Ōhau and Waikawa Estuaries – Nutrient Limit Setting

Numerical Modelling

August 2022

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August 2022
Report No. 2022/EXT/1776
ISBN 978-1-99-000998-3

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Report

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The expert in WATER ENVIRONMENTS

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Prepared for Horizons Regional Council

Represented by Staci Boyte

Cover Photo: Ōhau River showing stratified phytoplankton bloom, Jan 2020

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Project number	44801735
Approval date	10/08/2022
Revision	Final 1.0
Classification	Open

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1 Executive Summary

HRC have commissioned DHI and Salt Ecology to undertake numerical modelling to determine current state and help in the establishment of nutrient (TN and TP) thresholds for the Ōhau and Waikawa Estuaries.

DHI have developed and calibrated three dimensional (3D) hydrodynamic models of the estuaries and lower rivers. The models are able to reproduce the complex mixing behaviour of riverine and saltwater, which is dependent on river flow and tidal state.

Nutrient input loads have been provided by Land Water People with a cross check by Salt Ecology using a different method.

The models have been run with predicted nutrient loads for 2018 land cover to define existing nutrient state and characterise the estuary in relation to bands of ecological condition at selected locations. The models are then used to define the nutrient input reduction that would be needed to move to an improved band or threshold for mean river flows, at each location.

Summer low flow conditions have also been investigated.

Key observations from the predictions for Ōhau Estuary, based on the estimates of Fraser and Snelder (2021), are as follows:

- Based on mean flow, all locations are D Band for TN and unsatisfactory for TP based on mean flow conditions.
- For low flow summer conditions, Pt 1 to Pt 3 have a better band/threshold than for compared to the mean flow conditions. There is no change for Pt 4 and Pt 5, since the salt wedge only propagates to these locations for low flow and mid to spring tides.
- For all locations to improve on the mean flow basis for TN would require a 63% load reduction to achieve Band C, a 77% load reduction for Band B and a 91% load reduction for Band A.
- For Pt 1 to Pt 3 to improve on an annual basis for TN would require a 60% load reduction to achieve Band C, a 75% load reduction for Band B and a 90% load reduction for Band A.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve the TN band to B will require a 25% load reduction, and A band will require a 73% load reduction.
- For all locations to improve on the mean flow basis for TP would require a 55% load reduction to achieve a Satisfactory threshold and an 85% load reduction to achieve an Excellent threshold.
- For Pt 1 to Pt 3 to improve on an annual basis for TP would require a 52% load reduction to achieve a Satisfactory threshold and an 85% load reduction to achieve an Excellent threshold.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve TP threshold to Excellent threshold will require a 75% load reduction.

Key observations from the predictions for Waikawa Estuary, based on the estimates of Fraser and Snelder (2021), are as follows:

- For all flow conditions and all locations are D for TN band and unsatisfactory for TP threshold.
- For all locations to improve on the mean flow basis for TN would require an 81% load reduction to achieve Band C, an 88% load reduction for Band B and a 95% load reduction for Band A.
- For Pt 1 to Pt 3 to improve on the mean flow basis for TN would require an 80% load reduction to achieve Band C, a 88% load reduction for Band B and a 95% load reduction for Band A.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve the TN band to C will require a 68% load reduction, a 80% load reduction for Band B and a 93% load reduction for Band A.
- For all locations to improve on the mean flow basis for TP would require a 76% load reduction to achieve a Satisfactory threshold and a 92% load reduction to achieve an Excellent threshold.
- For Pt 1 to Pt 3 to improve on the mean flow basis for TP would require a 75% load reduction to achieve a Satisfactory threshold and a 92% load reduction to achieve an Excellent threshold.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve on an annual basis for TP would require a 63% load reduction to achieve a Satisfactory threshold and a 90% load reduction to achieve an Excellent threshold.

Although a location might be typically exposed to high nutrient concentrations, on many occasions the stream flow maybe sufficient so that the location is well flushed and therefore the high concentrations do not create eutrophication issues.

The analysis indicates that if phytoplankton growth occurs, for all locations in both estuaries, typically the growth will be flushed away within days (close to a week for summer low flows), however on occasions, it may take over a month for flows to be sufficient to flush away the growth in lower parts of the estuaries and two to three weeks in the upper parts of the estuary.

When revised condition band thresholds become available it is recommended this assessment is updated based on the revised band thresholds.

2 Introduction

Horizons Regional Council (HRC) have commissioned DHI Environment and Water Ltd (DHI) and Salt Ecology to undertake numerical modelling to determine current state and help in the establishment of Total Nitrogen (TN) and Total Phosphorous (TP) nutrient thresholds for the Ōhau and Waikawa Estuaries.

DHI have developed and calibrated three dimensional (3D) hydrodynamic models of the estuaries and lower stream/rivers. The models are able to reproduce the complex mixing behaviour of riverine and saltwater within the estuaries, which is dependent on river/stream flow and tidal state.

A key input to the modelling is an assessment of annual nutrient loads delivered to the system, which have been provided by Land Water People, with a cross check using a different method by Salt Ecology (described in Section 3).

The models have been run with current nutrient loads to define existing nutrient state and characterise the estuary in relation to bands of ecological condition (i.e. A, B, C, D).

The models have then been used to define the nutrient input reductions that would be needed to move to an improved band for mean river/stream flow. Summer low flow conditions have also been investigated.

Although a location might be typically exposed to high nutrient concentrations, on many occasions the river/stream flow may be sufficient so that the location is well flushed and therefore the high concentrations do not create issues. This has also been investigated.

2.1 Overview of Study Areas

Waikawa Estuary and Ōhau Estuary are located in the southwestern part of the North Island, in the Manawatu-Wanganui region.

Waikawa Estuary is a relatively long (>4km), 13ha, poorly flushed Shallow Short Residence Time Tidal River Estuary (SSRTRE) whose mouth is mostly open to the sea, but occasionally closes, and is commonly constricted by a build-up of beach sand (Stevens, 2019).

Ōhau Estuary is a moderate-sized (~50ha) SSRTRE which discharges to the open coast at Ōhau on the Manawatu coast. The lower reaches are relatively shallow (mean depth ~0.5m) and comprise a low tide river channel and relatively large high tide lagoon running parallel to the outer coast. This lagoon is variable in size depending on the state of mouth closure or restriction and can extend for 2-3km along the coast when the mouth is closed. The mouth however remains open most of the time and the estuary drains readily and is relatively well-flushed by the Ōhau River (Stevens et al., 2020).

In both systems seawater can be trapped beneath surface freshwater flows, particularly in deeper pools. These deeper parts of the estuary tend to be those that experience the greatest water quality degradation, due to stratification of the water column increasing retention time of bottom waters which can facilitate the growth of phytoplankton. These areas are also commonly the least well flushed and provide the most favourable areas for the settlement of sediments and organic matter (Stevens et al., 2020a).

2.2 Background to Threshold Development

The eutrophication of estuaries through excessive nutrient inputs can cause ecological problems such as algal blooms and poor physical and chemical conditions for estuarine life. Macroalgae and phytoplankton blooms are both primary symptoms of eutrophication and can cause secondary symptoms including changes in sediment chemistry, reductions in water clarity, reduced dissolved oxygen or highly diurnally variable oxygen, reduced invertebrate diversity and reductions in seagrass (Plew et al. 2020).

Until recently, there was limited guidance in New Zealand on how to assess eutrophication impacts in NZ estuaries, making it difficult to determine the current trophic state, or to assess the impact of changing nutrient loads on trophic state. This has made it challenging to predict the consequences of management decisions regarding land-use and point source discharges or setting nutrient limits for upstream environments for estuaries (Zeldis & Plew, in prep).

As an initial step to help address such challenges, an Estuary Trophic Index (ETI) was recently developed to provide a nationally consistent approach to the assessment and prediction of estuary eutrophication (Robertson et al. 2016 a,b). Three ETI tools were built enabling users to:

1. assess the susceptibility of estuaries to eutrophication based on their nutrient loads and their flushing/dilution characteristics (Tool 1);

2. score an estuary along an ecological gradient from minimal to high eutrophication using values of monitored indicators derived from field surveys (Tool 2); and

3. predict estuary health in the absence of detailed knowledge of indicator states, or to scenario-test effects of changed upstream loading or land use on estuary health, by combining the products and attributes of Tools 1 and 2 (Tool 3).

The ETI provides these capabilities within three web-based applications:

- Tool 1: Determining eutrophication susceptibility using physical and nutrient load data
- Tool 2: Assessing Estuary Trophic State using measured trophic indicators
- Tool 3: Assessing Estuary Trophic State using a Bayesian Belief Network

The overarching approach has been to define thresholds for key attributes that indicate ecological state under a 4-band structure (A–D) consistent with the National Objectives Framework for Freshwater (NOF-FW) approach widely applied in New Zealand. For macroalgae, the bandings used in the ETI are based on thresholds from the Opportunistic Macroalgal Blooming Tool (OMBT) (WFD-UKTAG 2014). The OMBT is a five-part multi-metric index that provides a comprehensive measure of the combined influence of macroalgal growth and distribution in an estuary. It produces an overall Ecological Quality Rating (EQR) ranging from 0 (major disturbance) to 1 (minimally disturbed) and rates estuarine condition in relation to macroalgal status within five overall quality status threshold bands (bad, poor, good, moderate, high). The individual metrics that are used to calculate the EQR include:

- *Percentage cover of opportunistic macroalgae*: The spatial extent and surface cover of algae present in intertidal soft sediment habitat in an estuary provides an early warning of potential eutrophication issues.

- *Macroalgal biomass*: biomass provides a direct measure of macroalgal growth. Estimates of mean biomass are made within areas affected by macroalgal growth, as well as across the total estuary intertidal area.

- *Extent of algal entrainment into the sediment matrix*: Macroalgae was defined as entrained when growing >30mm deep within sediments, which indicates that persistent macroalgal growths have established.

Biomass thresholds included in the OMBT were lowered for use in the New Zealand ETI based on unpublished data from >25 shallow well-flushed intertidal New Zealand estuaries (Robertson et al. 2016b) and the results from similar estuaries in California (Sutula et al. 2014).

The modified bandings used in New Zealand are 0–100, 100–200, 200–500, 500–1450, and >1450 g wet weight m^{-2}. The ETI combined the lowest two threshold categories to fit a 4-band (A–D) structure - see Plew et al. (2020) for further detail. These thresholds are considered to provide an early warning of nutrient related impacts in New Zealand prior to the establishment of adverse enrichment conditions that are likely difficult to reverse.

To determine the potential estuary nutrient concentrations that reflect the macroalgae bands above, data from 21 estuaries (Robertson et al. 2016b; Zeldis et al. 2017) were assessed. Plew et al. (2020) derived bandings for potential total nitrogen (TN) and potential nitrate (NO_3) corresponding to EQR bands by fitting linear regressions between predicted potential concentrations and observed EQR. These regressions were used to calculate potential TN and NO_3 concentrations corresponding to EQR thresholds of 0.8, 0.6 and 0.4, which are the thresholds between A-B, B-C and C-D bands in the ETI. Plew et al. (2020) used observed annual nitrogen loads and annual mean flows to calculate potential concentrations for the estuaries with EQR observations from peak growth (summer) periods. Bandings therefore relate annual loads and flows and potential summer macroalgae response. These thresholds are shown in Table 2-1 below.

The potential NO_3 thresholds calculated from the regressions are 18% lower than for TN, but the R^2 for the TN vs EQR and NO_3 vs EQR relationships are nearly identical ($R^2 = 0.71$) (Plew et al. (2020).

The focus is on nitrogen with this approach as it is likely to be the limiting nutrient for macroalgae growth in most estuaries which seldom show phosphorus limitation for N/P molar ratios less than 30 (Atkinson & Smith 1983).

Table 2-1 Macroalgal bands with corresponding EQR ratings, potential total nitrogen (TN) and potential nitrate (NO_3) ranges, and a description of expected ecological state for each band. Potential TN and NO_3 concentrations are based on annual loads and annual mean flow. Descriptions of expected ecological states are adapted from Robertson et al. (2016b).

Macroalgae susceptibility band	A	B	C	D
Eutrophication level	Minimal	Moderate	High	Very high
Ecological Quality Rating	1.0 > EQR ≥ 0.8	0.8 > EQR ≥ 0.6	0.6 > EQR ≥ 0.4	EQR < 0.4
Potential TN concentration (mg m^{-3})	TN ≤ 80	TN > 80 to ≤ 200	TN >200 to ≤ 320	TN > 320
Potential NO_3 concentration (mg m^{-3})	NO_3 ≤ 65	NO_3 >65 to ≤ 165	NO_3 >165 to ≤ 260	NO_3 > 260
Expected ecological state	Ecological communities (e.g. bird, fish, seagrass, and macroinvertebrates) are healthy and resilient. Algal cover <5% and low biomass of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality high.	Ecological communities (e.g. bird, fish, seagrass, and macroinvertebrates) are slightly impacted by additional macroalgal growth arising from nutrients levels that are elevated. Limited macroalgal cover (5–20%) and low biomass of opportunistic macroalgal blooms and with no growth of algae in the underlying sediment. Sediment quality transitional.	Ecological communities (e.g. bird, fish, seagrass, and macroinvertebrates) are moderately to strongly impacted by macroalgae. Persistent, high % macroalgal cover (25–50%) and/or biomass, often with entrainment in sediment. Sediment quality degraded.	Ecological communities (e.g. bird, fish, seagrass, and macroinvertebrates) are strongly impacted by macroalgae. Persistent very high % macroalgal cover (>75%) and/or biomass, with entrainment in sediment. Sediment quality degraded with sulphidic conditions near the sediment surface.

To date, there are only data from a relatively small number of New Zealand estuaries directly comparable to Ōhau and Waikawa. As such, there is uncertainty associated with the currently proposed thresholds. Further refinement of the thresholds using data from a larger set of SSRTREs is recommended, with a likely outcome being that more stringent thresholds may be needed to prevent algal problems from occurring in SSRTREs when the openings to the sea are restricted.

The thresholds proposed by Plew et al. (2020) are based on the measured relationship between nuisance macroalgal response and nutrient load. Nutrient load was determined using the modelled inputs from CLUES, with estuary volume and flushing used to determine a potential nutrient concentration within the estuary. It is termed 'potential concentration' as it does not account for any nutrient uptake or storage in vegetation or sediment, nor losses through denitrification processes. This relationship has then been used in conjunction with the long-term monitoring data from Invercargill City Council in New River Estuary (25+ years of regular nutrient and phytoplankton monitoring) to predict likely phytoplankton response thresholds.

At present there are relatively few estuaries (21) that have been used in the determination of the initial macroalgal response relationship. The estuaries are also limited in their geographical spread (14 are from the Nelson region), and in the range of nutrient concentrations represented (many have very low inputs). Recent work for Environment Southland (Salt/NIWA project) has summarised data from several additional estuaries across a wider range of nutrient concentrations. Salt will expand this dataset early in the new financial year so that NIWA can revise the relationship, and from this, the thresholds used to define condition bands.

Overall, refining the hydrodynamic model is unlikely to be necessary, but using it to model potential changes under the revised condition band thresholds (when they are available) would be strongly recommended.

Probably the single greatest limitation in assessing the validity of the thresholds remains a lack of data from SSRTREs, which have a greater potential to be impacted by phytoplankton than SIDEs. Collecting regular chl-a and nutrient data (at a national scale) from SSRTREs would be very helpful in this regard. The data gathered from the Ōhau and Waikawa estuaries will be used in looking at this more closely, along with data collected from similar estuary systems in Otago.

In the absence of guidelines and thresholds for Total Phosphorous (TP), the thresholds derived by Hunt (2016) shown in Table 2-2 have been applied for this assessment. Further details can be found in Hunt (2016), but the thresholds are derived as relevant to “causes nuisance plant growth”.

Table 2-2 TP Thresholds (Hunt, 2016)

Threshold		
Excellent	**Satisfactory**	**Unsatisfactory**
≤10 mg/m^3	>10 and ≤30 mg/m^3	>30mg/m^3

2.3 Projection and Datum

The study was carried out using New Zealand Vertical Datum 2016 and New Zealand Transverse Mercator coordinate system.

3 Data

This section provides an overview of the data utilised for this study. A field campaign was undertaken by HRC to collect data specifically for the study.

3.1 Bathymetry

An accurate and reliable bathymetry is a key component of a hydraulic model. A good bathymetry will significantly improve the calibration and therefore accuracy of such a model and will ensure important processes (such as flow and freshwater and ocean water mixing) can be simulated by the model.

HRC carried out a bathymetry survey for both of the estuaries and lower river/streams using a single beam echo sounder. This was complemented with available LIDAR from HRC (provided in a 1 m x 1m resolution grid). An overview of the bathymetry data provided by HRC is shown in Figure 3-1.

3.2 Hydrographic and Salinity Data Collection

Hydrographic data within the vicinity of the study sites were collected by HRC during January to March 2022. An overview of the hydrographic data which were collected for each estuary is shown in Figure 3-2.

3.1.1 Water Level

HRC deployed a water level recorder in the Ōhau Estuary, while there is a permanent water level recorder in Waikawa Estuary at locations shown in Figure 3-2. The temporary water level recorder was deployed from 13th January to 9th March 2021 for Ōhau Estuary.

The water level measurements (NZVD 2016 Datum) from each location are presented in Figure 3-3.

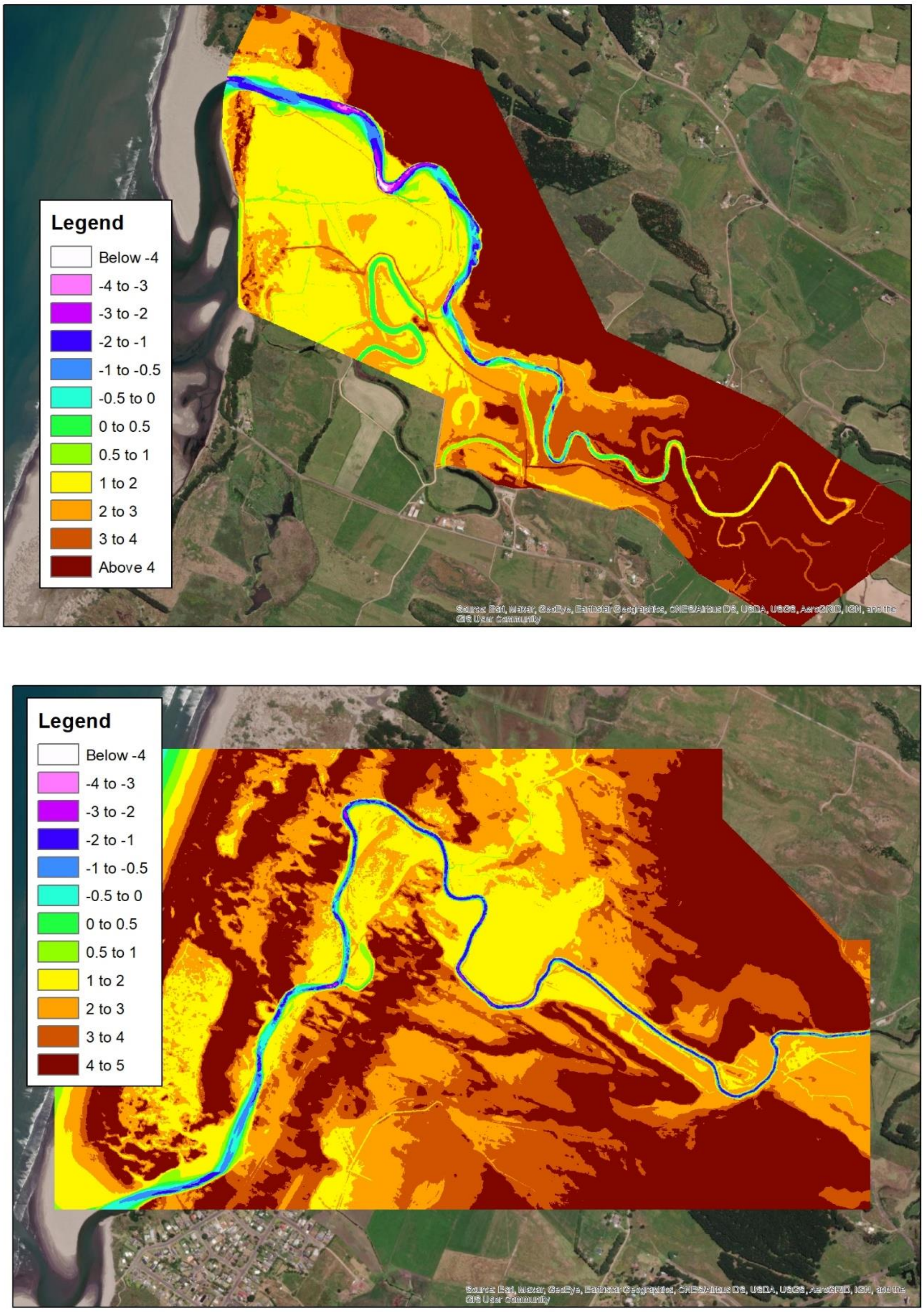


Figure 3-1 Bathymetry data provided by HRC for Ōhau Estuary (top) and Waikawa Estuary (bottom). Depths are relative to New Zealand Vertical Datum 2016.

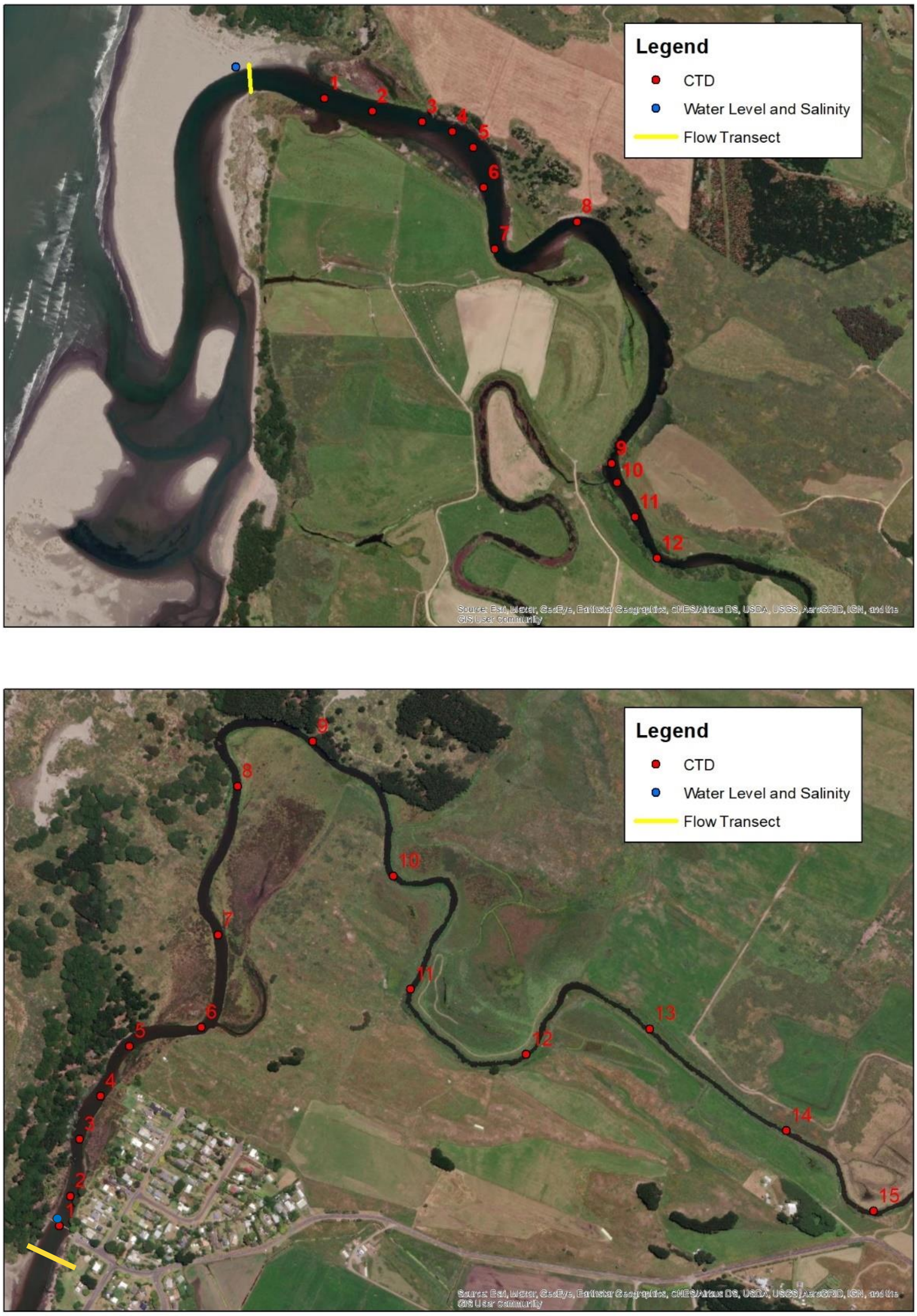
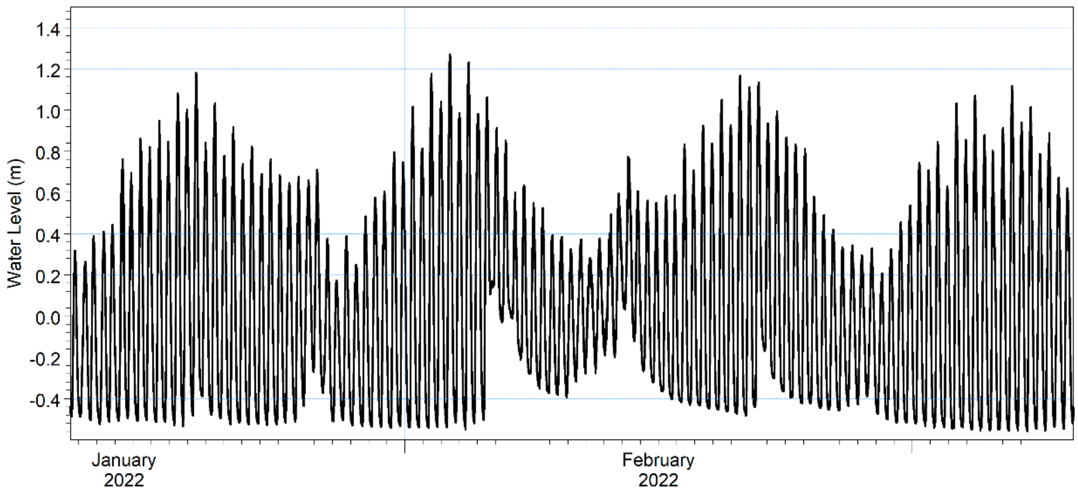


Figure 3-2 Overview of hydrographic and salinity data collection locations for Ōhau Estuary (top) and Waikawa Estuary (bottom)



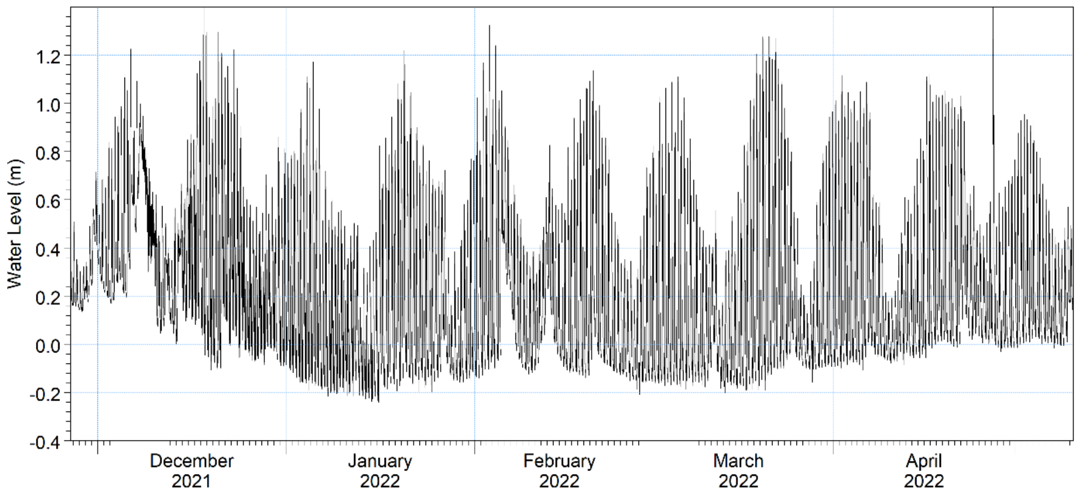


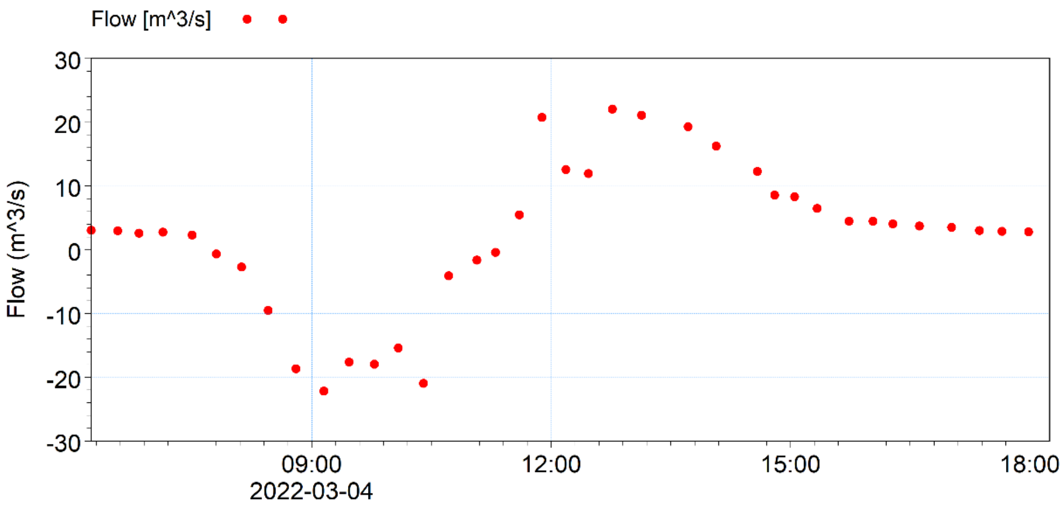
Figure 3-3 Water level data for Ōhau Estuary (top) and Waikawa Estuary (bottom). Levels are relative to New Zealand Vertical Datum 2016.

3.1.2 ADCP Flow Transects

Flow measurements over close to a full tide cycle were collected using a downward facing ADCP along the transects shown in Figure 3-2.

HRC collected flow measurements for the Ōhau Estuary on the 4th March 2022 and the Waikawa estuary on the 31st March 2021.

The flow measurements for the two transects are shown in Figure 3-4.



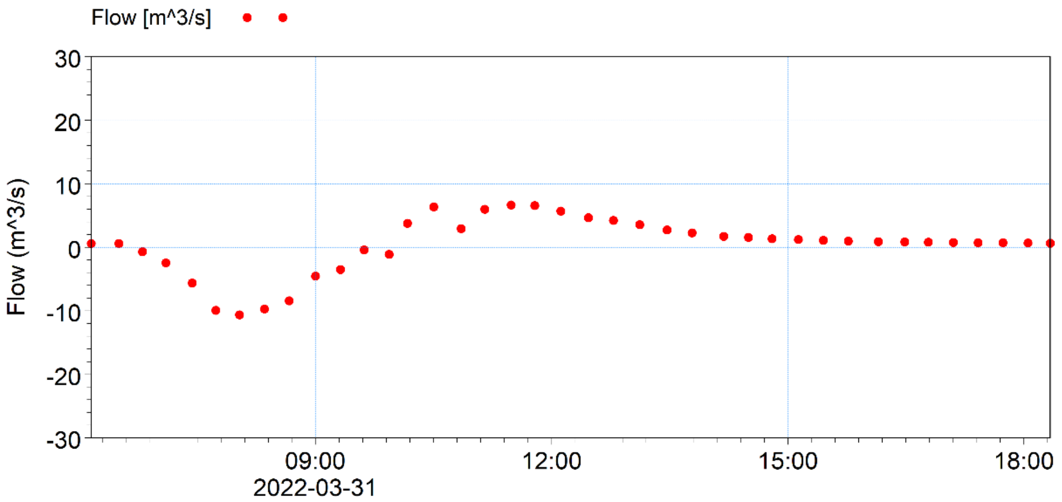


Figure 3-4 Flow transects for Ōhau Estuary (top) and Waikawa Estuary (bottom). Positive flow is flow out of the estuary.

3.1.3 Salinity Data

On the 4th March 2022, HRC undertook a salinity profiling campaign for Ōhau Estuary and on 31st March 2022, the same for Waikawa Estuary. The measurements were carried out using a CTD (Conductivity Temperature Depth) meter at close to a high tide. An overview of the locations where all CTD casts were performed is shown in Figure 3-2. On the day of the CTD casts, continuous salinity measurements were also taken at the location of the water level recorder at the top and bottom of water column.

For Ōhau Estuary, the salt wedge propagated up to data collection site 9 on Figure 3-2. Representative examples of the CTD casts can be found in Section 4.6.

For Waikawa Estuary, the salt wedge propagated up to data collection site 12 on Figure 3-2. Representative examples of the CTD casts can be found in Section 4.6.

The continuous salinity measurements for both estuaries on the day of the CTD profiles is presented in Figure 3-5.

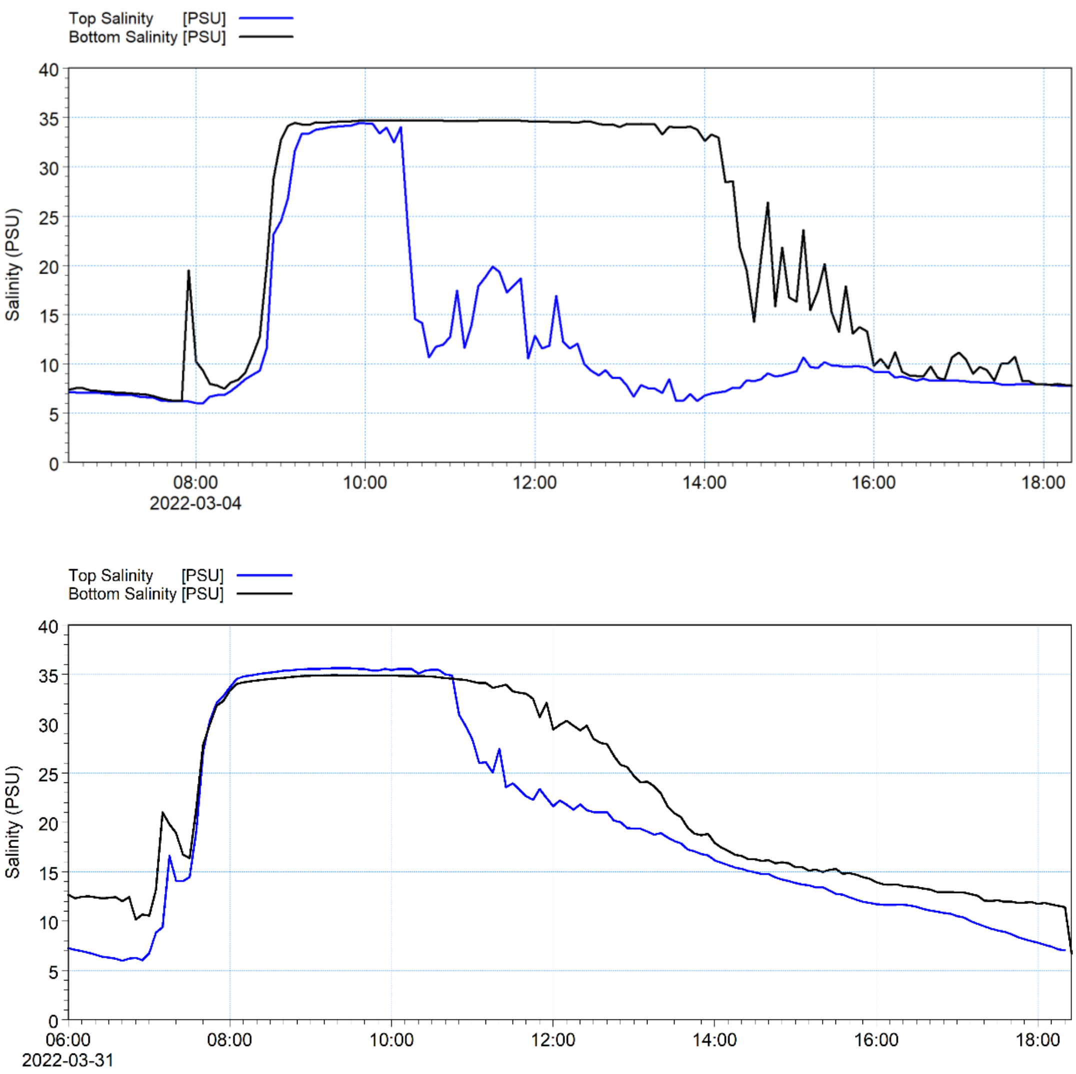


Figure 3-5 Continuous salinity measurement day of CTD casts at top and bottom of water column for Ōhau Estuary (top) and Waikawa Estuary (bottom).

3.2 River/Stream Flow Data

HRC have provided flow data for the Ōhau River at Rongomatane for the period 2010 to present and Waikawa Stream at North Manakau Road for the period 2010 to 2020. The mean flow for each year (2010 to 2020) and the mean of these mean flows (required for developing nutrient concentrations based on CLUES estimates) for are presented in Table 3-1.

Table 3-1 Yearly mean flow statistics for Ōhau River at Rongomatane and Waikawa Stream at North Manakau Road for 2010 to 2020.

Year	Mean Flow (m^3/s)	
	Ōhau River at Rongomatane	Waikawa Stream at North Manakau Road
2010	6.2	1.3
2011	6.6	1.4
2012	5.2	1.2
2013	5.1	1.2
2014	6.3	1.4
2015	7.5	1.8
2016	7.5	1.6
2017	8.5	1.8
2018	6.0	1.3
2019	6.6	1.3
2020	6.7	1.5
All	***6.6***	***1.4***

4 Nutrient Loads

This section provides an overview of nutrient input loads, which have been calculated by two different organisations, Salt Ecology and Land Water People. The loads were assessed in two, ways as a rough cross check on accuracy, with the estimates from Land Water People considered most accurate based on the use of more detailed land cover layers.

4.1 CLUES Estimates

Salt Ecology used NIWAs Catchment Land Use for Environmental Sustainability (CLUES) model (Elliott et al. 2016, Morrisey et al. 2020) with LCDB5 (2018/19), to derive annual cumulative (instream) nutrient loads generated from the Ōhau and Waikawa catchments. Modelled catchment loads of 75.7 tonnes/yr and 6.1 tonnes/yr for TN and TP respectively for Waikawa Stream and 201.5 tonnes/yr and 19.3 tonnes/yr have been derived for TN and TP respectively for Ōhau River .

4.2 Fraser and Snelder Estimates

Land Water People (Fraser and Snelder, 2021) updated site contaminant load estimates for rivers within Manawatū-Whanganui region, previously provided by Fraser and Snelder (2020), and Snelder et al. (2020). Whereas the loads estimated by Fraser and Snelder (2019), and Snelder et al. (2020) applied to 2017 (based only on flow duration curves) and 2012 (based only on observed flows), respectively, the new derived loads apply for 2018.

Fraser and Snelder (2021), calculated a catchment load of 68.2 tonnes/yr and 5.1 tonnes/yr derived for TN and TP respectively for Waikawa Stream and 164.7 tonnes/yr and 12.5 tonnes/yr for TN and TP respectively for Ōhau River .

Since the estimates between CLUES method and Fraser and Snelder method, were so similar, the locally derived and validated loads of Fraser and Snelder were used for all modelling.

5 Model Build and Calibration

The section provided an overview of the model build and calibration of the 3D hydrodynamic model. Further details of the 3D hydrodynamic model (MIKE 3 FM) can be found in the MIKE 3 HD FM User Guide (DHI, 2020).

5.1 Mesh

Bathymetry data for the models were obtained from the HRC bathymetry surveys and LIDAR data.

A flexible mesh allows the computational domain to be discretised into a mixture of triangular and quadrangular elements of various sizes. This enables high-resolution definition where necessary and low-resolution for other areas, reducing computational requirements.

Model resolution (both vertically and horizontally) is a balance between resolving the local hydrodynamics and achieving reasonable simulation times.

The model extent and example of model mesh (the lower river where the maximum extent of salt wedge was observed for Ōhau Estuary) is shown in Figure 5-1 for Ōhau Estuary and Figure 5-2 for Waikawa Estuary.

For the main river/stream, quadrangular elements with a resolution of 4 m width and 10 m length have been applied, approximately 30 m each side of the river/stream centreline. The rest of the model domain has triangular elements with sides of approximately 15 m (i.e. an element area of approximately 100 m).

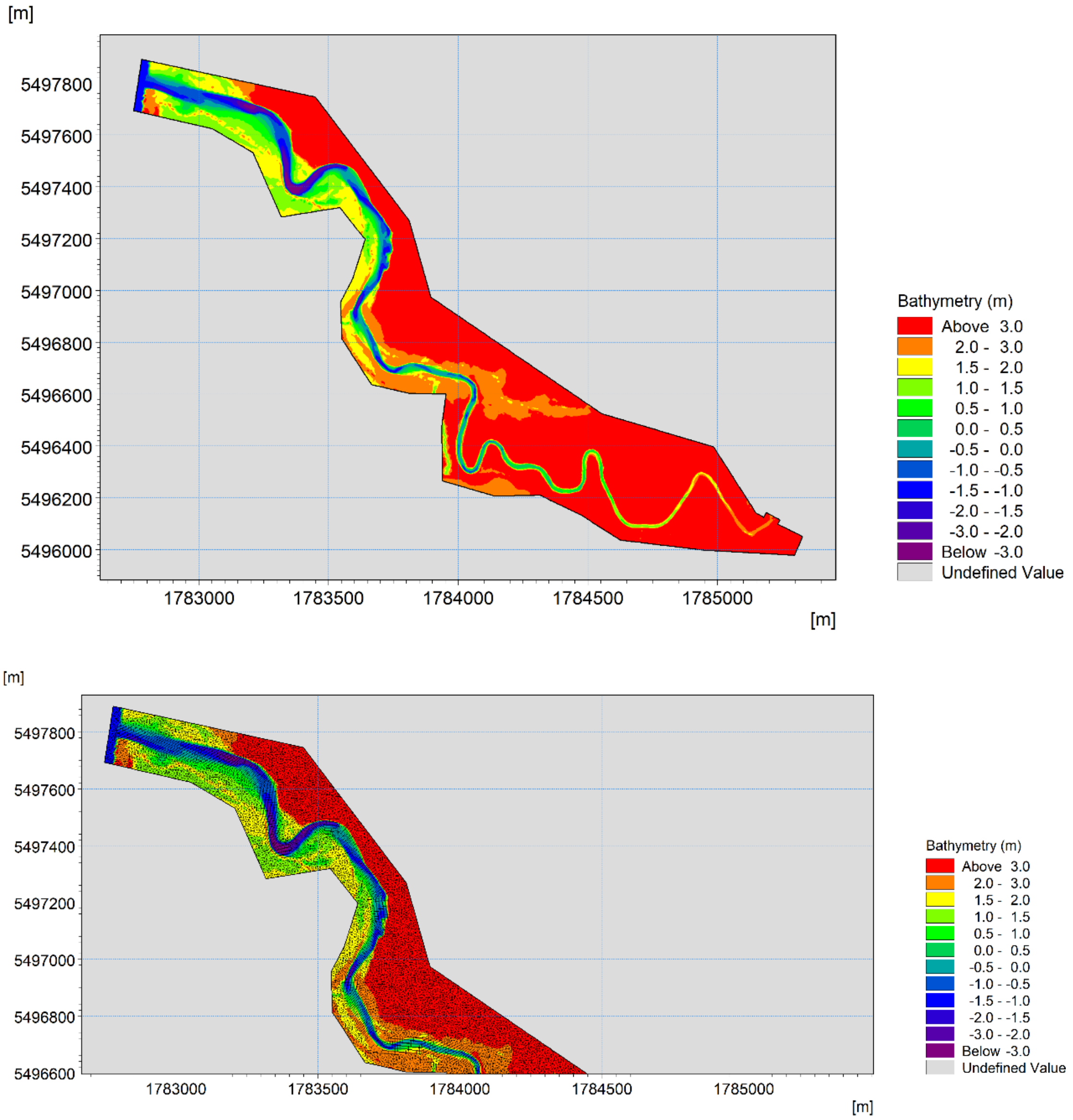
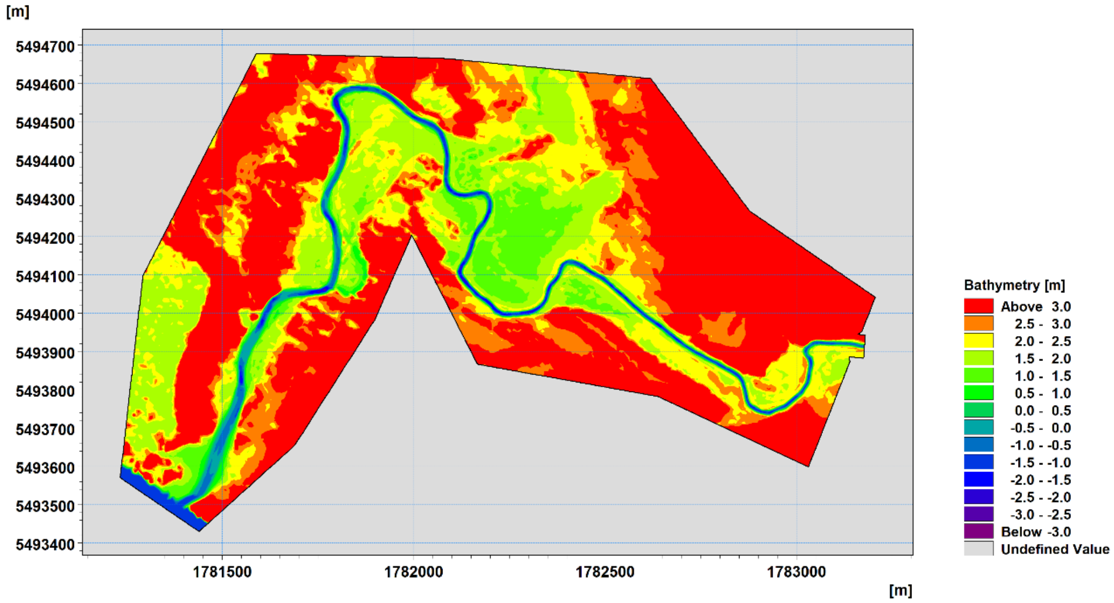


Figure 5-1 Ōhau Estuary model extent (top) and lower river mesh (bottom).



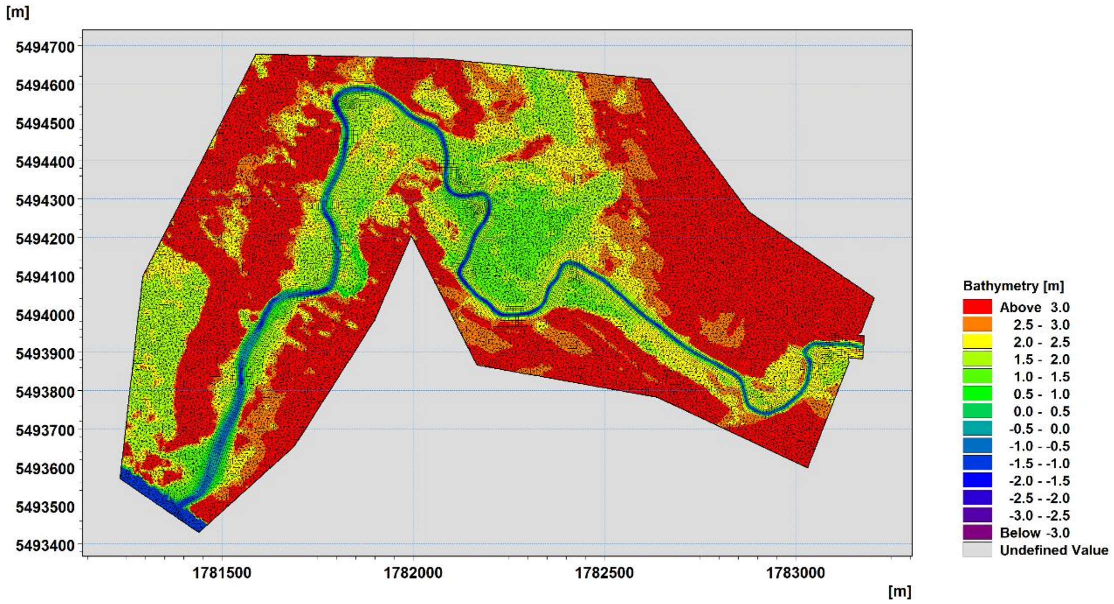


Figure 5-2 Waikawa Estuary model extent (top) and stream mesh (bottom).

5.2 Downstream Boundaries

Since the bathymetry data provided by HRC did not extend to the mouth of the estuaries, the water level data (filtered to remove high frequency noise) from the lower estuaries has been used as the downstream boundary for the models. A salinity of 35 PSU is applied at the downstream boundary.

Appropriate open ocean TN and TP concentrations have been obtained from the New Zealand Estuary Trophic Index database (Zeldis et al., 2017). This suggests that for the Manawatu coastline (i.e. Whanganui River), background oceanic concentrations of 17.9 mg/m^3 and 7.3 mg/m^3, can be assumed for TN and TP respectively.

5.3 Freshwater Inflows

Freshwater inflows for the Ōhau and Waikawa Streams have been applied as upstream boundaries for the models. The freshwater inflows are assigned a salinity of zero PSU.

Appropriate freshwater TN and TP concentrations have been derived from the nutrient loads calculated by Land Water People (Fraser and Snelder, 2021).

TN and TP were provided as annual loads. To determine an appropriate associated concentration, the load has been divided by annual volume of freshwater, assessed from mean flow, to generate a concentration.

Concentrations were calculated by dividing the annual load of TN and TP by the volume of water calculated from the yearly mean flows for 2018.

Using these methods the concentrations shown in Table 5-1 were calculated.

Table 5-1 River/stream flow TN and TP concentrations based on load estimates from Land Water People (Fraser and Snelder) and observed inflows.

River/Stream	Fraser and Snelder	
	TN (mg/m^3)	TP (mg/m^3)
Waikawa	1689.5	126.3
Ōhau	876.3	66.5

5.4 Representation of Nutrients in Estuary Models

TN and TP are not represented in the models as such, instead a dilution factor is calculated based on the predicted salinity. Thus the mixing processes driving the gradients in salinity from freshwater sources (0 PSU) to open ocean (35 PSU) are assumed to be driving the predicted reductions in nutrients that occur moving away from the sources of catchment derived nutrients.

Table 5-2 presents an overview of calculated TN and TP for each estuary and nutrient calculation method based on salinity.

Table 5-2 Overview of calculated TN and TP concentrations (mg/m^3) based on using salinity dilution factor approach.

Salinity (PSU)	Dilution Factor	Ōhau Estuary		Waikawa Estuary	
		TN	TP	TN	TP
0	1.00	876.30	66.50	1689.50	126.30
1	0.97	851.77	64.81	1641.74	122.90
2	0.94	827.25	63.12	1593.98	119.50
3	0.91	802.72	61.43	1546.22	116.10
4	0.89	778.20	59.73	1498.46	112.70
5	0.86	753.67	58.04	1450.70	109.30
6	0.83	729.15	56.35	1402.94	105.90
7	0.80	704.62	54.66	1355.18	102.50
8	0.77	680.09	52.97	1307.42	99.10
9	0.74	655.57	51.28	1259.66	95.70
10	0.71	631.04	49.59	1211.90	92.30
11	0.69	606.52	47.89	1164.14	88.90
12	0.66	581.99	46.20	1116.38	85.50
13	0.63	557.47	44.51	1068.62	82.10
14	0.60	532.94	42.82	1020.86	78.70
15	0.57	508.41	41.13	973.10	75.30
16	0.54	483.89	39.44	925.34	71.90
17	0.51	459.36	37.75	877.58	68.50
18	0.49	434.84	36.05	829.82	65.10
19	0.46	410.31	34.36	782.06	61.70
20	0.43	385.79	32.67	734.30	58.30
21	0.40	361.26	30.98	686.54	54.90
22	0.37	336.73	29.29	638.78	51.50
23	0.34	312.21	27.60	591.02	48.10
24	0.31	287.68	25.91	543.26	44.70
25	0.29	263.16	24.21	495.50	41.30
26	0.26	238.63	22.52	447.74	37.90
27	0.23	214.11	20.83	399.98	34.50
28	0.20	189.58	19.14	352.22	31.10
29	0.17	165.05	17.45	304.46	27.70
30	0.14	140.53	15.76	256.70	24.30
31	0.11	116.00	14.07	208.94	20.90
32	0.09	91.48	12.37	161.18	17.50
33	0.06	66.95	10.68	113.42	14.10
34	0.03	42.43	8.99	65.66	10.70
35	0.00	17.90	7.30	17.90	7.30

5.5 Model Set Up

An appropriate initial condition for the salinity throughout river/estuary systems was derived by running the models for a one-day warmup period.

An overview of the MIKE 3 FM model specifications for the model are presented in Table 5-3.

Table 5-3 Specifications for hydrodynamic models.

Parameter	Value
Layers	Combined sigma and z-level. Sigma:8 layers with sigma depth = -0.8 m. Non equidistant layers – 0.245, 0.2, 0.2, 0.1, 0.1, 0.075, 0.05, 0.03 z- level: 5 layers. 1, 1, 0.5, 0.5, 0.2
Solution Technique	High order, slow algorithm. Minimum time step: 1×10^{-7} s. Maximum time step: 30 s. Critical CFL number: 0.95.
Enable Flood and Dry	Drying depth: 0.005 m. Wetting depth: 0.1 m.
Eddy Viscosity	Horizontal: Smagoringsky formulation, constant 0.28 (dimensionless) Vertical: k-epsilon formulation.
Resistance	Constant roughness height – 0.0001m.
Coriolis Forcing	Varying in domain based on the geographical information given in the mesh file.

5.6 Calibration

This section provides an overview of the model calibration for both estuaries.

5.6.1 Ōhau Estuary

A comparison of the observed and predicted flow close to the downstream boundary is shown in Figure 5-3. The peak flood flow was underpredicted by approximately 20%, while the peak ebb flow was underpredicted by approximately 30%.

A comparison of observed and predicted time series of salinity close to downstream model boundary at the water surface and close to the seabed is presented in Figure 5-4. There is a very good match between observed and predicted salinities.

A comparison of measured and predicted salinity for selected CTD casts is shown in Figure 5-5.

The sharp interface between the surface freshwater and underlying salt wedge is not well resolved by the model, which results in higher predicted salinities in the surface water than those measured. This is not uncommon for 3D hydrodynamic models, since there has to be a compromise on number of layers in the vertical to achieve reasonable run times (which results in layers in order of 10 to 20 cm thick) and trying to resolve saltwater/freshwater interfaces that can exist anywhere in the top half of the water column and be less than 10 cm thick. However, the maximum extent of the salt wedge was very well matched, with very low salinities predicted (less than 5 PSU) at CTD location 10, where no salinity was observed.

The model was deemed sufficiently calibrated with the data available for the objective of the assessment. Although the flow is underpredicted, the fact that there was a reasonable comparison between observed and predicted salinity, especially the maximum extent of the salt wedge, provides confidence the model is reasonably predicting the salt intrusion behaviour within the estuary.

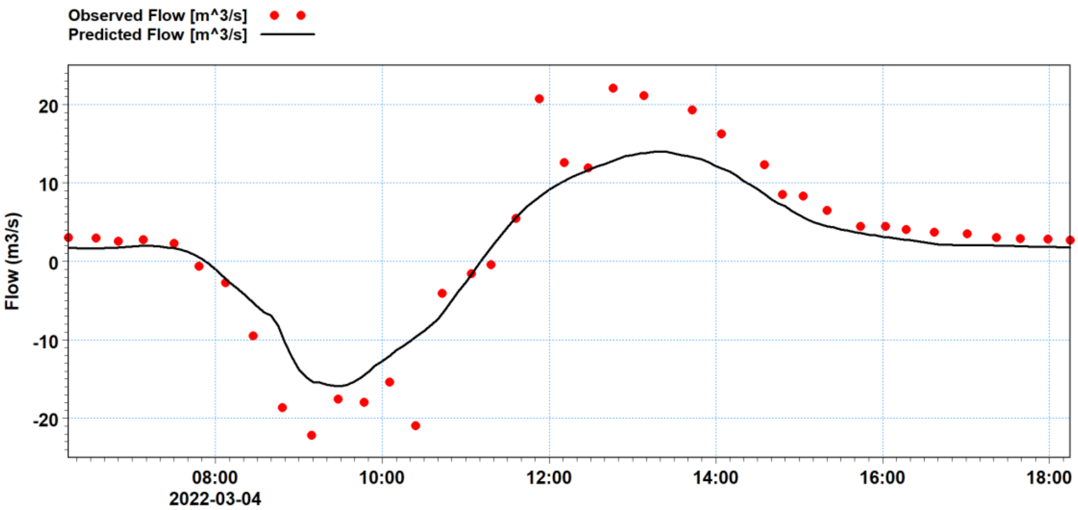
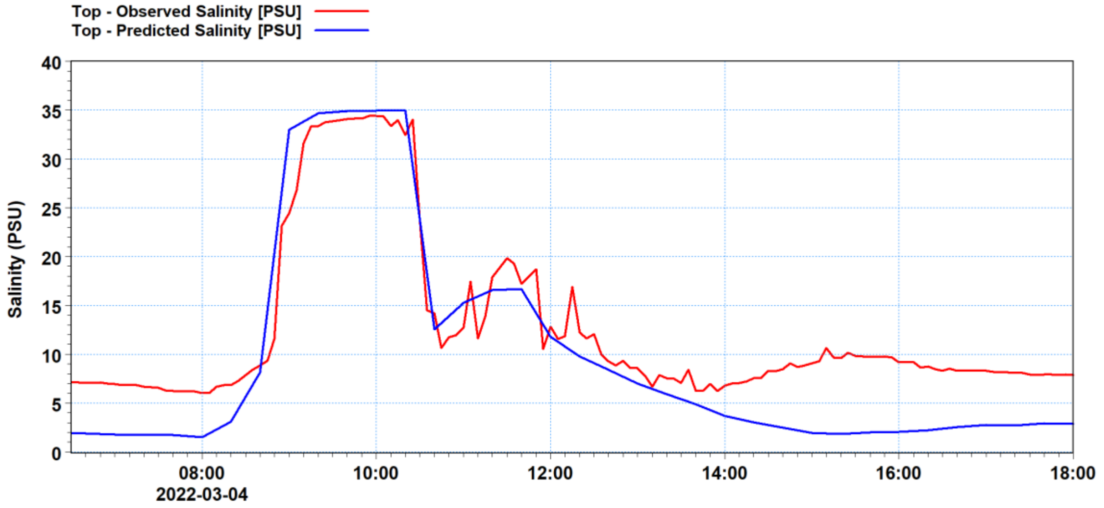


Figure 5-3 Comparison of measured and predicted flow through transect close to downstream model boundary for Ōhau Estuary.



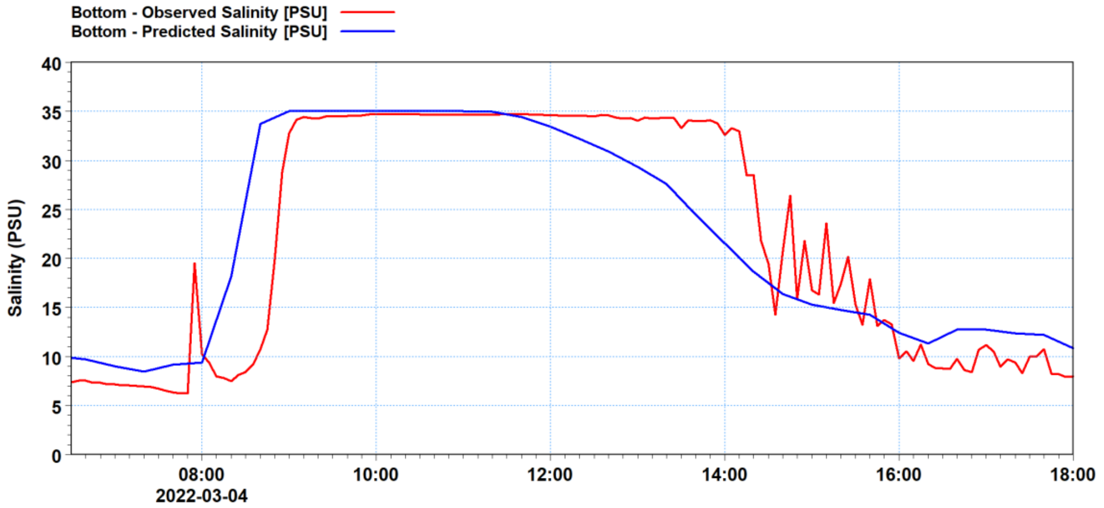


Figure 5-4 Comparison of measured and predicted salinity for Ōhau Estuary, close to the water surface (top) and at the seabed (bottom).

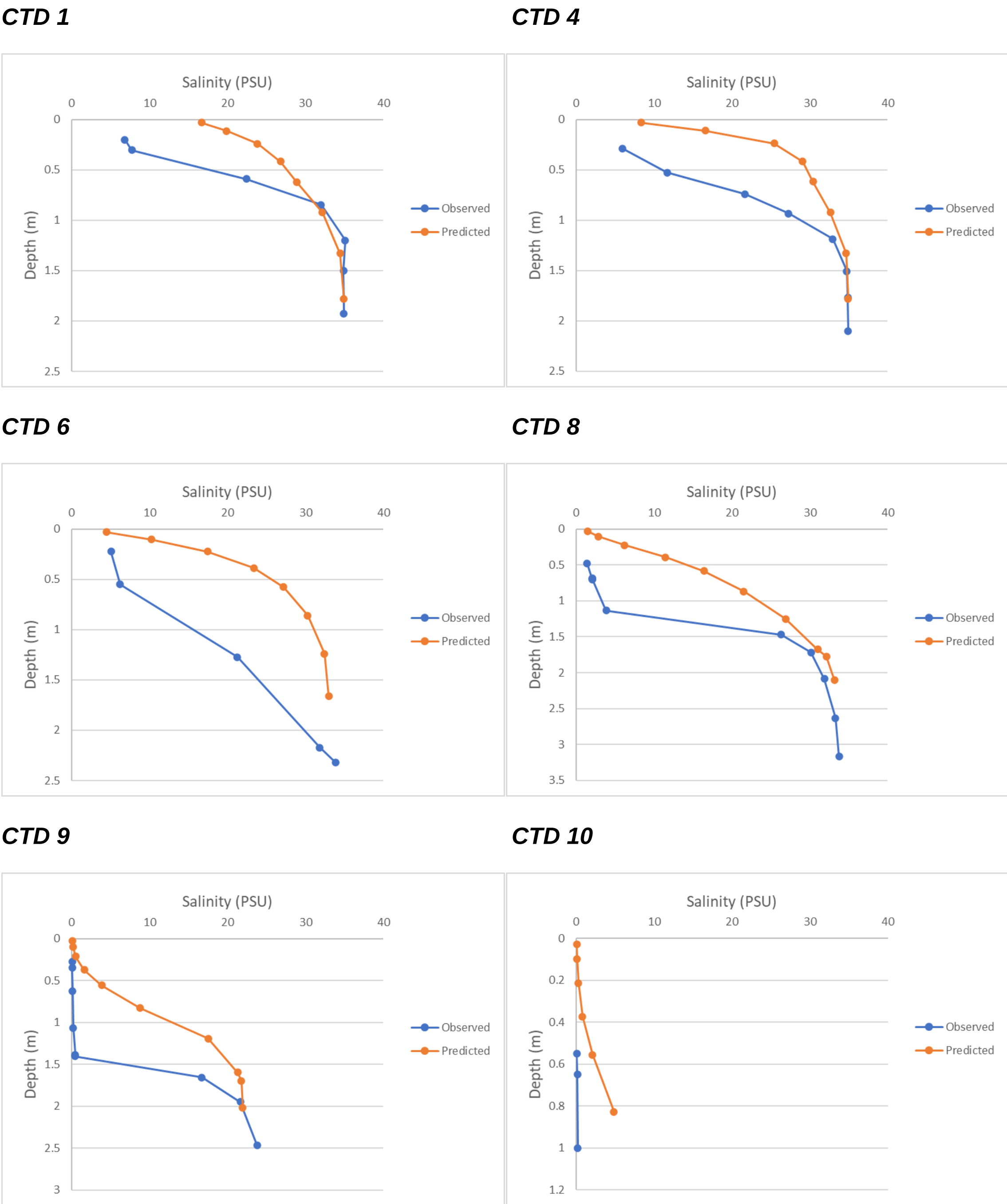


Figure 5-5 Comparison of measured and predicted salinity for Ōhau Estuary for selected CTD casts.

5.6.2 Waikawa Estuary

A comparison of the observed and predicted flow close to the downstream boundary is shown in Figure 5-6. The peak flood flow was underpredicted by less than 5%, with a slight lag in the timing of the incoming flow, while the peak ebb flow was underpredicted by approximately 30%.

A comparison of observed and predicted time series of salinity close to the downstream model boundary at the water surface and close to the seabed is presented in Figure 5-7. There is a very good match between observed and predicted salinities, typically within 5 PSU or less.

A comparison of measured and predicted salinity for selected CTD casts is shown in Figure 5-8. Similar to Ōhau Estuary, the sharp interface between the surface freshwater and underlying salt wedge is not well resolved by the model, which results in higher predicted salinities in the surface water than those measured. However, the maximum extent of the salt wedge was very well matched, with no salinity predicted at CTD location 15, where very low salinities (less than 2 PSU) was observed.

The model was deemed sufficiently calibrated with the data available for the objective of the assessment. The flood flow is reasonably well matched, there was a good comparison between observed and predicted salinity, especially the maximum extent of the salt wedge, which again provides confidence the model is reasonably predicting the salt intrusion behaviour within the estuary.

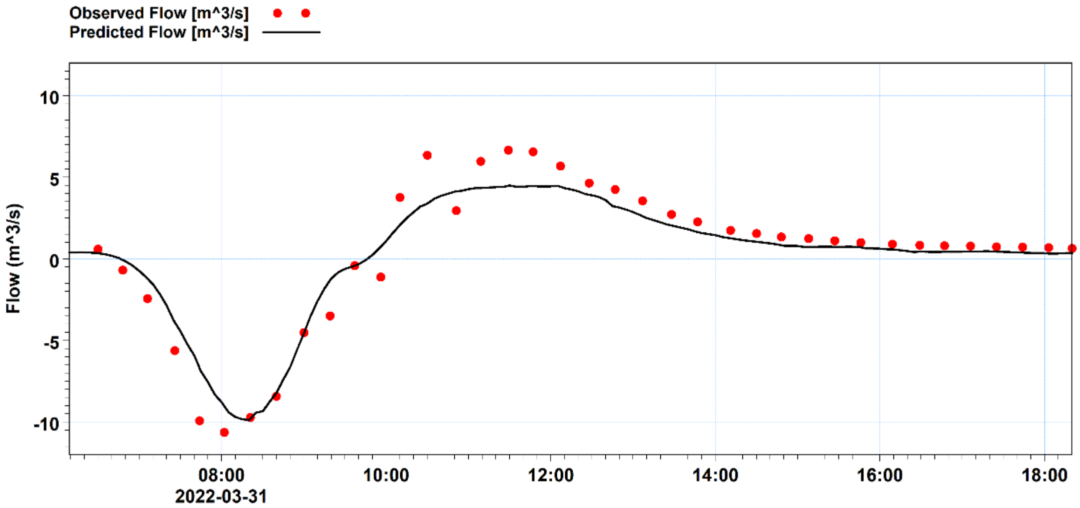


Figure 5-6 Comparison of measured and predicted flow through transect close to downstream model boundary for Waikawa Estuary.

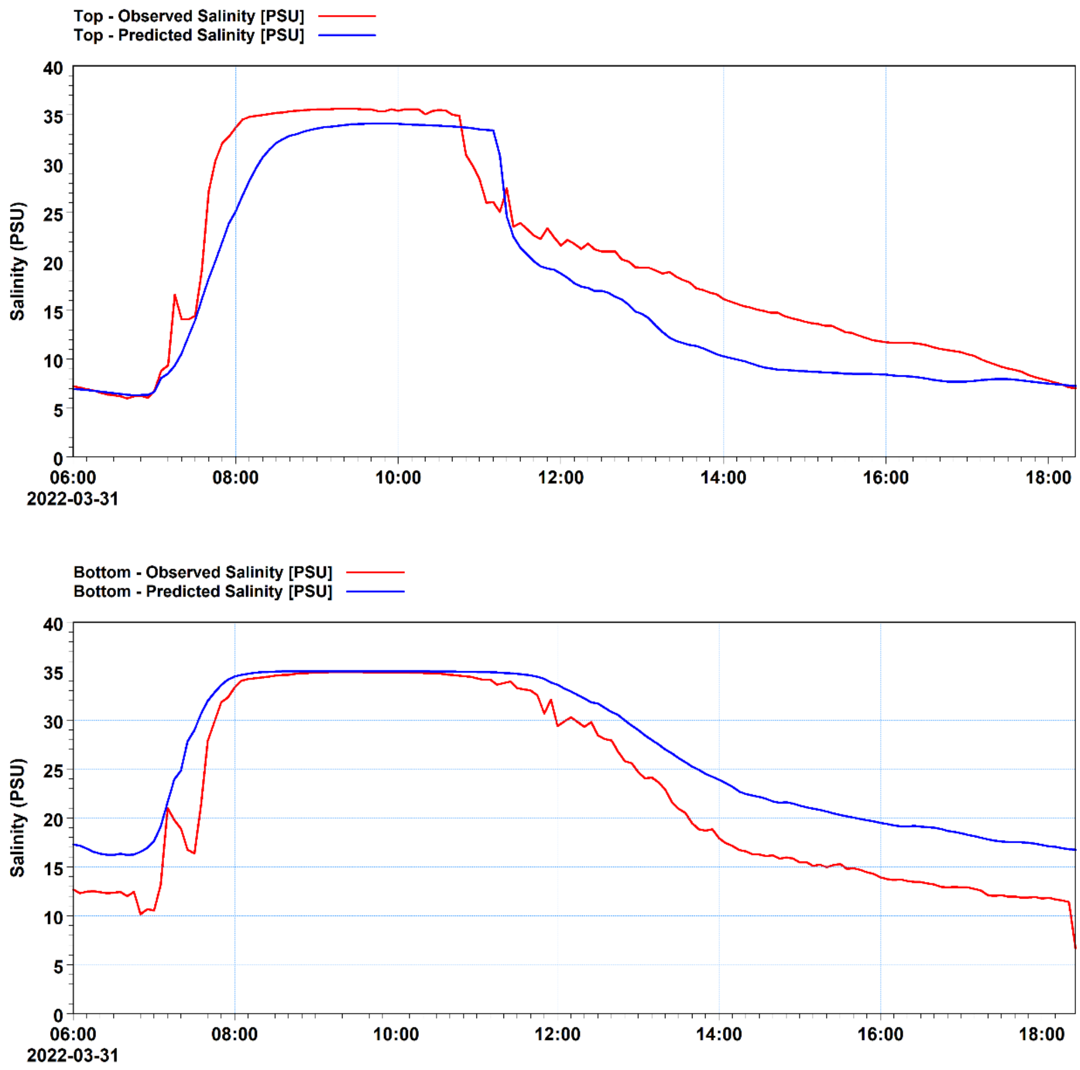
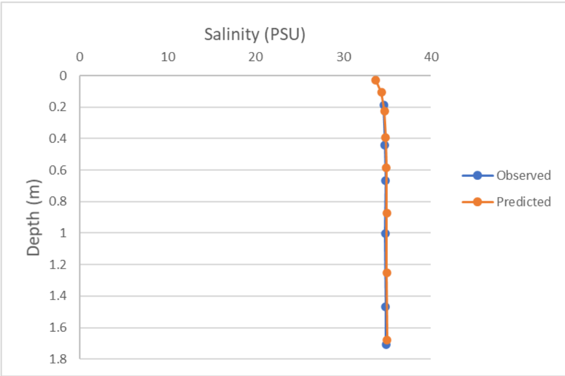
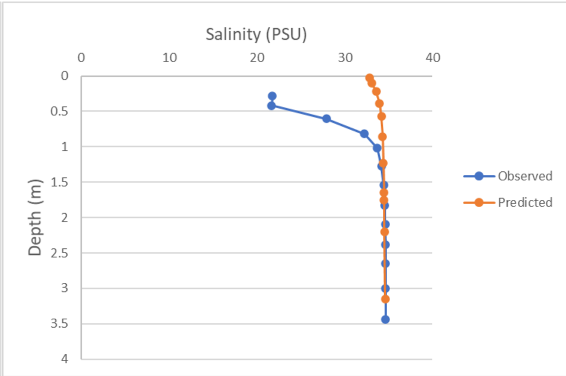


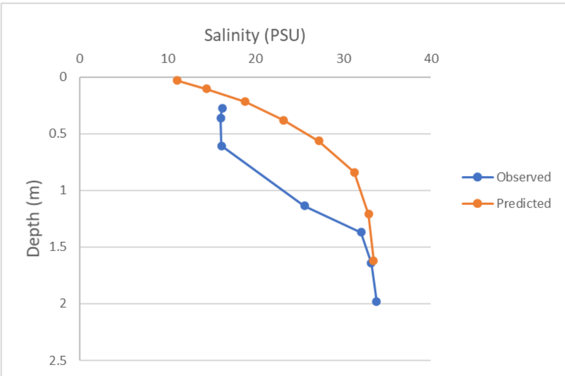
Figure 5-7 Comparison of measured and predicted salinity for Waikawa Estuary, close to the water surface (top) and at the seabed (bottom).



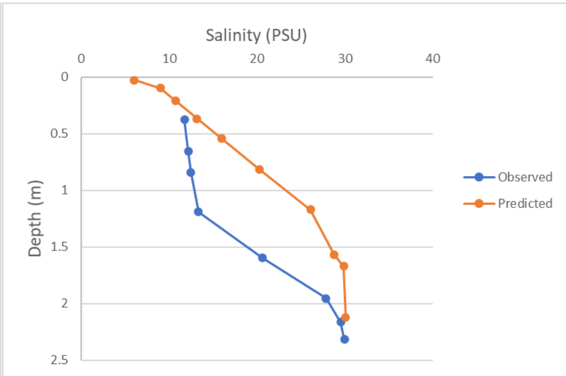
CTD 1



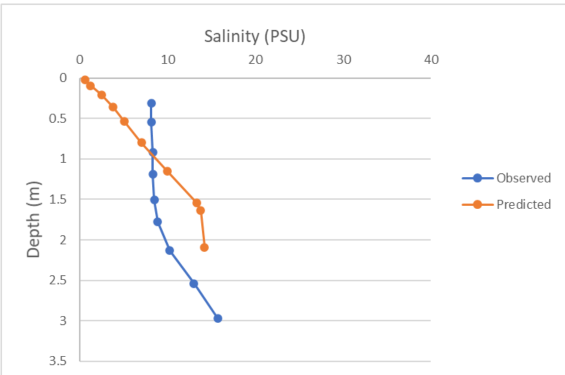
CTD 6



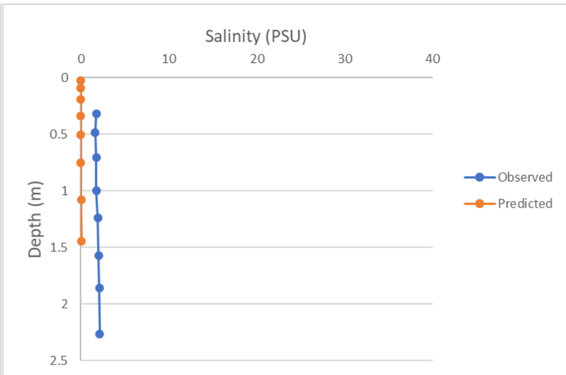
CTD 8



CTD 10



CTD 12



CTD 15

Figure 5-8 Comparison of measured and predicted salinity for Waikawa Estuary for selected CTD casts.

6 Assessment Methodology and Findings

Simulations have been undertaken for a neap/spring tidal cycle for four different stream/river flows, to cover a range of inflows for both estuaries.

Observed water levels from the downstream water level recorders have been applied as the downstream boundary for the design simulations. A 15-day period to cover a neap spring tidal cycle was identified (including a one day warm up period), when there was low flow in the river/stream, shown in Figure 6-1.

Table 6-1 presents the simulated flow for each river/stream and percentile (based on analysis of 1st January 2010 to 1st January 2021 flow data). A 10th percentile flow can be considered similar to summer low flows; 50th percentile flow is median flow; 75th percentile flow (close to mean flow); and 95th percentile, a small fresh in the river/streams.

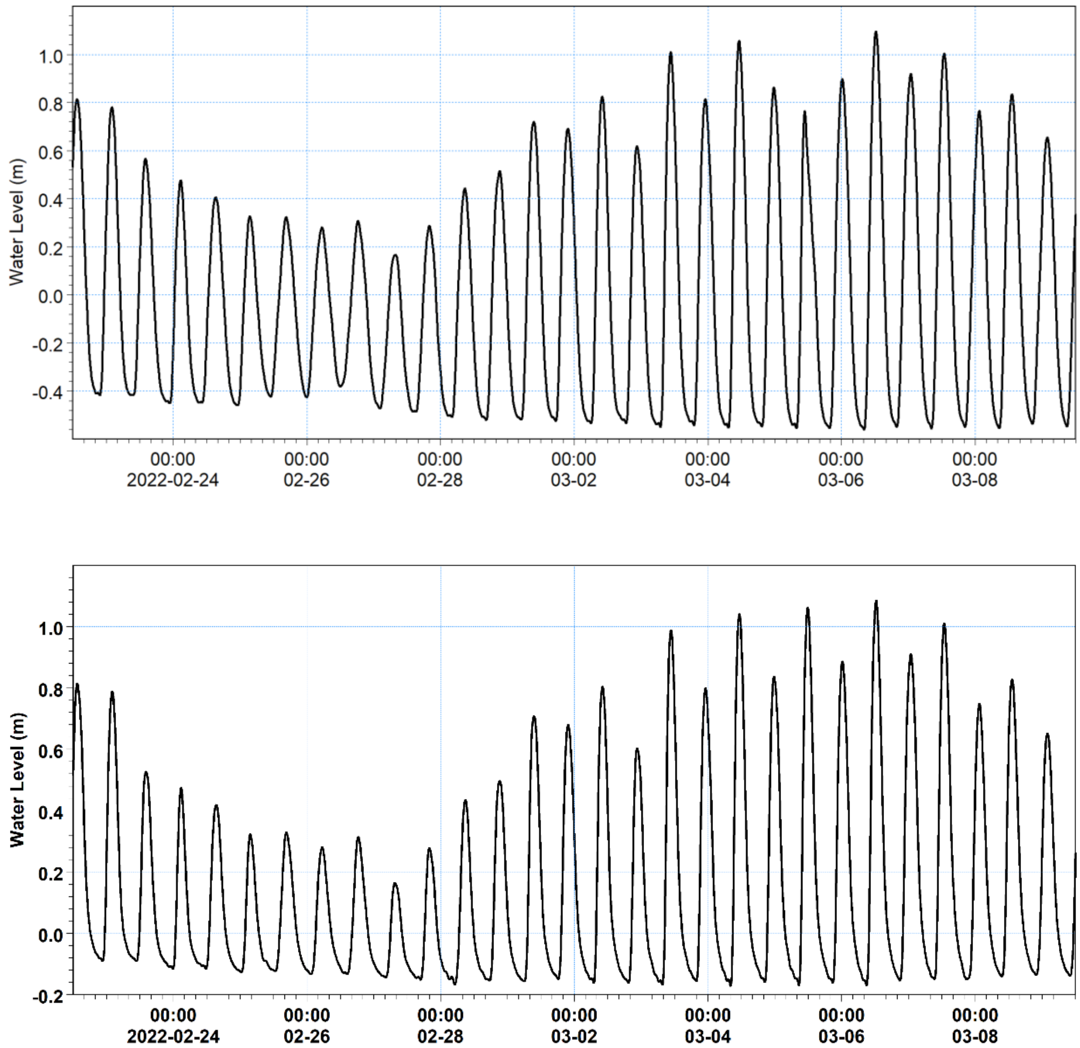


Figure 6-1 Downstream boundary condition applied for each estuary for the neap/spring tidal cycle for Ōhau Estuary (top) and Waikawa Estuary (bottom).

Table 6-1 The simulated flow for each river/stream and its corresponding percentile (based on 1st January 2010 to 1st January 2021 flow data).

River/Stream	Flow (m^3/s)	Percentile
Waikawa	0.4	10th
	0.9	50th
	1.5	75th
	4.0	95th
Ōhau	1.9	15th
	3.9	50th
	6.9	75th
	18.6	95th

Time series of salinity were extracted from 5 locations through the model domain (see Figure 6-2), at close to the estuary/riverbed.

The mean salinity was then calculated for each time series (see Table 6-2 to Table 6-3) and from this the associated TN and TP concentrations were calculated (see Table 6-4 to Table 6-7) based on the salinity dilution factor approach (see Section 4.4).

The mean flow, mean concentrations have been used for determining the current TN band or TP threshold for each of the locations in the estuaries, as shown in Table 6-8 to Table 6-9.

The low flow scenario, mean concentrations have also been utilised as a proxy for band or threshold during summer low flow conditions (typically occurring January, February and March) also shown in Table 6-8 to Table 6-9.

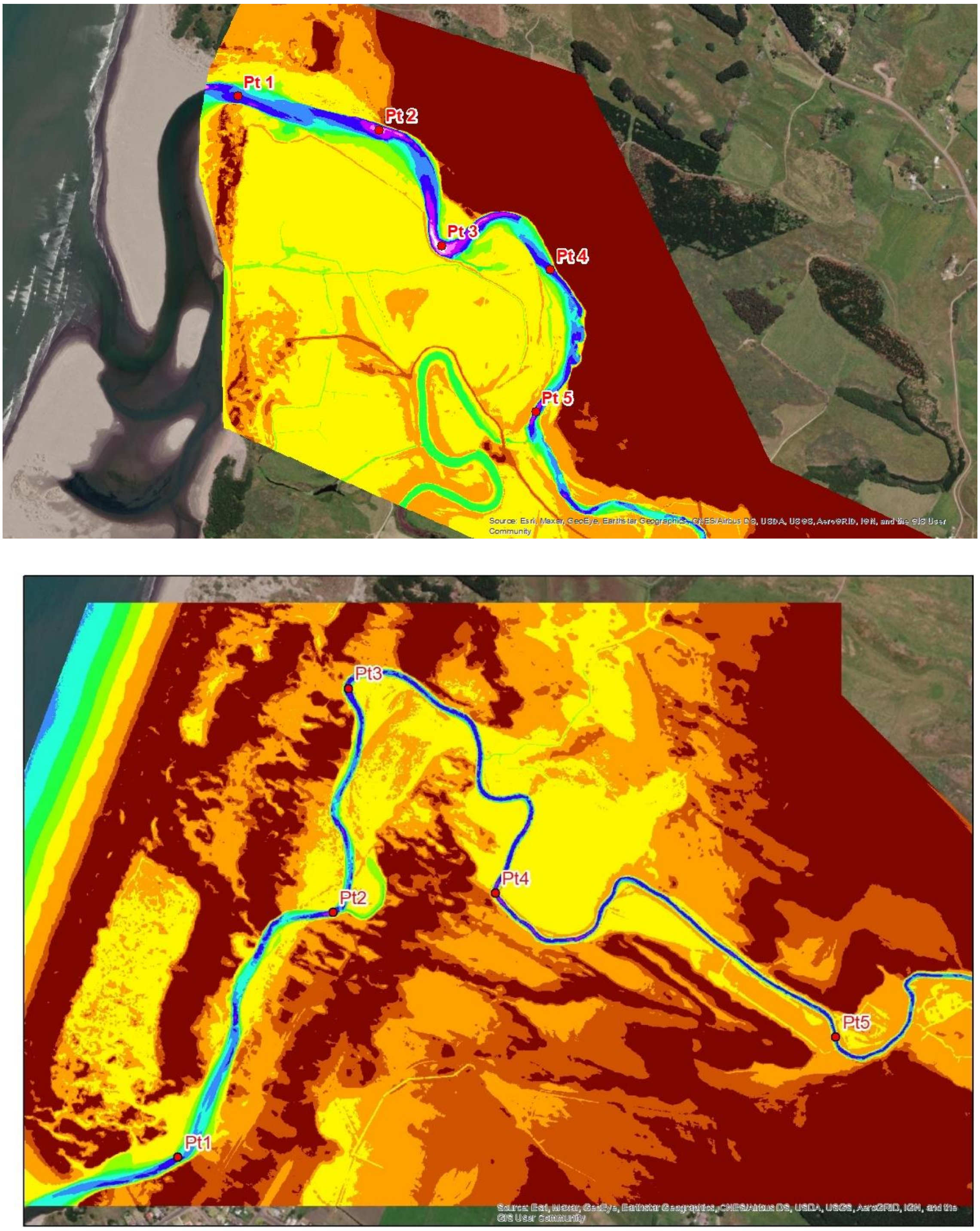


Figure 6-2 Locations where time series of salinity were extracted from the domain at close to the estuary/riverbed in Ōhau Estuary (top) and Waikawa Estuary (bottom).

Table 6-2 Predicted mean salinity (PSU) for locations in Ōhau Estuary

Location	Flow (m^3/s)			
	1.9	**3.9**	**6.9**	**18.6**
Pt 1	25.0	14.6	7.4	0.0
Pt 2	31.6	21.4	10.0	0.0
Pt 3	26.0	14.4	3.3	0.0
Pt 4	9.6	2.1	0.1	0.0
Pt 5	2.1	0.0	0.0	0.0

Table 6-3 Predicted mean salinity (PSU) for locations in Waikawa Estuary

Location	Flow (m^3/s)			
	0.4	**0.9**	**1.5**	**4.0**
Pt 1	26.4	18.5	12.3	4.4
Pt 2	18.7	7.6	4.9	0.5
Pt 3	14.8	4.0	1.8	0.0
Pt 4	2.9	0.2	0.0	0.0
Pt 5	0.0	0.0	0.0	0.0

Table 6-4 Predicted TN concentrations (mg/m^3) for locations in Ōhau Estuary

Location	Flow (m^3/s)			
	1.9	**3.9**	**6.9**	**18.6**
Pt 1	263.2	508.4	459.4	876.3
Pt 2	91.5	361.3	631.0	876.3
Pt 3	238.6	532.9	802.7	876.3
Pt 4	631.0	827.2	876.3	876.3
Pt 5	827.2	876.3	876.3	876.3

Table 6-5 Predicted TP concentrations (mg/m^3) for locations in Ōhau Estuary

Location	Flow (m^3/s)			
	1.9	**3.9**	**6.9**	**18.6**
Pt 1	24.2	41.1	37.7	66.5
Pt 2	12.4	31.0	49.6	66.5
Pt 3	22.5	42.8	61.4	66.5
Pt 4	49.6	63.1	66.5	66.5
Pt 5	63.1	66.5	66.5	66.5

Table 6-6 Predicted TN concentrations (mg/m^3) for locations in Waikawa Estuary

Location	Flow (m^3/s)			
	0.4	0.9	1.5	4.0
Pt 1	447.7	782.1	1116.4	1498.5
Pt 2	782.1	1307.4	1450.7	1641.7
Pt 3	973.1	1498.5	1594.0	1689.5
Pt4	1546.2	1689.5	1689.5	1689.5
Pt 5	1689.5	1689.5	1689.5	1689.5

Table 6-7 Predicted TP concentrations (mg/m^3) for locations in Waikawa Estuary

Location	Flow (m^3/s)			
	0.4	0.9	1.5	4.0
Pt 1	37.9	61.7	85.5	112.7
Pt 2	61.7	99.1	109.3	122.9
Pt 3	75.3	112.7	119.5	126.3
Pt4	116.1	126.3	126.3	126.3
Pt 5	126.3	126.3	126.3	126.3

Table 6-8 Current TN band and TP Threshold for locations in Ōhau Estuary.

Location	Mean Flows		Summer Low Flows	
	Current TN Band	Current TP Threshold	Current TN Band	Current TP Threshold
Pt 1	D	Unsatisfactory	C	Satisfactory
Pt 2	D	Unsatisfactory	B	Satisfactory
Pt 3	D	Unsatisfactory	C	Satisfactory
Pt 4	D	Unsatisfactory	D	Unsatisfactory
Pt 5	D	Unsatisfactory	D	Unsatisfactory

Table 6-9 Current TN band and TP Threshold for locations in Waikawa Estuary.

Location	Mean Flows		Summer Low Flows	
	Current TN Band	Current TP Threshold	Current TN Band	Current TP Threshold
Pt 1	D	Unsatisfactory	D	Unsatisfactory
Pt 2	D	Unsatisfactory	D	Unsatisfactory
Pt 3	D	Unsatisfactory	D	Unsatisfactory
Pt 4	D	Unsatisfactory	D	Unsatisfactory
Pt 5	D	Unsatisfactory	D	Unsatisfactory

The near bed salinity time series for all locations in Ōhau Estuary with a 1.9 m³/s inflow over a neap spring tide cycle is shown as an example of the model outputs in Figure 6-3. For neap tides (26th to 28th February), the dominance of the river/stream inflow (and resulting lower salinities) becomes apparent at all locations, while for spring tides (5th to 7th March), the salt wedge dominates the pools in the lower estuary (Pt 2 and Pt 3) and is able to propagate up to Pt 5. It should be noted that although Pt 2 and Pt 3 are predominantly saline throughout the simulation (and thus have lower nutrient concentrations), over a neap tide, as the salinity drops, the nutrient concentration would increase, and phytoplankton growth could still occur over this short 3 day window.

Therefore, sitting in B band, does not mean phytoplankton growth will never occur. Once growth commences, phytoplankton may reach nuisance levels, since the water where growth occurs can become trapped in a stable halocline in deeper pools and not be flushed out until river/stream flows become elevated again.

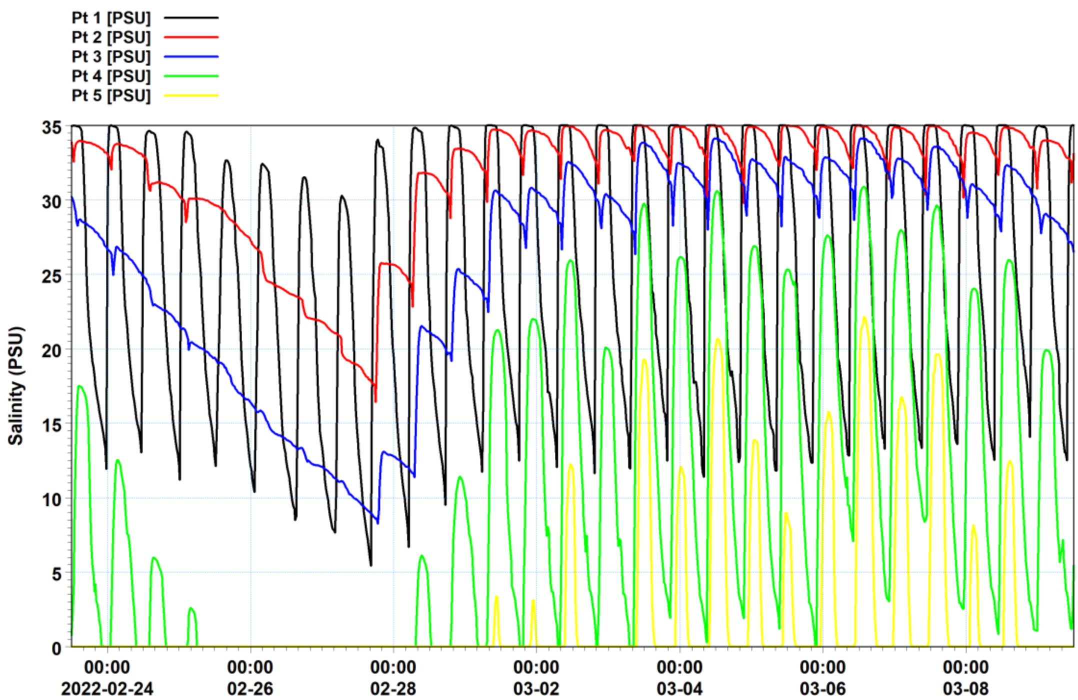


Figure 6-3 Near bed salinity time series for all locations in Ōhau Estuary with a 1.9 m3/s inflow over a neap spring tide cycle

Calculations were then carried out to assess the catchment nutrient load reductions required to move to improved TN bands or TP thresholds, which are presented in Table 6-10 to Table 6-13.

It should be noted that the load reduction only accounts for catchment derived nutrient loads and not the downstream nutrients from the open ocean.

Key observations from the predictions for Ōhau Estuary, based on the estimates of Fraser and Snelder (2021), are as follows:

- Based on mean flow, all locations are D Band for TN and unsatisfactory for TP based on mean flow conditions.

- For low flow summer conditions, Pt 1 to Pt 3 have a better band/threshold than compared to the mean flow conditions. There is no change for Pt 4 and Pt 5, since the salt wedge only propagates to these locations for low flow and mid to spring tides.
- For all locations to improve on the mean flow basis for TN would require a 63% load reduction to achieve Band C, a 77% load reduction for Band B and a 91% load reduction for Band A.
- For Pt 1 to Pt 3 to improve on an annual basis for TN would require a 60% load reduction to achieve Band C, a 75% load reduction for Band B and a 90% load reduction for Band A.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve the TN band to B will require a 25% load reduction, and A band will require a 73% load reduction.
- For all locations to improve on the mean flow basis for TP would require a 55% load reduction to achieve a Satisfactory threshold and an 85% load reduction to achieve an Excellent threshold.
- For Pt 1 to Pt 3 to improve on an annual basis for TP would require a 52% load reduction to achieve a Satisfactory threshold and an 85% load reduction to achieve an Excellent threshold.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve TP threshold to Excellent threshold will require a 75% load reduction.

Key observations from the predictions for Waikawa Estuary, based on the estimates of Fraser and Snelder (2021), are as follows:

- For all flow conditions and all locations are D for TN band and unsatisfactory for TP threshold.
- For all locations to improve on the mean flow basis for TN would require an 81% load reduction to achieve Band C, an 88% load reduction for Band B and a 95% load reduction for Band A.
- For Pt 1 to Pt 3 to improve on the mean flow basis for TN would require an 80% load reduction to achieve Band C, a 88% load reduction for Band B and a 95% load reduction for Band A.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve the TN band to C will require a 68% load reduction, a 80% load reduction for Band B and a 93% load reduction for Band A.
- For all locations to improve on the mean flow basis for TP would require a 76% load reduction to achieve a Satisfactory threshold and a 92% load reduction to achieve an Excellent threshold.
- For Pt 1 to Pt 3 to improve on the mean flow basis for TP would require a 75% load reduction to achieve a Satisfactory threshold and a 92% load reduction to achieve an Excellent threshold.
- During summer low flow conditions, for Pt 1 to Pt 3 to improve on an annual basis for TP would require a 63% load reduction to achieve a Satisfactory threshold and a 90% load reduction to achieve an Excellent threshold.

Table 6-10 Percentage reduction in TN load required to achieve band A, B or C for locations in Ōhau Estuary.

Location	Band	Mean Flows	Summer Low Flows
Pt 1	C	31	N/A
	B	58	25
	A	84	73
Pt 2	C	50	N/A
	B	69	N/A
	A	88	15
Pt 3	C	60	N/A
	B	75	17
	A	90	70
Pt 4	C	63	50
	B	77	69
	A	91	88
Pt 5	C	63	61
	B	77	76
	A	91	90

Table 6-11 Percentage reduction in TP load required to achieve threshold satisfactory or excellent locations in Ōhau Estuary.

Location	Threshold	Mean Flows	Summer Low Flows
Pt 1	Satisfactory	23	N/A
	Excellent	81	75
Pt 2	Satisfactory	41	N/A
	Excellent	83	42
Pt 3	Satisfactory	52	N/A
	Excellent	85	73
Pt 4	Satisfactory	55	41
	Excellent	85	83
Pt 5	Satisfactory	55	53
	Excellent	85	85

Table 6-12 Percentage reduction in TN load required to achieve band A, B or C for locations in Waikawa Estuary.

Location	Band	Mean Flows	Summer Low Flows
Pt 1	C	72	29
	B	83	57
	A	93	85
Pt 2	C	78	60
	B	86	75
	A	95	91
Pt 3	C	80	68
	B	88	80
	A	95	93
Pt 4	C	81	79
	B	88	87
	A	95	95
Pt 5	C	81	81
	B	88	88
	A	95	95

Table 6-13 Percentage reduction in TP load required to achieve threshold satisfactory or excellent for locations in Waikawa Estuary.

Location	Threshold	Mean Flows	Summer Low Flows
Pt 1	Satisfactory	67	24
	Excellent	91	86
Pt 2	Satisfactory	73	55
	Excellent	92	90
Pt 3	Satisfactory	75	63
	Excellent	92	90
Pt 4	Satisfactory	76	75
	Excellent	92	92
Pt 5	Satisfactory	76	76
	Excellent	92	92

Although a location might be exposed to TN/TP concentrations that are D band/unsatisfactory, the river/stream flow may be sufficient to either not allow phytoplankton growth; or flush any growth that occurs during lower flow periods out of the estuary.

To investigate this, an additional analysis was undertaken (see Table 6-14 and Table 6-15), where for each location in each estuary, the simulated flow where there was no salt intrusion predicted at the location (indicating location well flushed) was identified, using predicted mean salinity of less than 1 PSU as threshold. Then for full record (1st January 2010 to 1st January

2021) and January to March (summer low flows), the Ōhau and Waikawa Stream flow records were analysed to determine 50th and 95th percentile durations where the flow record was below this flow. This provides an indication of duration of time that a location may have phytoplankton growth before subsequent river/stream flows are elevated enough to flush the growth away.

The Ōhau River and Waikawa Stream are flashy, and there can be elevated flows for very short periods (i.e. hours). The analysis assumes that these flashy elevated flows would be sufficient to flush out the estuaries. Additional modelling would be required to investigate robustness of this assumption and refine the analysis if required.

The analysis indicates that if phytoplankton growth occurs, for the lower locations in both estuaries (Pt 1, Pt 2 and Pt 3), typically the growth will be flushed away within days (close to a week for summer low flows), however on occasions, it may take over a month for flows to be sufficient to flush away the growth.

For the locations (Pt 4 and Pt 5), again typically the growth will be flushed away within days, however on occasions, it may be in order of two to three weeks for flows to be sufficient to flush away the growth.

Table 6-14 Design simulation flow, where location in Ōhau Estuary was fully flushed with river/stream inflow and calculated 50th and 95th percentile duration below this flow for all year and with summer low flows.

Location	Flow (m^3/s)	50th Percentile Duration Below Flow		95th Percentile Duration Below Flow	
		All Year	Summer Low Flows	All Year	Summer Low Flows
Pt 1	18.6	3.4 days	5.4 days	32.1 days	39.0 days
Pt 2	18.6	3.4 days	5.4 days	32.1 days	39.0 days
Pt 3	18.6	3.4 days	5.4 days	32.1 days	39.0 days
Pt 4	6.9	2.3 days	4.2 days	17.5 days	22.5 days
Pt 5	3.9	2.0 days	3.3 days	13.5 days	16.6 days

Table 6-15 Design simulation flow, where location in Waikawa Estuary was fully flushed with river/stream inflow and calculated 50th and 95th percentile duration below this flow for all year and with summer low flows.

Location	Flow (m^3/s)	50th Percentile Duration Below Flow		95th Percentile Duration Below Flow	
		All Year	Summer Low Flows	All Year	Summer Low Flows
Pt 1	4.0	3.9 days	6.4 days	33.5 days	38.3 days
Pt 2	4.0	3.9 days	6.4 days	33.5 days	38.3 days
Pt 3	4.0	3.9 days	6.4 days	33.5 days	38.3 days
Pt 4	0.9	1.8 days	3.3 days	13.8 days	17.2 days
Pt 5	0.4	1.4 days	2.1 days	13.3 days	10.4 days

It is difficult to provide any analysis of uncertainty in the predictions for this assessment. DHI were only supplied limited data to illustrate the model doing a reasonable job of reproducing salinity intrusion and for this study that was considered sufficient. To come up with uncertainty estimates, measurements on more than one occasion would be required, from which you can then calculate model performance statistics and infer uncertainty. However it is expected, the largest uncertainty in the estimates would be a result of the assumed inflow concentrations themselves.

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