are present [i.e. shallow RPD, excessive algal growth, high NZ AMBI biotic coefficient], then elevated TN, TP and TOC concentrations provide strong supporting information to indicate that their respective loadings are exceeding the assimilative capacity of the estuary.

The 2018 results for the three mid-estuary sites showed TOC (0.8-1.1 %) and TN (860-1220 mg kg^{-1}) were in the "low" to "moderate" risk indicator ratings, with TP (rating not yet developed) at relatively moderate levels at each site (648-888 mg kg^{-1}) (Figure 7B, C and D, Table 3). Again, these results indicate minimal change occurred in terms of TOC, TN and TP levels in that part of the estuary between 2018 and baseline years (ANOVA $p >$ 0.05; Appendix 4).

Aquatic Macrophyte and Macroalgal Cover

Based on representative benthic sampling at each transect site on 14 February 2018, as in baseline years (including 2009), the lower Waimatuku Stream and the upper-middle Waimatuku Estuary supported growths of rooted aquatic macrophytes (Figure 8). *Ranunculus trichophyllus* (water buttercup, see Figure 9) was relatively abundant (20 % cover) in the clear, 0-0.5 m deep, flowing freshwater of the lower Waimatuku Stream Site A, growing in 1 m long strands in the filamentous algal-dominated gravel bed, while *Mimulus guttatus* (monkey musk) was common along the margins.

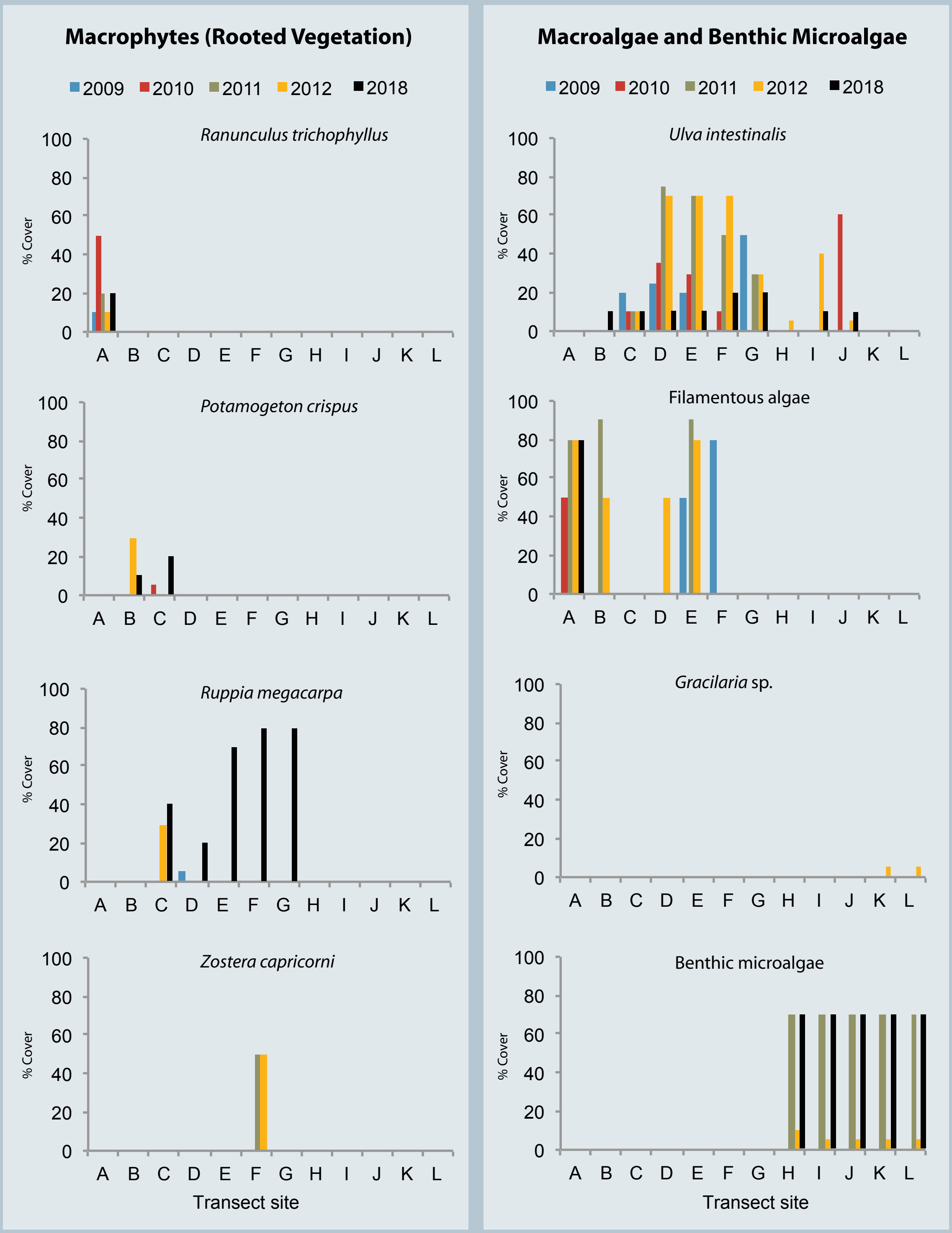


Figure 8. Percent cover of aquatic vegetation at 12 discrete Waimatuku estuary transects 2009-2012 and 2018.

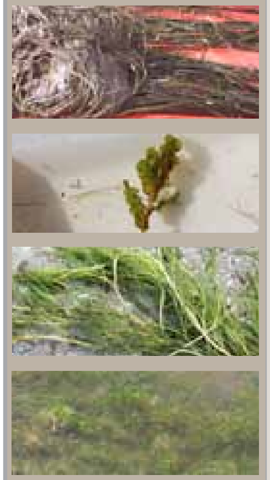
4. Results and Discussion (Continued)

In the upper-middle estuary, the native seagrass *Ruppia megacarpa* (horse's mane weed - Figure 8) and introduced *Potamogeton crispus* (pondweed) were the dominant plants (Figure 8).

Ruppia was present throughout the upper and middle estuary as occasional dense patches in the 0-1 m depth range, indicating expansion into middle estuary sites (D, E, F and G) since 2012. This expansion is likely to continue given what occurs in similar situations (e.g. Wilson Inlet, an Australian ICOLL type estuary; Boardman 1994). That is, brackish conditions favour germination and once established abundant and potentially nuisance growths occur favoured by low turbidity and elevated external nutrient levels. In some situations (e.g. Waiau Lagoon, Southland) other brackish tolerant macrophytes can also become highly abundant (e.g. *P. crispus*). *P. crispus*, present at 0-1 m depths (10-20 % cover at Sites B and C), was also highly abundant (80-100 % cover) in upper-middle Waimatuku Estuary margins (i.e. adjacent to discrete monitoring sites) where it was often associated with surface growths of *Azolla* sp. (5 % cover) and the nuisance macroalgae *Ulva intestinalis* (60-70 % cover) (see top photo overleaf). It is important to note that while rooted macrophytes are highly beneficial at low-moderate densities (i.e. through stabilising/oxygenating sediments, providing food and habitat for other biota, buffering catchment nutrients, limiting production of ecologically less functional algae), nuisance-level growth can result in negative impacts on the amenity of the estuary (i.e. primarily through reduced oxygenation of sediments and overlying waters driven by plant respiration and/or decomposition processes, and limiting boat use through motor snagging) (Boardman 1994). Seagrass (*Zostera capricornia*) was not observed in the estuary in 2018 (Figure 8).

The lower estuary remained predominantly unvegetated (apart from occasional patches of *U. intestinalis* present in the channel at sites I and J), but supported a film of microalgae (taxa unknown) on the shallow subtidal sediment surface, which was also present in 2011 and 2012 (Figure 11). The observed temporal variability in benthic microalgal coverage between 2011 and 2018 may have been attributable to differences in grazing pressure, light levels, salinity regimes and/or flushing. Dead macrophyte (taxa unknown) beds underlain by locally anoxic surface sediments were observed at sand-dominated Sites I and J (see bottom left photo overleaf). Reasons for this die-off are unknown but may include exposure to elevated toxic compounds (e.g. sulphides), unfavourable salinity regimes, reduced clarity, stem breakage in high flows, and/or smothering by nuisance macroalgae (i.e. *U. intestinalis* was present as mats among growing *Ruppia* and *P. crispus* beds in the upper-mid estuary, and on sediments among the dead macrophyte beds in the lower estuary).

Figure 9. Dominant macrophytes and macroalgae, Waimatuku Estuary.



***Ruppia megacarpa* (Horse's mane weed)** is a native surface-flowering submerged aquatic annual or perennial; stems 20-30 cm long and are often zigzag in form. Grows in fresh to hypersaline coastal lakes, lagoons and estuaries and is relatively common in the 0-1.5m depth range (depending on water clarity). Water quality parameters, primarily salinity and clarity, are major determinants of the plant's distribution. Early stage growth requires a low salinity environment, but with age the plants become more tolerant of higher salinities.

***Potamogeton crispus* (Curly pondweed)** is an introduced species that is tolerant of slightly brackish as well as freshwater. It can survive in low light and low temperatures, and prefers high nutrient water. It spreads mostly by means of vegetative buds (turions) that germinate in autumn, grow vigorously in spring, and die off in the summer. The decaying plant matter can make the water extremely enriched, encourage nuisance algal mats near the sediment surface, inhibit the growth of native aquatics, and can interfere with boating and other water recreation. These plants germinate in autumn, grow vigorously in spring, and die off in the summer.

***Ranunculus trichophyllus* (Water buttercup)** is an introduced species common in freshwater and slightly saline waterbodies. Stems are up to 2m long, leaves are narrow and bright green. Flowers are white with a yellow centre.

***Ulva intestinalis*,** a nuisance green macroalgae, is found worldwide, and can grow to nuisance proportions in nutrient enriched estuaries, coastal lagoons and embayments. It can cause sediment deterioration, oxygen depletion, bad odours and have adverse impacts to biota.

***Potamogeton crispus* beds in upper estuary channel**

Figure 10. Examples of thick *Potamogeton crispus* beds associated with *Azolla* sp. and *Ulva intestinalis* in middle estuary margins (top), *Ruppia megacarpa* from the middle estuary channel (middle left), and decomposing macrophyte beds underlain by locally anoxic sands (bottom left) and benthic microalgae on sands (right) in the lower Waimatuku Estuary, 14 February 2018.

5. SUMMARY AND CONCLUSIONS

Synoptic fine scale and macrophyte monitoring undertaken on 14 February 2018, combined with ecological risk indicator ratings in relation to the key estuary stressors (i.e. sedimentation and eutrophication) have been used to assess condition of the Waimatuku Estuary. The overall key findings were as follows:

Sedimentation (muddiness)

Sediments were in relatively good condition with limited accumulation of muds and generally good sediment oxygenation in the middle-lower channel, but were in poorer condition (elevated muds and poorly oxygenated) at monitoring sites located in the upper channel. Mud contents measured at three subtidal channel sites chosen to represent the main middle estuary benthic habitat were low. Ecologically, the low mud content at these sites indicates a *'minor stress on sensitive organisms, especially if nutrient loads are elevated'* (Robertson et al. 2016b) for that part of the estuary. Overall, the findings indicate excessive deposition of muds in Waimatuku Estuary is currently only a problem in the deeper, less well flushed upper estuary where substrata were dominated by muds.

Eutrophication

The NZ Estuary Trophic Index tool (NZ ETI; Robertson et al. 2016a,b) combines a range of broad and fine scale indicators to provide an overall assessment of eutrophic expression in an estuary, including primary productivity through macroalgal growth and phytoplankton, and supporting indicators of sediment muddiness, oxygenation, organic content, nutrients, macroinvertebrates, and the presence of gross eutrophic zones (a combined presence of dense macroalgal growth, muds and poor sediment oxygenation). The ETI score is largely driven by nuisance-level macroalgae (and associated benthic degradation) occurring over >10 % of the estuary area. Although it is invalid to give an ETI score for the primary reason that the macroalgal component currently cannot be applied in subtidal situations, the presence of eutrophic symptoms in the upper-mid Waimatuku Estuary in February 2018 indicated that this threshold was exceeded for subtidal benthic macroalgae and sediment oxygenation in the mid-upper estuary. However, the water quality results for the surface and bottom waters, indicate little evidence of eutrophication symptoms in the overyling water column habitat, despite the presence of above threshold nutrient concentrations, as indicated by the following:

- An absence of poorly flushed stratified areas containing isolated bottom water where nutrient concentrations can build-up.
- Chlorophyll a concentrations, the primary indicator of water column eutrophication, were all less than the NZ ETI eutrophication threshold level.
- Dissolved oxygen concentrations, the main supporting indicator of water column eutrophication, although supersaturated during daylight (i.e. as a function of macrophyte abundance), did not breach the threshold for eutrophic conditions.

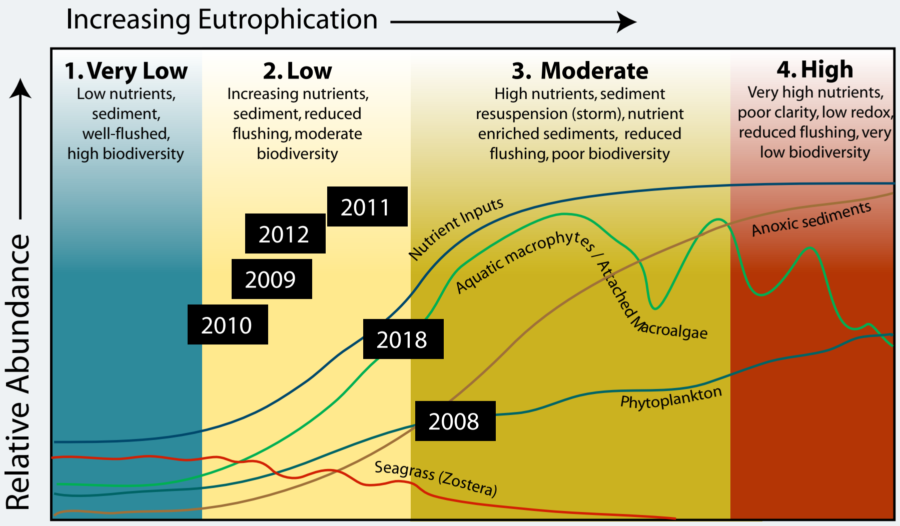
Taken as a whole, the available data indicates that on the day of sampling, elevated nutrients in the estuary were responsible for high levels of attached macrophyte/macroalgal production, but because of the short residence time for phytoplankton in the estuary (i.e. the estuary is well-flushed), localised phytoplankton blooms were absent from the water column habitat. However, given only one comprehensive sampling event and the possibility of stratification occurring at other times during the growing season, there is a possibility that stratified bottom water phytoplankton blooms could occur, particularly if the flow at the estuary mouth becomes further constricted.

5. Summary and Conclusions (Continued)

Comparison with baseline results

Statistical comparison of the baseline (2010-2012) and 2018 results was possible for some indicators. Comparisons show that baseline benthic results were similar to those from nearby middle estuary sites in 2018, indicating that part of the estuary has not changed significantly in terms of sediment mud, TOC, TN and TP concentrations in the past decade. Shallow estuarine waters, often stratified (even at low tide) during baseline years, were highly brackish and non-stratified in 2018. Macroalgae was present throughout the mid-upper estuary but had reduced in extent since baseline years, with rooted macrophytes characterising a much greater extent of estuary area. This reduction in macroalgal coverage may reflect the increased cover of low salinity tolerant rooted macrophytes, which very effectively utilise surrounding nutrients, thereby preventing algal growth in the estuary. Seagrass (*Zostera capricornia*), present in 2011 and 2012, was not observed in the estuary in 2018. Intertidal and subtidal flats in lower estuary supported a benthic microalgal film also evident in 2011 and 2012.

In overview, the combined 2018 synoptic survey results place the Waimatuku Estuary in a low-moderate state overall in relation to subtidal channel condition and trophic status, indicating conditions have deteriorated slightly since 2012 (Figure 11). Given its above threshold catchment nutrient load coupled with potential further eastward mouth migration and consequent constriction, eutrophication (presently expressed as nuisance macroalgal production and reduced sediment oxygenation in the upper-middle estuary) and to a lesser extent sedimentation are expected to be ongoing issues in the estuary. In addition, while the presence of high levels of macrophyte growth has some negative consequences for the estuary's amenity (i.e. reduced oxygenation of sediment and overlying waters driven by respiration and/or decomposition processes, fouling shorelines and snagging boats and fishing gear), these are almost certainly outweighed by positive aspects of its presence (i.e. through stabilising/oxygenating sediments, providing food and habitat for other biota, buffering catchment nutrients and sediments, limiting production of ecologically less functional algae). Management actions should therefore consider the positive utility of the macrophytes as well as the potential problems they cause.



Conceptual representation of response of tidal river estuary with constricted mouth to increased nurients. 2018 trophic status had deteriorated slightly since 2012, but remained within the range of previous monitoring years.

Figure 11. Waimatuku Estuary - subtidal channel condition and trophic state (2008, 2008, 2010, 2011, 2012 and 2018).

6. MONITORING AND MANAGEMENT

Waimatuku Estuary has been identified by ES as a priority for monitoring, and is a key part of ES's coastal monitoring programme. Based on the current monitoring results and those reported previously (Robertson and Stevens 2008, 2009; Stevens and Robertson 2010, 2011, 2012), it is recommended that monitoring continues as outlined below:

1. Continue synoptic monitoring once every 5 years (next scheduled for February 2023) as follows:
   - Aquatic macrophyte and macroalgal presence, location, accurate % cover and life stage throughout the estuary including discrete sampling at established transect sites.
   - Water quality (e.g. chlorophyll *a*, DO, salinity, depth and clarity) at all twelve established transect sites, plus TN, DIN, TP concentrations at three fine scale sites.
   - Sediment quality (redox conditions, grain size, total nitrogen, total phosphorus and total organic carbon).

   Because current fine scale Sites D, E and G only represent the middle estuary, it is recommended that future fine scale monitoring instead be undertaken at upper, mid and lower estuary Sites C, E and J.
2. To more defensibly characterise the extent of eutrophication and to a lesser extent sedimentation issues, as well as confirm the estuary has not changed its risk rating during interim years, it is recommended that cost effective indicator monitoring be undertaken annually (next scheduled for February 2019) as follows: RPD (via ORP probe), water column chlorophyll *a*, DO, salinity, clarity, substrata type and vegetative % cover at Transects C, E and J combined with a coarse assessment of vegetative cover elsewhere in the estuary.
3. Undertake broad scale habitat mapping every 5 years. Although overdue (last scheduled for summer 2013), it is recommened this component be next undertaken to coincide and therefore bolster the synoptic monitoring component (as outlined in 1. above). Note undertaking this component would also allow for full application of the NZ ETI.

In terms of management, the 2018 synoptic survey results underscore the need to manage nutrient and to a lesser extent fine sediment sources entering the estuary from the catchment. This typically involves the following key steps:

- Develop and assign catchment nutrient and sediment input guideline criteria to Waimatuku Estuary based on available catchment input/ecological response information from other relevant estuaries.
- Estimate catchment nutrient and suspended sediment inputs using available catchment models and stream monitoring data.
- Determine the extent to which the estuary meets guideline catchment input criteria.
- Develop management and/or restoration plans for the estuary as appropriate.

7. ACKNOWLEDGEMENTS

This survey and report has been undertaken with the help and support of Nick Ward and Keryn Roberts (Coastal Scientists, Environment Southland). Their review of this report was much appreciated. We are also very grateful to Jodie Robertson (Robertson Environmental) for help with the field sampling, aquatic plant identification and report preparation.

8. REFERENCES

Atkinson, I.A.E. 1985. Derivation of vegetation mapping units for an ecological survey of Tongariro National Park Nth Island, NZ. NZ Journal of Botany, 23; 361-378.

Boardman, B. 1994. Ruppia in Wilson Inlet. Report to the community - Department of Environment. p12.

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

Davey, A. 2009. Confidence of Class for WFD Marine Plant Tools. WRC report EA7954. 34pp.

Ellis, J., Cummings, V., Hewitt, J., Thrush, S., Norkko, A. 2002. Determining effects of suspended sediment on condition of a suspension feeding bivalve (Atrina zelandica): results of a survey, a laboratory experiment and a field transplant experiment. Journal of Experimental Marine Biology and Ecology, 267, 147–174.

8. References (Continued)

Fenchel, T. and Riedl, R. 1970. The sulphide system: a new biotic community underneath the oxidized layer of marine sand bottoms. Mar Biol 7: 255-268.

Hargrave, B.T., Holmer, M. and Newcombe, C.P. 2008. Towards a classification of organic enrichment in marine sediments based on biogeochemical indicators. Marine Pollution Bulletin, 56(5), pp.810–824.

Hunting, E.R. and Kampfraath, A.A. 2012. Contribution of bacteria to redox potential (E h) measurements in sediments. International Journal of Environmental Science and Technology, 10(1): 55-62.

Jørgensen, N. and Revsbech, N.P. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnology and Oceanography 30:111-122.

Keeley, N.B. et al. 2012. Exploiting salmon farm benthic enrichment gradients to evaluate the regional performance of biotic indices and environmental indicators. Ecological Indicators, 23, pp.453–466.

Lohrer, A., Thrush, S., Hewitt, J., Berkenbusch, K., Ahrens, M., Cummings, V. 2004. Terrestrially derived sediment: response of marine macrobenthic communities to thin terrigenous deposits. Marine Ecology Progress Series, 273, 121–138.

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

Robertson, B.M., Robertson, B.P., and Stevens, L.M. 2017. Waikawa Estuary: Fine Scale Monitoring 2016/17. Report prepared by Wriggle Coastal Management for Otago Regional Council. 31p.

Robertson, B.M., Stevens, L., Robertson, B.P., Zeldis, J., Green, M., Madarasz-Smith, A., Plew, D., Storey, R., Hume, T. and Oliver, M. 2016a. NZ Estuary Trophic Index. Screening Tool 1. Determining eutrophication susceptibility using physical and nutrient load data. Prepared for Envirolink Tools Project: Estuarine Trophic Index MBIE/NIWA Contract No: C01X1420. 47p.

Robertson, B.M., Stevens, L., Robertson, B.P., Zeldis, J., Green, M., Madarasz-Smith, A., Plew, D., Storey, R., Hume, T. and Oliver, M. 2016b. NZ Estuary Trophic Index. Screening Tool 2. Screening Tool 2. Determining Monitoring Indicators and Assessing Estuary Trophic State. Prepared for Envirolink Tools Project: Estuarine Trophic Index MBIE/NIWA Contract No: C01X1420. 68p.

Robertson, B. and Stevens, L. 2016. Manawatu-Wanganui Estuaries. Habitat Mapping, Vulnerability Assessment and Monitoring Recommendations Related to Issues of Eutrophication and Sedimentation. Prepared for Envirolink Medium Advice Grant: 1624-HZLC127 Assessment of the susceptibility of Horizons' estuaries to nutrient enrichment and sedimentation. MBIE/NIWA Contract No:CO1X1513. 102pp + appendices.

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

Robertson, B.M. and Stevens, L. 2009. Waimatuku Estuary 2009 Synoptic Survey, Macrophyte Mapping and Vulnerability Assessment. Report prepared by Wriggle Coastal Management for Environment Southland. 20p.

Robertson, B.M. and Stevens, L. 2008. Southland Coast - Te Waewae Bay to the Catlins, habitat mapping, risk assessment and monitoring recommendations. Report prepared for Environment Southland. 165p.

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

Robertson, B.P., Gardner, J.P.A., Savage, C., Roberston, B.M. and Stevens, L.M. 2016. Optimising a widely-used coastal health index through quantitative ecological group classifications and associated thresholds. Ecological Indicators. 69. 595-605.

Robertson, B.P., Gardner, J.P.A. and Savage, C. 2015. Macrobenthic - mud relations strengthen the foundation for benthic index development : A case study from shallow, temperate New Zealand estuaries. Ecological Indicators, 58, pp.161–174. Available at: http://dx.doi.org/10.1016/j.ecolind.2015.05.039.

Robertson, B.P. 2013. Determining the sensitivity of macroinvertebrates to fine sediments in representative New Zealand estuaries. Honours dissertation, Victoria University of Wellington.

Robertson, B.P., Gardner, J.P.A. and Savage, C.S. 2015. Macrobenthic - mud relations strengthen the foundation for benthic index development : A case study from shallow, temperate New Zealand estuaries. Ecological Indicators, 58, pp.161–174. Available at: http://dx.doi.org/10.1016/j.ecolind.2015.05.039.

Robertson, B.P., Gardner, J.P.A., Savage, C.S., Roberston, B.M. and Stevens, L.M. 2016. Optimising a widely-used coastal health index through quantitative ecological group classifications and associated thresholds. Ecological Indicators, 69, 595-605.

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

Sakamaki ,T., Nishimura, O. 2009. Is sediment mud content a significant predictor of macrobenthos abundance in low-mud-content tidal flats? Marine and Freshwater Research, 60, 160.

Stevens, L.M. and Robertson, B.M. 2011. Waimatuku Estuary 2011. Fine Scale Monitoring and Macrophyte Mapping. Report prepared by Wriggle Coastal Management for Environment Southland. 14p.

Stevens, L.M. and Robertson, B.M. 2010. Waimatuku Estuary 2010. Fine Scale Monitoring and Macrophyte Mapping. Report prepared by Wriggle Coastal Management for Environment Southland. 13p.

8. References (Continued)

Stevens, L.M. and Robertson, B.M. 2012. Waimatuku Estuary 2011. Fine Scale Monitoring and Macrophyte Mapping. Report prepared by Wriggle Coastal Management for Environment Southland. 16p.

Thrush, S.F., Hewitt, J., Norkko, A., Nicholls, P., Funnell, G. and Ellis, J. 2003. Habitat change in estuaries: predicting broad-scale responses of intertidal macrofauna to sediment mud content. Marine Ecology Progress Series 263, 101–112.

Wehkamp, S., Fischer, P. 2012. Impact of hard-bottom substrata on the small-scale distribution of fish and decapods in shallow subtidal temperate waters. Helgoland Marine Research, 67, 59–72.

WFD-UKTAG (Water Framework Directive – United Kingdom Technical Advisory Group). (2014). UKTAG Transitional and Coastal Water Assessment Method Macroalgae Opportunistic Macroalgal Blooming Tool. Retrieved from http://www.wfduk.org/sites/default/files/Media/Characterisation of the water environment/Biological Method Statements/TraC Macroalgae OMBT UKTAG Method Statement.PDF.

References for Table 1

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

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

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

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

Hsieh, Ying-Hsin, and Irshad M Sulaiman. 2018. Chapter 5 - Campylobacteriosis: An Emerging Infectious Foodborne Disease. In Handbook of Food Bioengineering, ed. Alina Maria Holban and Alexandru Mihai B. T. Foodborne Diseases Grumezescu, 119–155. Academic Press. doi:https://doi.org/10.1016/B978-0-12-811444-5.00005-1.

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

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

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

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

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

Robertson, B.M. and Stevens, L.M. 2007. Waikawa Estuary 2007 Fine Scale Monitoring and Historical Sediment Coring. Prepared for Environment Southland. 29p.

Robertson, B.M. and Stevens, L.M. 2010. New River Estuary: Fine Scale Monitoring 2009/10. Report prepared by Wriggle Coastal Management for Environment Southland. 35p.

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

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

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

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

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

APPENDIX 1. DETAILS ON ANALYTICAL METHODS

Sediment Indicator	Laboratory	Method	Detection Limit
Grain Size	R.J Hill	Wet sieving, gravimetric (calculation by difference).	0.1 g 100^{-g} dry wgt
Total Organic Carbon	R.J Hill	Catalytic combustion, separation, thermal conductivity detector (Elementary Analyser).	0.05g 100^{-g} dry wgt
Total recoverable phosphorus	R.J Hill	Nitric/hydrochloric acid digestion, ICP-MS (low level) USEPA 200.2.	40 mg kg^{-1} dry wgt
Total nitrogen	R.J Hill	Catalytic combustion, separation, thermal conductivity detector (Elementary Analyser).	500 mg kg^{-1} dry wgt
Dry Matter (Env)	R.J. Hill	Dried at 103 °C (removes 3-5 % more water than air dry)	

Water Quality Indicator	Laboratory	Method	Detection Limit
Filtration, Unpreserved	R.J Hill	Sample filtration through 0.45 µm membrane filter.	-
Total Kjeldahl Digestion	R.J Hill	Sulphuric acid digestion with copper sulphate catalyst.	-
Total Phosphorus Digestion	R.J Hill	Acid persulphate digestion.	-
Total Nitrogen	R.J Hill	Calculation: TKN + Nitrate-N + Nitrite-N. Please note: Default Detection Limit of 0.05 g m^{-3} is only attainable when the TKN has been determined using a trace method utilising duplicate analyses. In cases where the Detection Limit for TKN is 0.10 g m^{-3}, the Default Detection Limit for Total Nitrogen will be 0.11 g m^{-3}.	0.05 g m^{-3}
Total Ammoniacal-N	R.J Hill	Saline, filtered sample. Phenol/hypochlorite colorimetry. Discrete Analyser. (NH4-N = NH4+-N + NH3-N). APHA 4500- NH3 F (modified from manual analysis) 22nd ed. 2012.	0.010 g m^{-3}
Nitrite-N	R.J Hill	Saline sample. Automated Azo dye colorimetry, Flow injection analyser. APHA 4500-NO3- I 22nd ed. 2012 (modified).	0.002 g m^{-3}
Nitrate-N	R.J Hill	Calculation: (Nitrate-N + Nitrite-N) - NO2N. In-House.	0.0010 g m^{-3}
Nitrate-N + Nitrite-N	R.J Hill	Saline sample. Total oxidised nitrogen. Automated cadmium reduction, Flow injection analyser. APHA 4500-NO3- I 22nd ed. 2012 (modified).	0.002 g m^{-3}
Total Kjeldahl Nitrogen (TKN)	R.J Hill	Total Kjeldahl digestion, phenol/hypochlorite colorimetry. Discrete Analyser. APHA 4500-Norg D. (modified) 4500 NH3 F (modified) 22nd ed. 2012.	0.10 g m^{-3}
Dissolved Reactive Phosphorus	R.J Hill	Filtered sample. Molybdenum blue colorimetry. Discrete Analyser. APHA 4500-P E (modified from manual analysis) 22nd ed. 2012.	0.004 g m^{-3}
Total Phosphorus	R.J Hill	Total phosphorus digestion, ascorbic acid colorimetry. Discrete Analyser. APHA 4500-P B & E (modified from manual analysis) 22nd ed. 2012. Also modified to include the use of a reductant to eliminate interference from arsenic present in the sample. NWASCA, Water & soil Miscellaneous Publication No. 38, 1982.	0.004 g m^{-3}

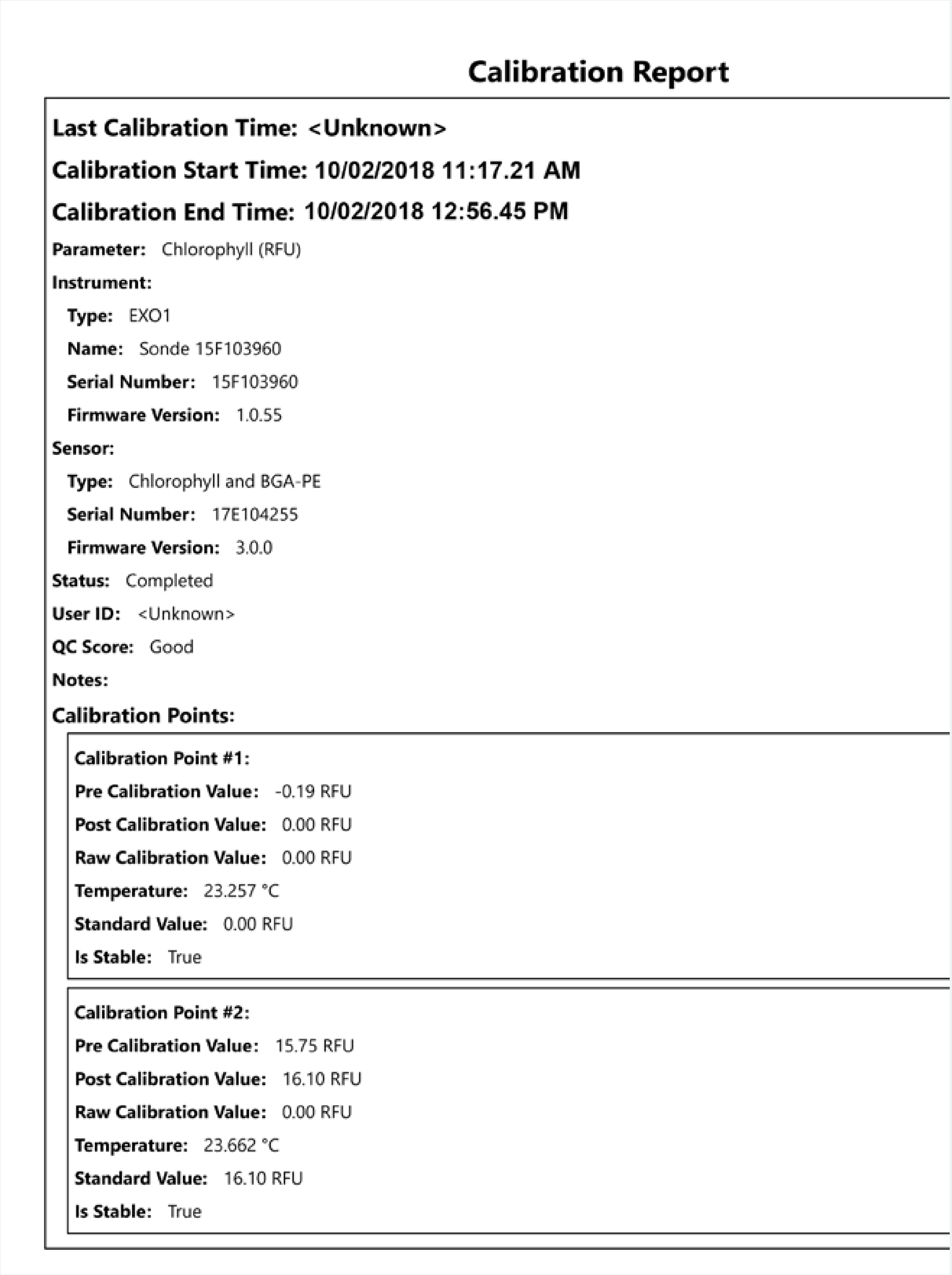
APPENDIX 2. 2017/18 DETAILED RESULTS

Aquatic vegetation and site details for all transect sites, Waimatuku Estuary, 14 February 2018. Water quality measures collected from the surface and mid-channel bottom water at high tide (1400).

Transect		Shape of cross section	Channel width	Channel depth	Secchi Disk Clarity	RPD Depth	Sediments	Sample Location	Temperature	Salinity	DO	Vegetative Cover	Height	Stage	Percent Cover
		west east	(m)	(m)	(m)	cm			ºC	ppt	$mg\ l^{-1}$		cm		%
	A		6	0.4	Bottom	>5	Gravel	Surface	19.7	0.1	11.1	*Ranunculus trichophyllus*	50	v	20
								Bottom	12.7	0.1	11.1	Periphyton & filamentous algae	10	v	80
Upper Estuary	B		15	2.0	0.5	>1	Muddy Gravels	Surface	18.8	0.2	12.1	*Ulva (Enteromorpha) intestinalis*	10	v	10
								Bottom	18.3	0.2	12.5	*Potamogeton crispus*	10	v	10
	C		15	1.0	0.5	>1	Muddy Gravels	Surface	19.5	0.2	16.3	*U. intestinalis*	10	v	10
								Bottom	18.1	0.2	13.4	*Ruppia megacarpa*	80	v	40
												Potamogeton crispus	10	v	20
Middle Estuary	D		18	1.0	Bottom	1-3	Muddy Sand/ Gravel	Surface	18.2	0.2	10.6	*U. intestinalis*	10	v	10
								Bottom	18.0	0.2	10.0	*Ruppia megacarpa*	80	v	20
	E		35	0.7	Bottom	1-3	Muddy Sand/ Gravel	Surface	18.2	0.2	10.6	*U. intestinalis*	5	v	10
								Bottom	18.0	0.2	10.0	*Ruppia megacarpa*	70	v	70
	F											*U. intestinalis*	5	v	20
												Ruppia megacarpa	60	v	80
	G		19	1.0	Bottom	1-3	Muddy Sand/ Gravel	Surface	19.6	0.2	12.1	*U. intestinalis*	5	v	20
								Bottom	19.5	0.2	11.8	*Ruppia megacarpa*	60	v	80
	H		20	1.0	0.5	>10	Clean mobile Sand	Surface	20.3	0.2	12.2	Benthic microalgae	<0.1	v	70
								Bottom	20.3	0.2	12.2				
Lower Estuary	I		9	0.5	Bottom	>10	Clean mobile Sand	Surface	20.8	0.3	11.7	*U. intestinalis*	5	v	10
								Bottom				Benthic microalgae	<0.1	v	70
	J		24	1.0	0.5	>10	Clean mobile Sand	Surface	22.3	0.3	10.3	*U. intestinalis*	5	v	10
								Bottom	21.1	0.4	10.2	Benthic microalgae	<0.1	v	70
	K		11	1.0	Bottom	>10	Clean mobile Sand	Surface	22.5	0.3	10.5	Benthic microalgae	<0.1	v	70
								Bottom	22.6	0.3	10.6				
	L		8	1.2	0.5	>10	Clean mobile Sand	Surface	22.7	0.4	10.5	Benthic microalgae	<0.1	v	70
								Bottom	22.8	0.3	10.7				

V=vegetative stage
F=flowering
Fr=fruiting

APPENDIX 3. SONDE CALIBRATION REPORT



Calibration Report

Last Calibration Time: <Unknown>

Calibration Start Time: 10/02/2018 11:17.21 AM

Calibration End Time: 10/02/2018 12:56.45 PM

Parameter: Chlorophyll (RFU)

Instrument:

- **Type:** EXO1
- **Name:** Sonde 15F103960
- **Serial Number:** 15F103960
- **Firmware Version:** 1.0.55

Sensor:

- **Type:** Chlorophyll and BGA-PE
- **Serial Number:** 17E104255
- **Firmware Version:** 3.0.0

Status: Completed

User ID: <Unknown>

QC Score: Good

Notes:

Calibration Points:

Calibration Point #1:

Pre Calibration Value: -0.19 RFU

Post Calibration Value: 0.00 RFU

Raw Calibration Value: 0.00 RFU

Temperature: 23.257 °C

Standard Value: 0.00 RFU

Is Stable: True

Calibration Point #2:

Pre Calibration Value: 15.75 RFU

Post Calibration Value: 16.10 RFU

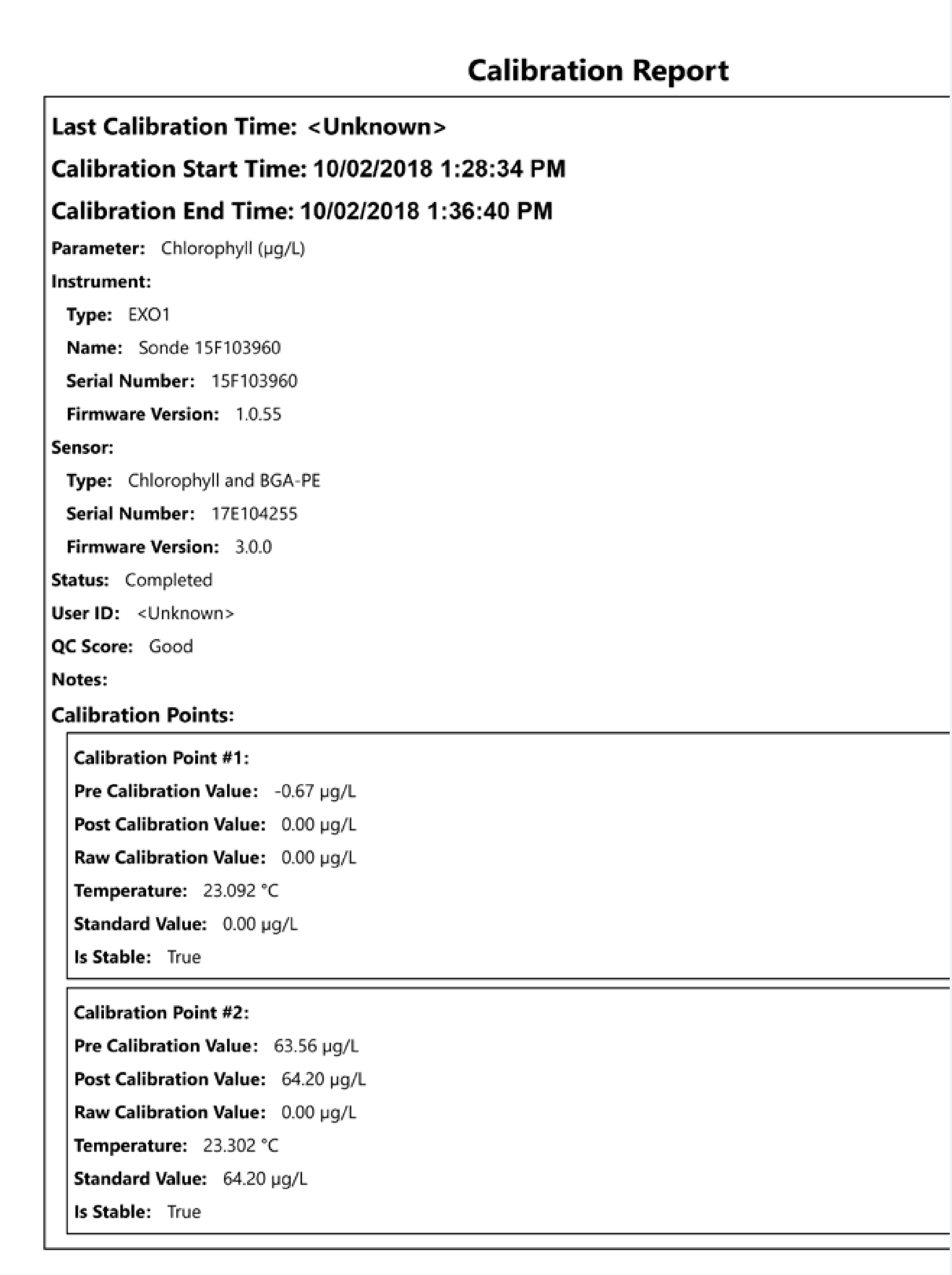
Raw Calibration Value: 0.00 RFU

Temperature: 23.662 °C

Standard Value: 16.10 RFU

Is Stable: True

APPENDIX 3. SONDE CALIBRATION REPORT (CONTINUED)



Calibration Report

Last Calibration Time: <Unknown>

Calibration Start Time: 10/02/2018 1:28:34 PM

Calibration End Time: 10/02/2018 1:36:40 PM

Parameter: Chlorophyll (µg/L)

Instrument:

- **Type:** EXO1
- **Name:** Sonde 15F103960
- **Serial Number:** 15F103960
- **Firmware Version:** 1.0.55

Sensor:

- **Type:** Chlorophyll and BGA-PE
- **Serial Number:** 17E104255
- **Firmware Version:** 3.0.0

Status: Completed

User ID: <Unknown>

QC Score: Good

Notes:

Calibration Points:

Calibration Point #1:

Pre Calibration Value: -0.67 µg/L

Post Calibration Value: 0.00 µg/L

Raw Calibration Value: 0.00 µg/L

Temperature: 23.092 °C

Standard Value: 0.00 µg/L

Is Stable: True

Calibration Point #2:

Pre Calibration Value: 63.56 µg/L

Post Calibration Value: 64.20 µg/L

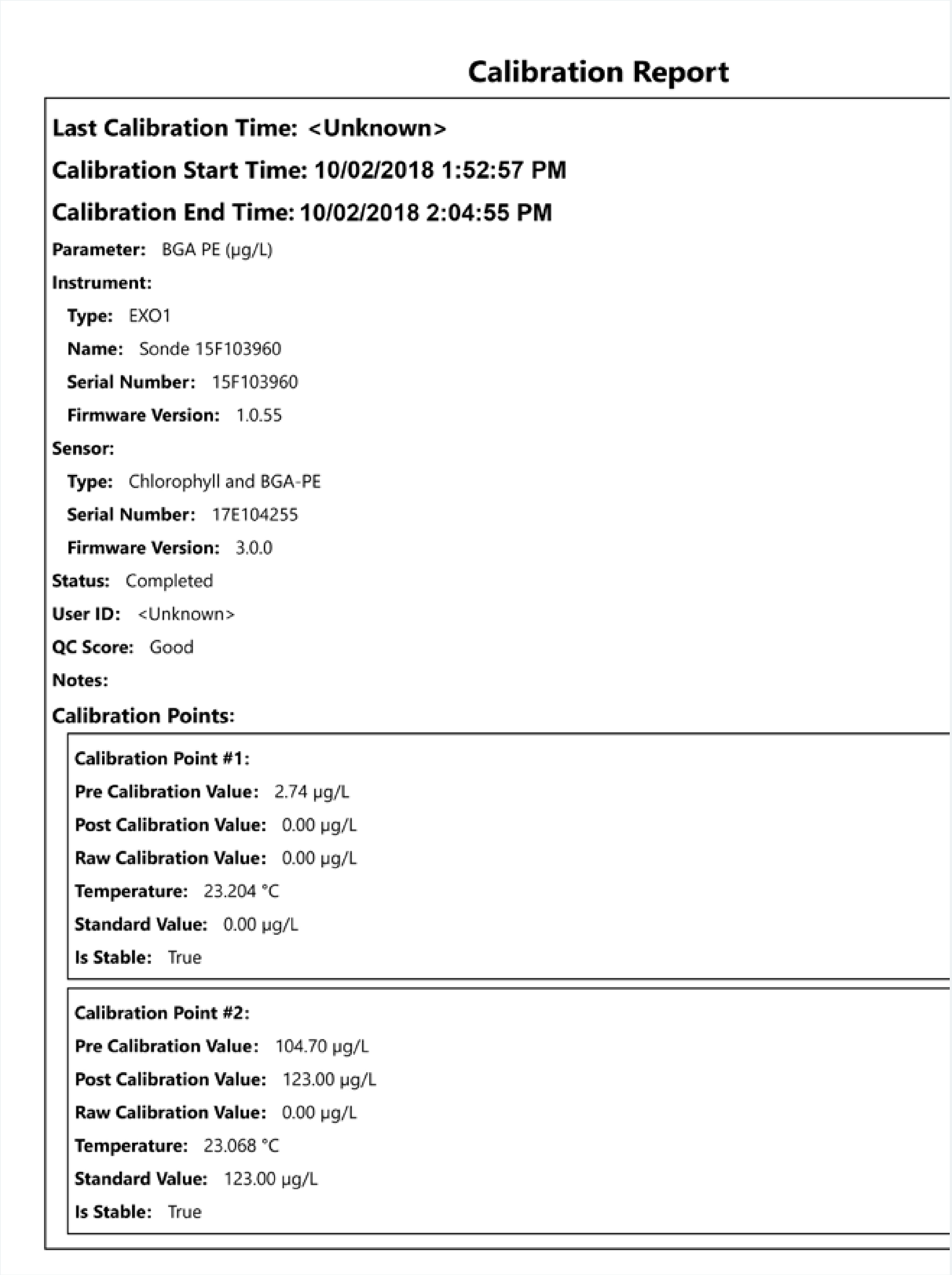
Raw Calibration Value: 0.00 µg/L

Temperature: 23.302 °C

Standard Value: 64.20 µg/L

Is Stable: True

APPENDIX 3. SONDE CALIBRATION REPORT (CONTINUED)



Calibration Report

Last Calibration Time: <Unknown>

Calibration Start Time: 10/02/2018 1:52:57 PM

Calibration End Time: 10/02/2018 2:04:55 PM

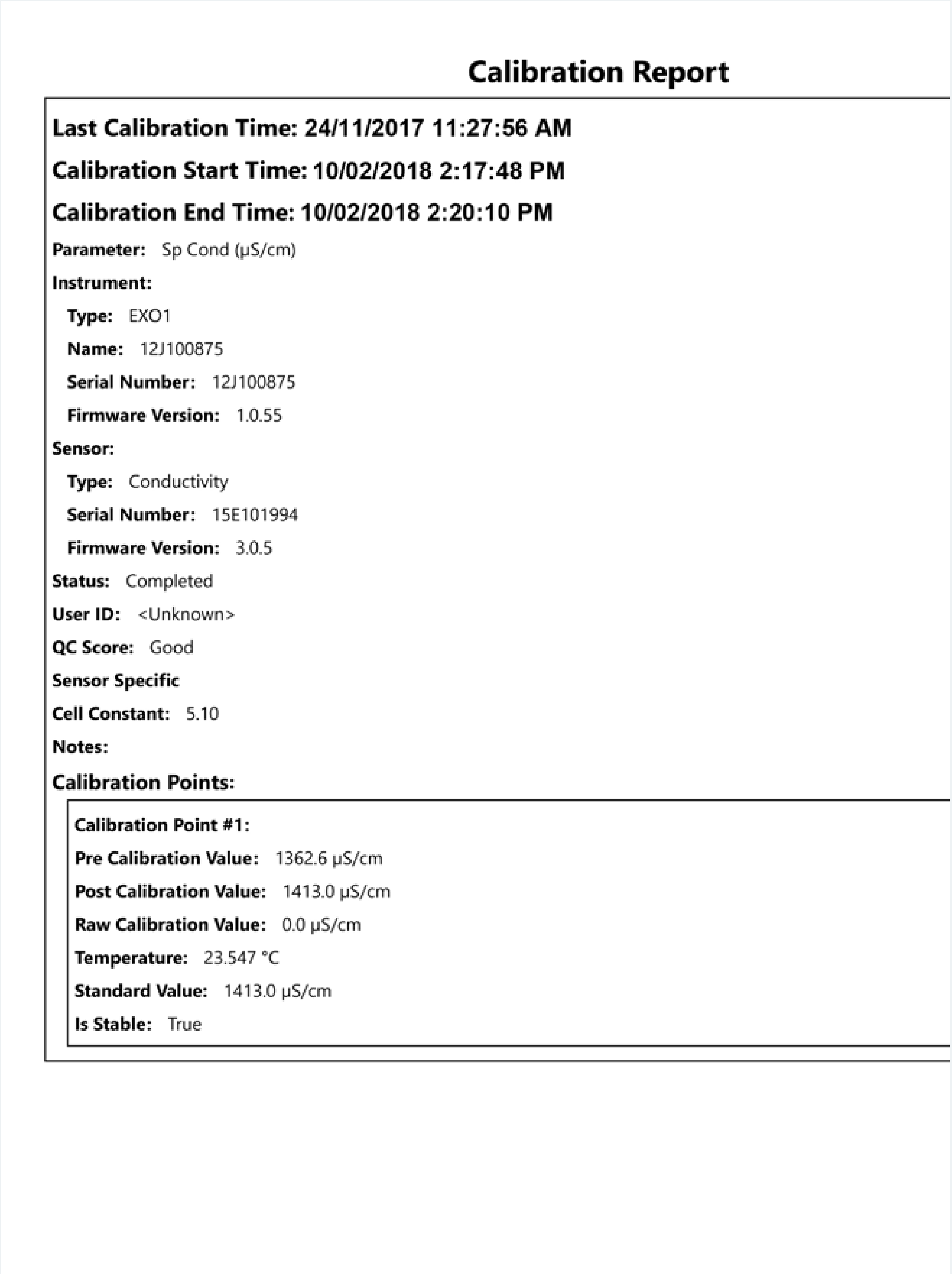
Parameter: BGA PE (μg/L)
Instrument:
  Type: EXO1
  Name: Sonde 15F103960
  Serial Number: 15F103960
  Firmware Version: 1.0.55
Sensor:
  Type: Chlorophyll and BGA-PE
  Serial Number: 17E104255
  Firmware Version: 3.0.0
Status: Completed
User ID: <Unknown>
QC Score: Good
Notes:

Calibration Points:

Calibration Point #1:
Pre Calibration Value: 2.74 μg/L
Post Calibration Value: 0.00 μg/L
Raw Calibration Value: 0.00 μg/L
Temperature: 23.204 °C
Standard Value: 0.00 μg/L
Is Stable: True

Calibration Point #2:
Pre Calibration Value: 104.70 μg/L
Post Calibration Value: 123.00 μg/L
Raw Calibration Value: 0.00 μg/L
Temperature: 23.068 °C
Standard Value: 123.00 μg/L
Is Stable: True

APPENDIX 3. SONDE CALIBRATION REPORT (CONTINUED)



Calibration Report

Last Calibration Time: 24/11/2017 11:27:56 AM

Calibration Start Time: 10/02/2018 2:17:48 PM

Calibration End Time: 10/02/2018 2:20:10 PM

Parameter: Sp Cond (µS/cm)

Instrument:

- **Type:** EXO1
- **Name:** 12J100875
- **Serial Number:** 12J100875
- **Firmware Version:** 1.0.55

Sensor:

- **Type:** Conductivity
- **Serial Number:** 15E101994
- **Firmware Version:** 3.0.5

Status: Completed

User ID: <Unknown>

QC Score: Good

Sensor Specific

Cell Constant: 5.10

Notes:

Calibration Points:

Calibration Point #1:

Pre Calibration Value: 1362.6 µS/cm

Post Calibration Value: 1413.0 µS/cm

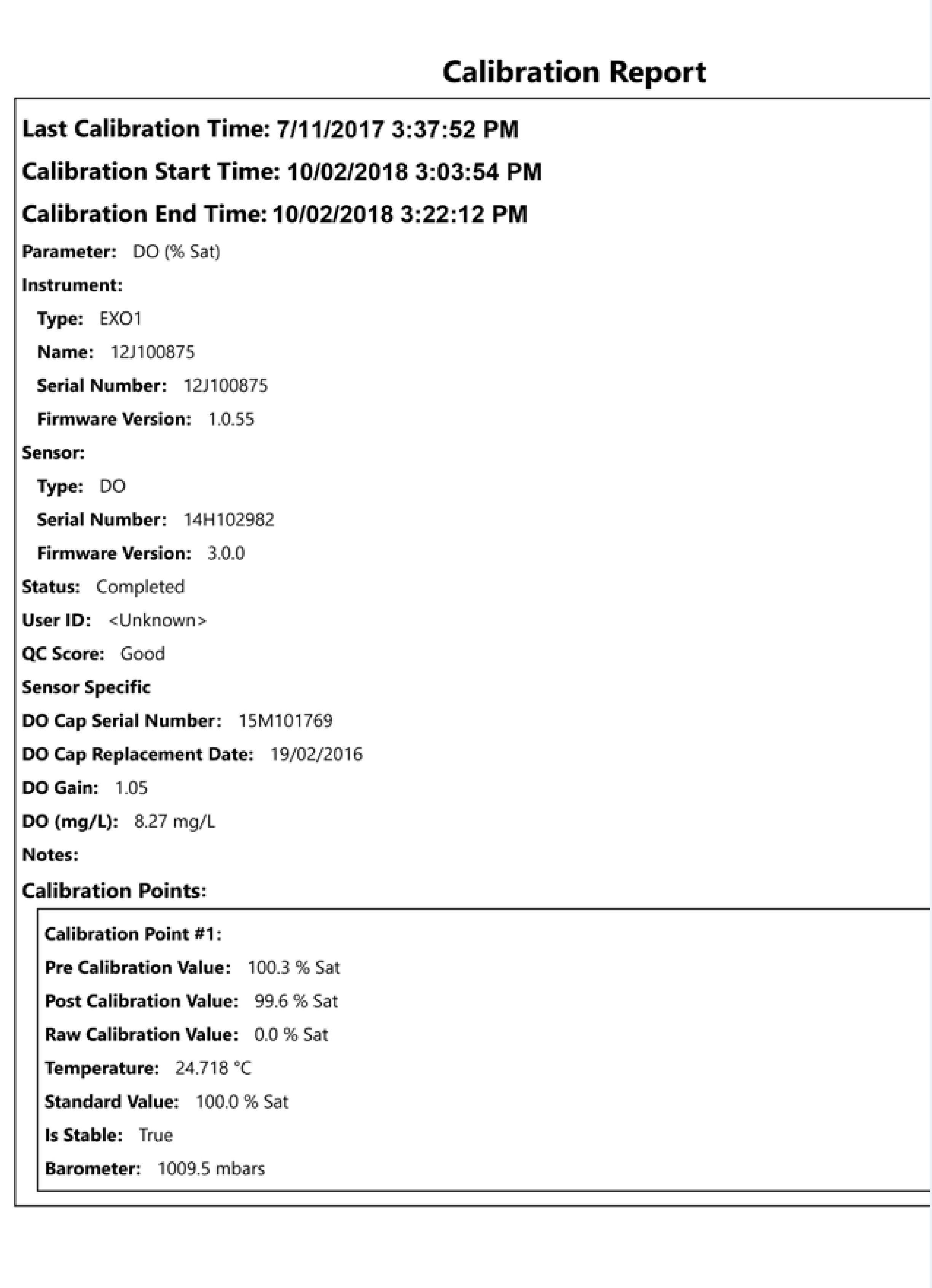
Raw Calibration Value: 0.0 µS/cm

Temperature: 23.547 °C

Standard Value: 1413.0 µS/cm

Is Stable: True

APPENDIX 3. SONDE CALIBRATION REPORT (CONTINUED)



Calibration Report

Last Calibration Time: 7/11/2017 3:37:52 PM

Calibration Start Time: 10/02/2018 3:03:54 PM

Calibration End Time: 10/02/2018 3:22:12 PM

Parameter: DO (% Sat)

Instrument:

- **Type:** EXO1
- **Name:** 12J100875
- **Serial Number:** 12J100875
- **Firmware Version:** 1.0.55

Sensor:

- **Type:** DO
- **Serial Number:** 14H102982
- **Firmware Version:** 3.0.0

Status: Completed

User ID: <Unknown>

QC Score: Good

Sensor Specific

DO Cap Serial Number: 15M101769

DO Cap Replacement Date: 19/02/2016

DO Gain: 1.05

DO (mg/L): 8.27 mg/L

Notes:

Calibration Points:

Calibration Point #1:

Pre Calibration Value: 100.3 % Sat

Post Calibration Value: 99.6 % Sat

Raw Calibration Value: 0.0 % Sat

Temperature: 24.718 °C

Standard Value: 100.0 % Sat

Is Stable: True

Barometer: 1009.5 mbars

APPENDIX 4. DETAILED STATISTICAL RESULTS

Summary of one-Way ANOVA and associated Tukey HSD tests for benthic data for Sites D, E, and G (combined baseline and 2018, *n* = 3) in Waimatuku Estuary.

Note: ANOVA F and P value (*p* = 0.05) - Is there a significant difference between at least two of the years means? Tukey post hoc test - Is there a significant difference between 2018 data and all of the baseline years 2010-2012? Also is 2018 data outside of the baseline data range?

Sediment variable	Site	One-way ANOVA	Post-hoc test (Tukey HSD)
Total Organic Carbon	Waimatuku Combined D, E, G	F = 1, P = 0.67.	Not Significant
Muddiness	Waimatuku Combined D, E, G	F = 1, P = 0.52.	Not Significant
Total Nitrogen	Waimatuku Combined D, E, G	F = 0, P = 0.76.	Not Significant
Total Phosphorus	Waimatuku Combined D, E, G	F = 5, P < 0.05.	Not Significant