Kakanui Estuary Hydrodynamic Model

Prepared for Otago Regional Council

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Executive summary

The Kakanui Estuary experiences high algae growth in summer months. Large mats of *Ulva*, predominantly *U. intestinalis*, can be observed over much of the estuary bed, and, at times, suspended algae concentrations are also high. The Otago Regional Council seeks information that will allow it to relate estuarine water quality with river flows and nutrient loads. This will inform decisions about setting catchment nutrient loads or minimum river flows with regards to implications for the Kakanui Estuary.

In this project, NIWA conducted a bathymetric survey of the Kakanui Estuary. The data from this survey were used to create a hydrodynamic model of the estuary. The hydrodynamic model was run for a range of Kakanui River flows and with 4 different mouth configurations (closed and 3 open mouths of different size) to determine the likely concentrations and distributions of nutrients within the estuary. Water level, flow data and photographs provided by the Otago Regional Council are used to make assessments of aspects of hydrodynamic behaviour of the estuary. NIWA also conducted tissue nitrogen, carbon and isotope analysis of *Ulva* present in the estuary to determine if any parts of the estuary were more susceptable to riverine nitrogen (as opposed to oceanic nitrogen).

The modelling and field data show that concentrations of nutrients in the estuary are controlled by the flow and concentration of nutrients in the Kakanui River and Waiareka Creek, and the state of the estuary mouth. When the estuary is open to the sea, such that seawater can enter on the incoming tide, nitrogen concentrations are reduced compared to the situation when the mouth is closed to the sea.

The *Ulva* tissue-N concentrations indicate that there is sufficient nitrogen available to allow moderate to high growth rates. These samples were collected after a period of partial mouth opening (where there was some tidal influence). The model predicts that, assuming mean Dissolved Inorganic Nitrogen (DIN) concentrations in the river inflows, concentrations of DIN in the estuary would be some 25-40% lower when the mouth is open compared to when the mouth is closed. This suggests that while opening the mouth will reduce in-estuary nutrient concentrations, it is likely to have only a small influence on *Ulva* growth rates without also reducing nitrogen input to the estuary.

1 Introduction

The Kakanui Estuary experiences high algae growth in summer months. Large mats of *Ulva*, predominantly *U. intestinalis*, can be observed over much of the estuary bed, and, at times, suspended algae concentrations are also high. The Otago Regional Council seeks information that will allow it to relate estuarine water quality with river flows and nutrient loads. This will inform decisions about setting catchment nutrient loads or minimum river flows with regards to implications for the Kakanui Estuary.

In this project, NIWA conducted a bathymetric survey of the Kakanui Estuary. The data from this survey were used to create a hydrodynamic model of the estuary. The hydrodynamic model was run for a range of river flows and with 4 different mouth configurations to determine the likely concentrations and distributions of nutrients within the estuary. We also use water level, flow data and photographs provided by the Otago Regional Council to make assessments of aspects of hydrodynamic behaviour of the estuary.

NIWA also conducted tissue nitrogen, carbon and isotope analysis of *Ulva* present in the estuary to determine if any parts of the estuary were more susceptable to riverine nitrogen (as opposed to oceanic nitrogen).

Information from these two approaches are used to produce a guide to what estuarine health conditions may be expected under different nutrient concentrations.

2 Field data

2.1 *Ulva* collection and tissue nitrogen, carbon and isotope analysis

Tissue samples of *Ulva intestinalis* were collected from 20 stations along both sides of the Kakanui Estuary on 4 Feb 2015 (see Figure 2-1). Only healthy *Ulva* specimens that were growing on the surface of the water and that were attached (to other vegetation or the substrate), were selected. Samples of *U. intestinalis* were also collected from a site on the open coast north of the Kakanui Estuary mouth to represent an open coast example for comparison with estuarine samples (Figure 2-1). After each collection samples were immediately rinsed in deionised water, surface dried with paper towels and then placed in labelled ziplock bags in a chilly bin for transportation to a laboratory. Samples were then stored frozen at -80 °C and later dried to a constant weight at 65 °C (~48 hours). After drying the tissue samples were then ground to a fine powder for nitrogen, carbon and isotope analysis using a Dumas elemental analyser (Europa Scientific ANCA-SL) interfaced to an isotope mass spectrometer (Europa Scientific 20-20 Stable Isotope Analyser). Samples were analysed against a urea standard / reference with a delta value of -0.45 ‰. Measurement precision was $\pm$1 %.

Figure 2-1: Locations where *Ulva* samples were collected on 4 Feb 2015.

2.2 River flows

Two rivers flow into the upper Kakanui Estuary: the Kakanui River and Waiareka Creek. Flow data for these two tributaries were supplied by the Otago Regional Council. A summary table of key flow statistics from the period of data received are given in Table 2-1. The Kakanui River provides the majority of the flow into the estuary. Flows in the Kakanui River are also more variable than in the Waiareka Creek. The Waiareka Creek has a stable base flow. Currently there is a minimum flow of 100 l s^{-1} imposed on this creek[1] . Note that the Mean Annual Low Flow (MALF) and 7 day MALF are

[1] The North Otago Irrigation Company has a consent to discharge into the Waiareka Creek up to 300 l s^{-1} at Queen's Flat and up to 1000 l s^{-1} downstream of the Weston-Ngapara Road Bridge at Elderslie. This water is used by irrigators further downstream. A condition of the consent is that the irrigation company maintain a minimum flow of at least 100 l s^{-1} in Waiareka Creek at its confluence with the Kakanui River. In practice, this flow is measured at the Taipo Road flow gauging site.

averages of the lowest daily flow or lowest 7 day mean flow recorded each year over the period of record and may therefore include periods from before the setting of this low flow condition.

Table 2-1: Summary of flow statistics for the Kakanui River and Waiareka Creek at the gauging sites closest to the Kakanui Estuary. Raw data were provided by the Otago Regional Council.

	Kakanui at McCones	Waiareka Creek at Tiapo (Rocklands) Rd
Start of record	17 Jan 2003	20 Feb 2007
End of record	13 Feb 2015	13 Feb 2015
Mean Flow	6.950 $m^3 s^{-1}$	0.413 $m^3 s^{-1}$
Median Flow	2.043 $m^3 s^{-1}$	0.222 $m^3 s^{-1}$
MALF	0.333 $m^3 s^{-1}$	0.060 $m^3 s^{-1}$
7 day MALF	0.388 $m^3 s^{-1}$	0.090 $m^3 s^{-1}$
Mean summer (Dec-Feb) flow	4.908 $m^3 s^{-1}$	0.324 $m^3 s^{-1}$
Mean flow Nov 2014-Jan 2015	0.703 $m^3 s^{-1}$	0.379 $m^3 s^{-1}$
Median Nov 2014 – Jan 2015	0.562 $m^3 s^{-1}$	0.333 $m^3 s^{-1}$

2.3 Water level recorders

Water level recorders were installed at 3 locations within the Kakanui Estuary by the Otago Regional Council:

- at the downstream end of the estuary next to limestone cliffs,
- at the bridge,
- and upstream of the junction with Waiareka Creek.

These instruments were installed on 16 October 2014. Water levels have been adjusted to Dunedin Vertical Datum 1958.

Figure 2-2: Location of water level recorders in the Kakanui Estuary.

2.4 Bathymetry survey

A bathymetry survey was conducted by NIWA on 3-4 February 2015. A boat-mounted Teledyne acoustic Doppler current profiler (ADCP) was used to map water depths through the estuary. ADCP's are normally used for measuring water velocities, but also provide a very accurate depth measurement. Positional data were obtained using RTK GPS, with the survey elevations corrected to Dunedin Vertical Datum 1958 using bench mark B228 (45° 10' 30.80997" S, 170° 50' 31.13605" E). The shoreline, shallow and low-lying areas were surveyed on foot. Existing LiDAR data were used to fill in areas above the water line not covered in the survey.

2.5 Salinity and temperature

Two Seabird SMP37 loggers were installed on a wire rope from the bridge across the Kakanui Estuary from 16 Oct 2014 to 3 Feb 2015. One instrument was placed near bed (~2 m depth) and the other near surface. These instruments record temperature, conductivity and pressure (depth). Unfortunately one instrument (near bed) failed due to water leakage. The second instrument did continuously record temperature but it appears that the conductivity sensor may have been intermittently blocked (presumably by algae).

Vertical profiles of temperature, salinity, chlorophyll-*a* fluorescence, oxygen and photosynthetically active radiation (PAR) were recorded in the estuary during the bathymetry survey on 4 Feb 2015 using a Seabird SBE19+ CTD (Conductivity, Temperature, Depth). These were done on the outgoing (profiles 3-13) and incoming (profiles 14-23) tide. Two profiles were taken from the bridge the previous day (3 Feb 2015, profiles 1 and 2) at approximately high tide.

Figure 2-3: Location of CTD profiles in the Kakanui Estuary.

3 Results from field data

3.1 *Ulva* tissue nitrogen, carbon and isotope analysis

Ulva intestinalis collected from both sides of the estuary showed no clear gradient patterns, with respect to distance from the mouth, for any of the four parameters measured; tissue-N, tissue-δ^{15}N, tissue-C and tissue-δ^{13}C (Figure 3-1). Tissue-N in *Ulva* from all 20 estuary sites was variable (1.42% to 4.08%) with a mean value of 2.65% (± 0.77 SD), while the marine *Ulva* example had a tissue-N value of 1.07% (Table 2-1 and Figure 3-1A). A mean value of 2.65% tissue-N for *Ulva* growing over the summer period is considered to reflect a moderate degree of nitrogen enrichment with reference to a national survey of *Ulva* (Barr *et al.* 2013). Note that at tissue-N values of less than 1% for *Ulva* growing in conditions that are otherwise not light or temperature limited (i.e. summer), nitrogen is probably in limiting supply for *Ulva* growth. Conversely values that are in excess of 4% tissue-N indicate that nitrogen is probably in saturating supply for growth in *Ulva*. Also dissolved inorganic nitrogen (DIN) concentrations measured in the estuary during the two months prior to the algal collection were moderate but variable at 66.6 mg m^{-3} (± 56.8 SD) or 4.8 µmol L^{-1} (± 4.0 SD) (Table 2-2) and probably approaching concentrations that would drive accelerated growth in *Ulva* (i.e., be approaching the nitrogen concentration required to give half its maximum growth rate).

Table 3-1: Summary of mean tissue nitrogen and carbon parameters for *Ulva intestinalis* collected in the Kakanui Estuary on the 4 February 2015. Parameters from *U. intestinalis* collected from a marine site are presented separately at the bottom of the table.

	Tissue-N (%)	Tissue-δ^{15}N (‰)	Tissue-C (%)	Tissue-δ^{13}C (‰)
Minimum	1.42	7.85	31.93	-21.57
Maximum	4.08	9.49	36.34	-13.26
Median	2.54	8.32	34.15	-16.73
Mean	2.65	8.38	34.40	-16.95
SD	0.77	0.44	1.16	2.20
Marine site	1.07	8.17	14.41	-11.25

Table 3-2: Summary of mean nutrient concentrations for water samples taken from the Kakanui Bridge from 19 November to 4 February 2015. Raw data were provided by the Otago Regional Council.

	Mean (mg m^{-3})	SD (mg m^{-3})	Mean (µmol L^{-1})	SD (µmol L^{-1})
Ammonium (NH_4^+)	29.8	30.1	2.1	2.2
Nitrate (NO_3^-)	36.4	39.5	2.6	2.8
Nitrite (NO_2^-)	0.0	0.0	0.0	0.0
Dissolved Inorganic Nitrogen (DIN)	66.6	56.8	4.8	4.0
Total Nitrogen (TN)	278.1	157.8	19.9	11.3
Dissolved Reactive Phosphorus (DRP)	14.4	7.8	0.5	0.3

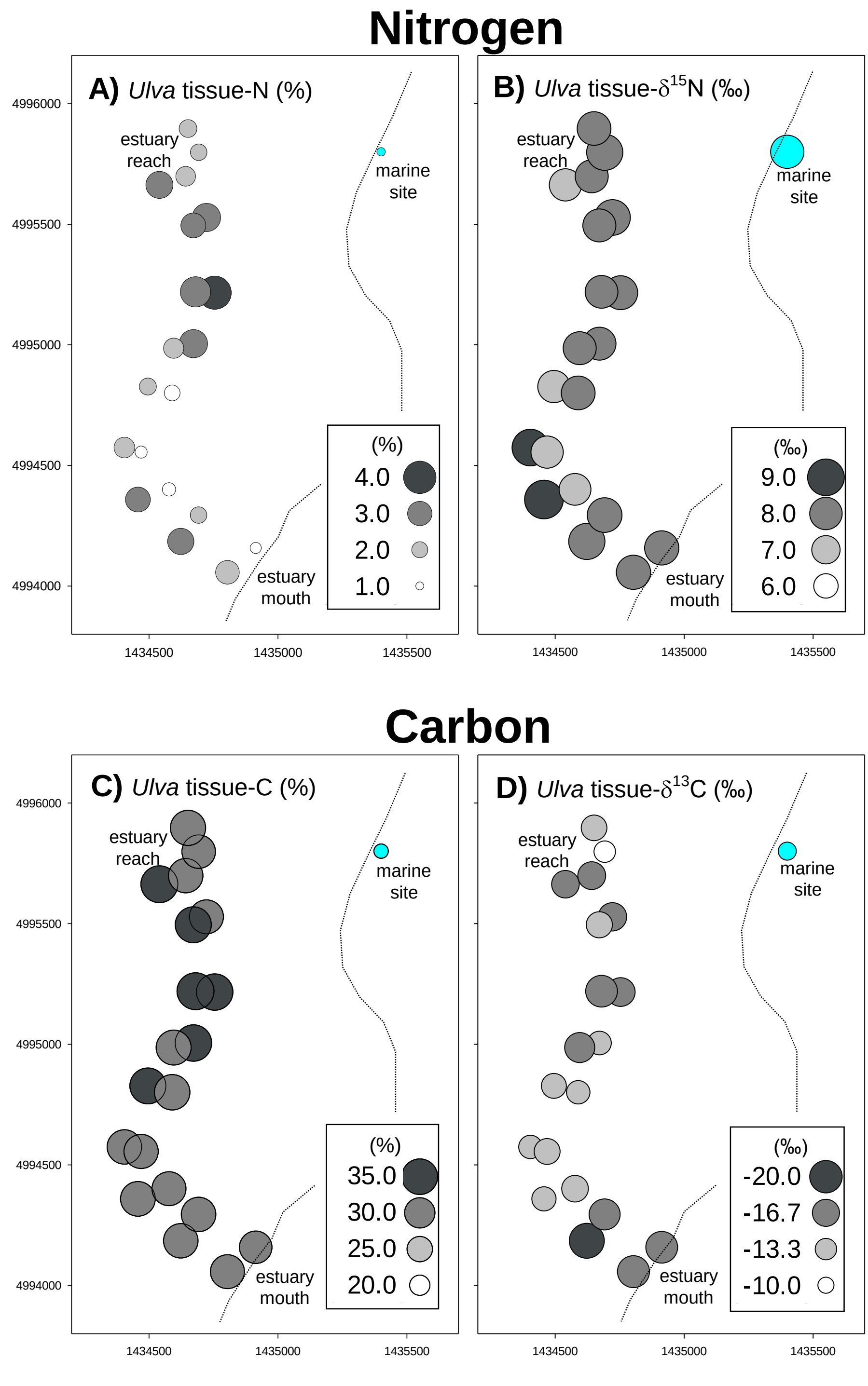

Figure 3-1: Comparison of (A) tissue-N, (B) tissue-δ^{15}N, (C) tissue-C and (D) tissue-δ^{13}C in *Ulva.* Samples were collected on 4 Feb 2015 from 20 sites along the Kakanui Estuary and one site on the open coast to represent a marine example (light blue symbol). Bubble size and shade in each plot legend indicates the relative value of the parameters displayed in the respective bubble plots. The dotted line on each plot indicates approximate shoreline.

The mean value of *Ulva* tissue-δ^{15}N from all estuary sites was 8.38**‰** (± 0.44 SD), while the marine *Ulva* example was 8.17**‰** (Table 2-1 and Fig 3-1, B). In addition, the estuary mean value for *Ulva* tissue-δ^{15}N was within the acceptable marine baseline range (6.6 - 8.8‰) for *Ulva* (Barr et al. 2013).

Based on the estuary mean value for *Ulva* there was nothing to suggest that there was a single riverine source of nitrogen isotopically differentiated from the marine source, as indicated by *Ulva* at the marine site (8.17**‰**). Similarly to tissue-N values in *Ulva* above, tissue-C from all estuary sites was higher at 34.40% (± 1.16 SD) than the marine *Ulva* example which had a tissue-C value of 14.41% (Table 2-1 and Figure 3-1C). In contrast, mean *Ulva* tissue-δ^{13}C for the estuary sites was slightly isotopically lighter at -16.95‰ (± 2.20 SD) than the marine *Ulva* example at -11.25**‰** (Table 2-1 and Fig 3-1, D).

3.2 Water levels and water balance

Water level data from the 3 recorders are plotted in Figure 3-2. Generally water levels were slightly higher at the upstream site than at the bridge (+19 mm on average), while the water levels near the mouth were lower than at the bridge (-36 mm on average). The slope of the water surface is consistent with mean flow in the downstream direction, although the water levels near the mouth may be slightly underestimated low – we may expect on incoming tides the water level at this site may at times be slightly higher than at the bridge. However the error is likely small (of the order of 2-3 cm).

The water levels at all three sites track together closely and reveal changes in the estuary behaviour over time.

- From the beginning of the record through to ~ 4 November, water levels slowly increased in the estuary while the tidal range decreased.
- From ~4 Nov to 24 Nov 2014 there was no tidal fluctuation observed, and water levels inside the estuary increased to 1-1.1 m above sea level.
- On 24 Nov there was a sudden drop in estuary water level to ~ 0.7 m. A small tidal fluctuation can be seen for the next 5 days
- From 29 Nov until 14 Dec 2014 water levels slowly increase to ~ 0.95 m with no tidal fluctuations observed.
- Between 14 Dec and 23 Dec 2014, the water level first slowly falls to ~ 0.6 m, then rise again to 0.9 m. No tidal fluctuations can be seen
- After 23 Dec 2014, the water level drops but begins to oscillate with the tide. There is some variation in both the magnitude of the oscillations (the range) and the middle of this range over time. However water levels seldom drop below 0 m even at low tide.

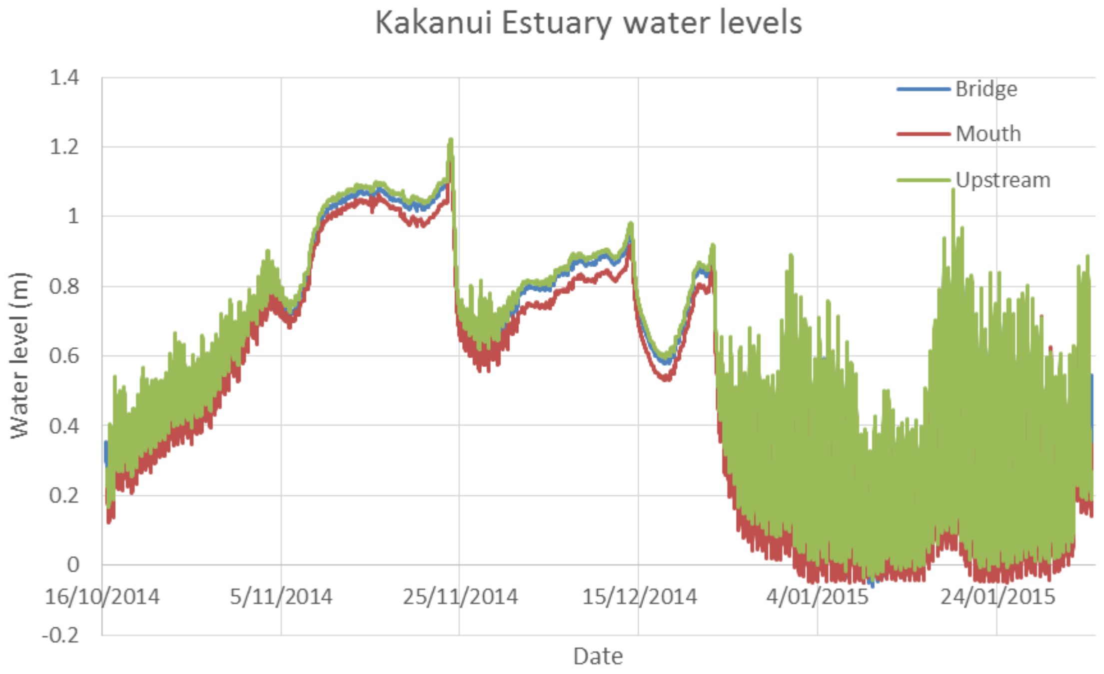

Figure 3-2: Time series of water levels in the Kakanui Estuary 16 Oct 2014 to 3 Feb 2015. Water levels are relative to Dunedin Vertical Datum 1958.

The bathymetry data was used to generate a hypsographic curve – a relationship between water level and volume (Figure 3-3). This allowed the estuary volume to be estimated over time. A water balance between the rate of change of estuary volume and the measured river inflows allowed the outflow from the estuary to be calculated:

$$Q_{out} = Q_{in} - \frac{dV}{dt}$$

- Q_{out} ($m^3\ s^{-1}$) is the flow through the mouth the estuary, with positive values indicating outflow
- Q_{in} ($m^3\ s^{-1}$) is the total river flow (the sum of inflows from the Kakanui River and Waiareka Creek)
- V (m^3) is the estuary volume.

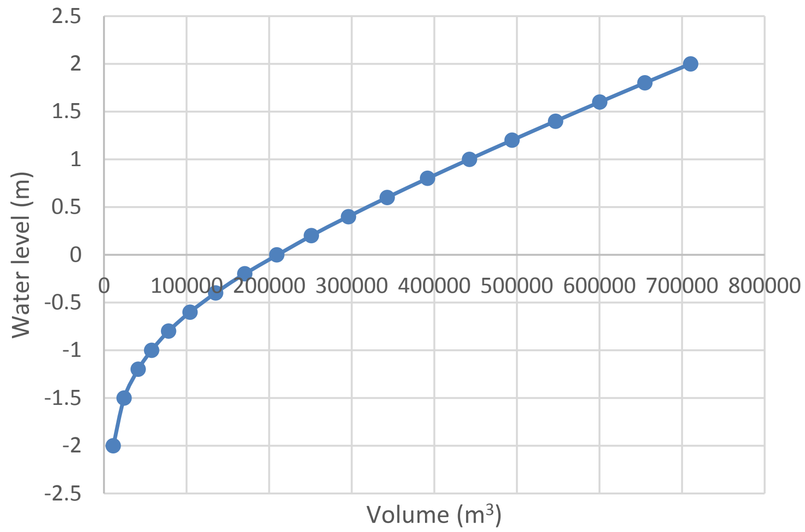

Figure 3-3: Hypsographic curve of the Kakanui Estuary. Water level relative to DVD1958. Volumes are calculated from the bathymetry survey conducted 3-4 Feb 2015.

The time-series of inflows, outflows and water levels reveal some interesting aspects of the behaviour of the estuary (Figure 3-4). The periods of increasing water level and decreasing tidal exchange (reduced variations in both the water level inside the estuary and the flow through the mouth of the estuary) indicate the estuary mouth becoming increasingly constricted. Photographs (Figure 3-10) indicate that the mouth did not close completely; water was still able to flow out from the estuary to the sea. However, the channel level of the inlet was above the high tide mark, and no sea water entered the estuary during these periods. We will consider these periods to indicate a closed mouth (closed with respect to tidal inflows from the sea, there is still a chanel by which water drains from the estuary to the sea).

During closed periods only small increases in river flow were required to open the mouth sufficiently that sea water could flow into the estuary at high tide. For example, on the 23 Nov 2014 following a period of mouth closure, the inflow increased from 1.0 $m^3 s^{-1}$ to a peak of 4.0 $m^3 s^{-1}$ at 16:00. Water levels inside the estuary began to drop from around 02:00 the next morning, eventually stabilising some 0.5 m lower.

The water balance shows that a small amount of tidal flow occurred through the mouth during this period of partial opening. However, the mouth appears to have closed over the next week with water levels gradually increasing inside the estuary.

A small flow increase (to 2.0 $m^3 s^{-1}$) on the 13 Dec 2014 was followed by a drop in water level in the estuary. This indicates deepening of the estuary mouth channel, but the level of the channel did not lower sufficiently to allow tides to affect water levels inside the estuary.

A third small increase in flow (to 2.3 $m^3 s^{-1}$) on the 23 Dec 2014 also triggered erosion of the estuary mouth. This time the mouth remained open through the remaining monitoring period with the estuary becoming tidally influenced. The water balance indicates that the magnitude of the tidal flows varied over this time, which may be due to changes in the shape of the estuary mouth. Peak tidal flows (~5 to 25 $m^3 s^{-1}$) were much higher than river discharge (~1 $m^3 s^{-1}$).

Another increase in flow (to 4.5 $m^3\ s^{-1}$) occurred on the 1st Feb 2015, followed by a large flow on the night of the 3rd Feb 2015. The water levels and outflows derived from the water balance suggest that both of these flow changes modified the estuary mouth.

Over most of the monitored period, inflows were steady and dropped gradually over time from ~2.2 $m^3\ s^{-1}$ in mid-Oct to 0.7 $m^3\ s^{-1}$ in late January.

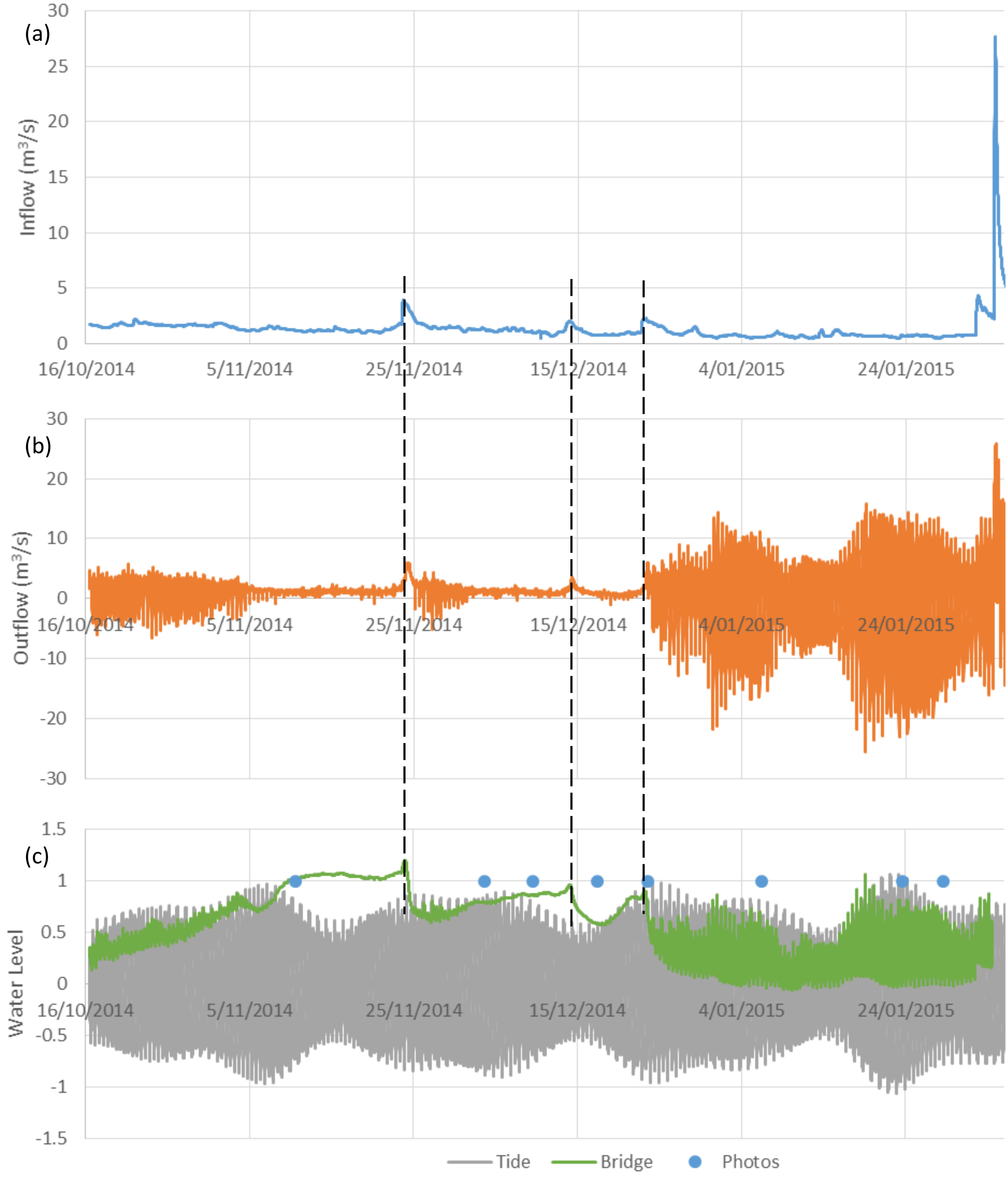

Figure 3-4: (a) River flow into and (b) calculated outflow from the Kakanui Estuary. (c) Water at the bridge and predicted tidal water levels. River flow is the total of the inflows from the Kakanui River and Waiareka Creek. The outflow from the estuary (positive outwards) has been calculated from a water balance. Tidal water levels were predicted from the NIWA tide model. The blue dots in Figure 3-4C show when photographs of the estuary mouth were taken. Dashed vertical lines show occasions when water level in the estuary dropped due to changes in the estuary mouth caused by small flow increases.

3.3 Salinities and temperature

Data from the near surface salinity mooring are plotted in Figure 3-5. Over much of the period that this instrument was in place, salinities near the surface at the Kakanui Bridge were low (<1 g/kg). This might be expected over periods when the mouth was closed to the sea. After the mouth opens (late December 2014) there were two periods where high surface salinities were observed, with large tidal fluctuations. Between and after these two periods, salinities of 0 were recorded, which we believe were caused by the conductivity cell being blocked. Temperatures show a diurnal fluctuation when the mouth is closed, and superimposed on this are tidal variations when the mouth is open. Over the period of the deployment temperatures increased from ~14°C to ~20°C.

Figure 3-5: Water depth (pressure), salinity and temperature from the near-surface mooring at the Kakanui Bridge. Note that the pressure measurements by this instrument are not corrected for variations in barometric pressure.

Vertical profiles obtained on the 3rd and 4th February 2015 (Figure 3-6) give a snap-shot of water column properties at this time. Note that a small flood occurred during the night of the 3rd Feb so the profiles may not be typical of summer conditions. The vertical profiles demonstrate that ocean water travels a considerable distance into the estuary.

Starting at the upstream end of the estuary, there is a deep hole at the location of profiles 10 and 21, near the confluence of the Waiareka Creek, and highly saline water (salinities of 30 g/kg) can be seen underlying a surface layer of fresh water 1 m (low tide) to 2 m (high tide) thick. The riverine water was cooler than the more-dense saline water.

Profiles 1 and 2 were taken on the 3rd Feb 2015 from the Kakanui Bridge, while profiles 7 and 18 were taken near by on the following day (after the small flood) on the ebb (outgoing) and flood (incoming) tide respectively. Comparing the two sets of profiles reveals a decrease in water temperature and salinity due to the high river discharge. The later two profiles were collected at a slightly shallower location, but do show that the surface layer of fresher water increased in thickness as a result of the flood.

Sites 3 and 4 (ebb tide) and 14 and 15 (flood tide) were taken in the lower reaches of the estuary. There are only small differences in vertical structure between the locations, but obvious changes due to differences in the phase of the tide. On the ebb tide, there was a strong salinity gradient between the outflowing fresher riverine water at the surface (<0.7m). The surface layer at this time was slightly (~0.5°C) cooler than the underlying more saline waters. On the flood tide (14+15) salinity increased at the surface but slightly decreased further down the water column compared to the ebb tide. This is due to rapid mixing between the jet of inflowing sea water and the fresher water in the estuary. The contrast between the inflowing sea water and the estuary is visually apparent in Figure 3-7 due to the estuary being discoloured by the flood on the night of the 3 February 2015.

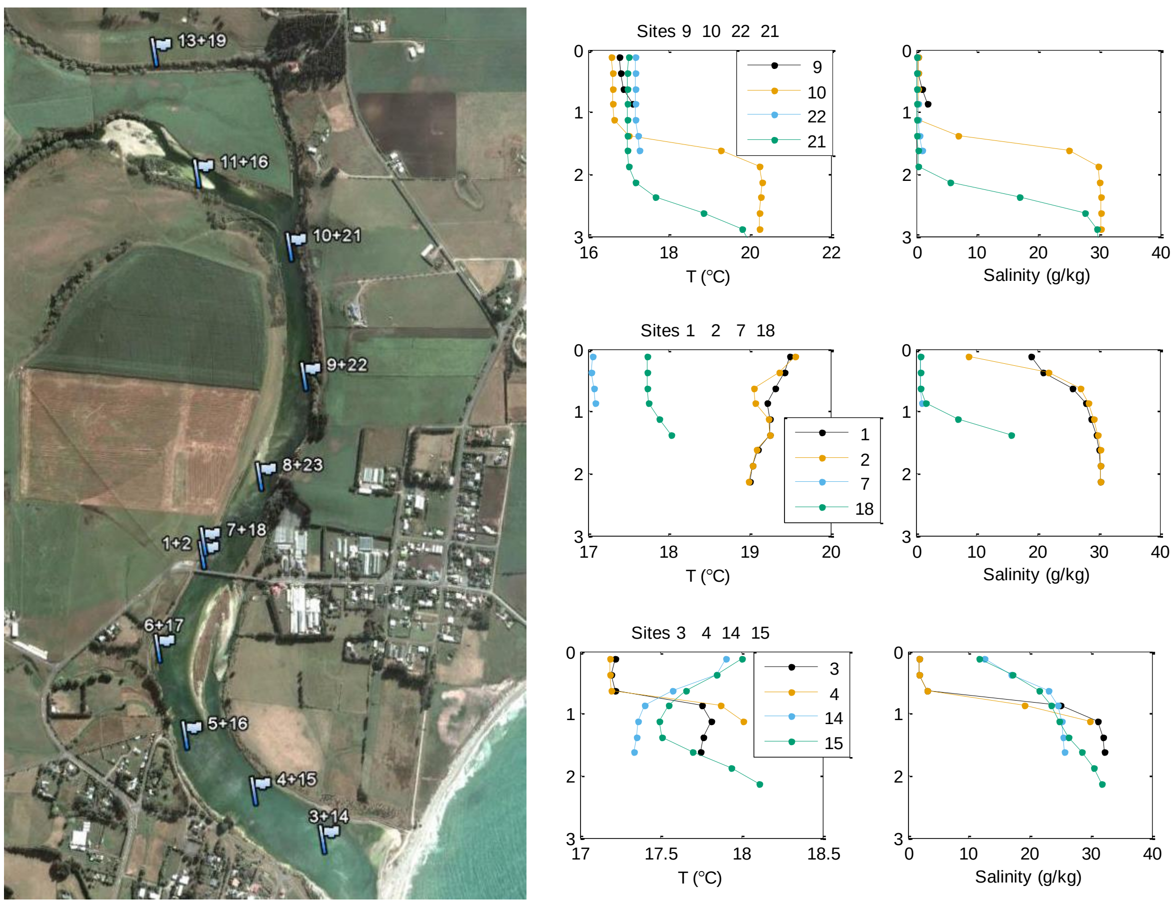

Figure 3-6: Selected profiles of temperature and salinity from the Kakanui Estuary. The locations of cast numbers are shown in the map. Profiles 1 and 2 were collected near high tide on the 3 Feb 2015. Casts 3 to 13 were collected on the ebb tide and 14 to 23 on the flood tide on 4 Feb 2015.

Figure 3-7: Photographs taken near the mouth of the Kakanui River showing the inflowing seawater mixing with the water in the estuary. The estuary water is brown coloured due to an overnight flood.

While both temperature and salinity affect the density of water, in most estuarine systems salinity has the greater influence. That is certaintly the case in the Kakanui at the time of the survey. In Figure 3-8, temperature has been plotted against salinity for all the vertical profiles. Also shown are contours of density anomaly. Salinity varies between 0.04 and 32.42 g kg^{-1}, which is a density difference of 24.4 kg m^{-3}. Temperature varies between 16.4°C and 21.1°C which is a difference in density of 0.95 kg m^{-3}.

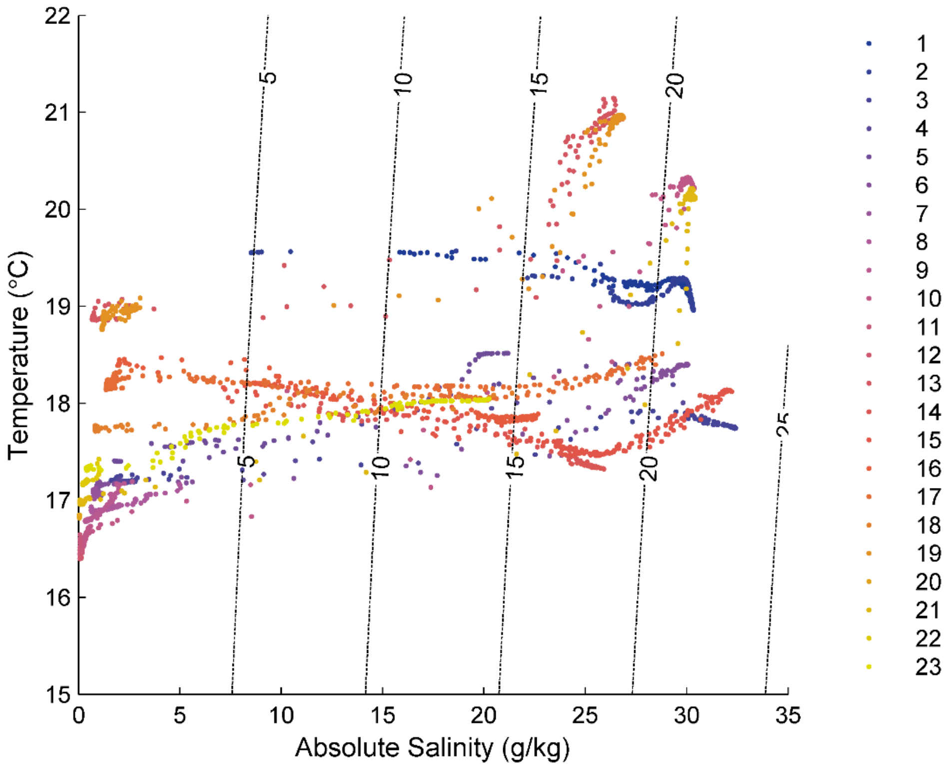

Figure 3-8: Plot of salinity vs temperature from all CTD profiles measured on the 3-4 Feb 2015. The dashed contour lines show the density anomaly (density - 1000 kg m^{-3}) as a function of salinity and temperature. The data points are coloured by profile number.

3.4 Nitrogen concentrations

Otago Regional Council collected a number of surface water samples at the Kakanui Bridge over the 2014/15 summer. These were analysed for a range of nutrients and water quality parameters. Here we consider only two quantities in order to compare nutrient concentrations over time and to see if there is any obvious trend with the state of the estuary mouth. Figure 3-9 shows time-series of Total Nitrogen (TN), Total Dissolved Nitrogen (TDN), Dissolved Inorganic Nitrogen (DIN) and water level at the Kakanui Bridge. TN and TDN were high prior to Jan 2015 when the mouth was generally closed to the sea (as evidenced by the small or lack of tidal range). The nutrient concentrations in the estuary will be strongly influenced by the concentrations in the Kakanui River and Waiareka Creek during this period. TN and TDN were still high on the 6th Jan after the estuary became tidally influenced, but dropped noticeably after this point. Note that this particular sample was taken at low tide when the water column at the bridge will contain a higher fraction of riverine water than at other phases of the tide. Thus this sample may infact represent riverine water rather than estuary water.

The high values of nitrogen on the 6th Jan may also reflect the time it takes for the the estuary to “flush” when the mouth opens partially to the sea.

Dissolved inorganic nitrogen (DIN) does not show such a clear trend before and after mouth opening. Before mouth opening, DIN concentrations were highly variable, but (with the notable exception of the 6th Jan) become more stable after the mouth opens. DIN indicates the forms of nitrogen most available to algae, and the concentrations measured may be influenced by any uptake of nitrogen within the estuary (with no algae present the concentrations of DIN would likely be higher).

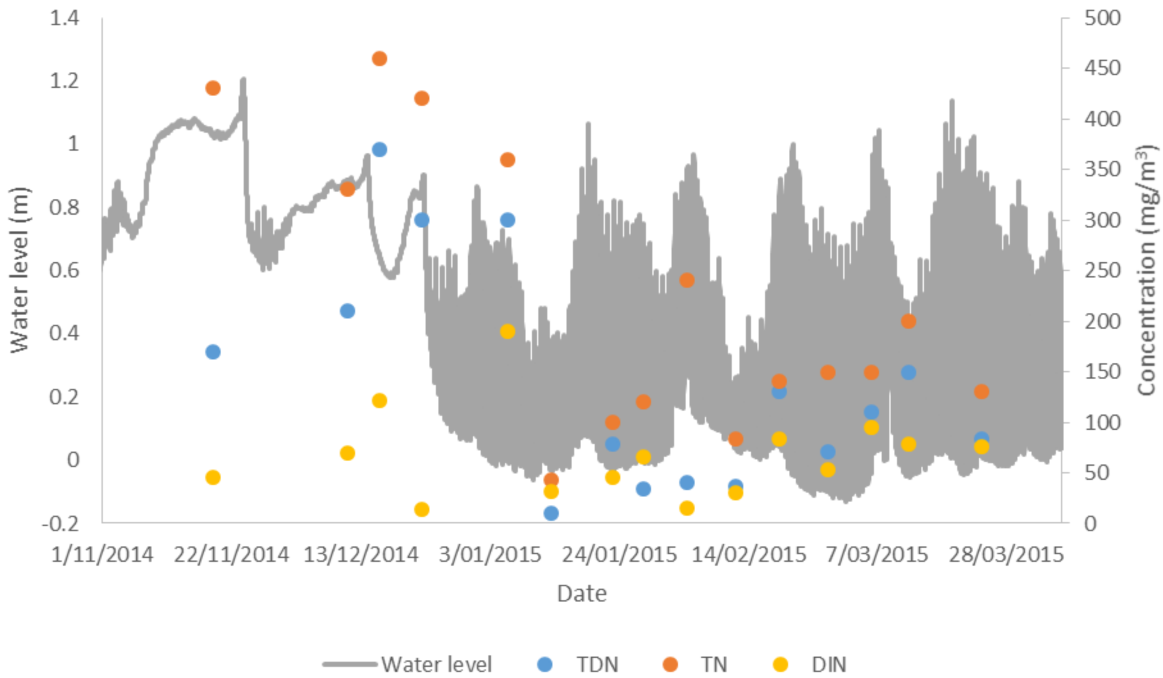

Figure 3-9: Measured concentrations of Total Nitrogen, Total Dissolved Nitrogen, Dissolved Inorganic Nitrogen and water level at the Kakanui Bridge. Nutrient data and water level data were collected by Otago Regional Council.

3.5 Photographs of the estuary mouth

A time series of photographs of the Kakanui Estuary were collected by the Otago Regional Council. Figure 3-10 shows photographs of the estuary mouth on 14 occasions. The photographs illustrate how the mouth continually changes. In the first 5 sets of photographs (10 November – 23 December 2014) the mouth is 'blocked' with little or no ocean flow into the estuary (Figure 3-4). The photographs show a narrow channel through the bar during this period. Maximum and minimum outflows through the mouth on the day of the photographs calculated from the water balance are indicated to the left of the photographs. The location and orientation of the channel changes over time. Wider mouth openings can be seen in the next 9 sets of photographs (6 January – 12 March 2015). Discharges through the mouth have been calculated up to the 4th February 2015, and the negative values indicate inflow from the sea. The photographs from 27 February and 12 March in particular show a wide river mouth where tidal flows to and from the sea are likely to be high. The photographs confirm that there is no 'typical' mouth configuration, but that a range of mouth openings need to be considered.


10 Nov 2014
0.6 to 1.5 m^3 s^{-1}
3 Dec 2014
0.6 to 1.7 m^3 s^{-1}
9 Dec 2014
0.6 to 1.7 m^3 s^{-1}
16 Dec 2014
0.7 to 1.4 m^3 s^{-1}
23 Dec 2014
0.1 to 6.0 m^3 s^{-1}
6 Jan 2015
-16.4 to 11.2 m^3 s^{-1}

14 Jan 2015 -9.1 to 6.2 $m^3\ s^{-1}$	
23 Jan 2015 -23.0 to 13.3 $m^3\ s^{-1}$	
28 Jan 2015 -17.1 to 11.9 $m^3\ s^{-1}$	
4 Feb 2015 -11.3 to 25.5 $m^3\ s^{-1}$	
19 Feb 2015	
27 Feb 2015	

Figure 3-10: Timeseries of photographs of the estuary mouth. Photographs were taken by the Otago Regional Council. The minimum and maximum calculated flow rates through the mouth (positive values indicating outflow) are indicated from the 10th November 2014 to 4th February 2015.

4 Hydrodynamic model

4.1 Hydrodynamic model

Simulations of the Kakanui Estuary were conducted using Delft3D, a hydrodynamic model developed by Deltares, a Dutch-based research institute. The Delft3D model is widely used throughout the world. The model itself is open-source (the source code is freely available[2]). The model is capable of both two and three dimensional simulations and calculates non-steady flow and transport phenomena resulting from tidal and meterological forcings on a curvilinear [3], boundary fitted grid. Further details of the settings used in the model are described in the following sections of the report.

4.2 Model grid and bathymetry

The model domain includes the Kakanui Estuary upstream beyond the confluence with the Waiareka Creek to where a riffle demarks the upper extent of the estuary, and extends several (~14) kilometres offshore (Figure 4-1). The coastal portion of the grid allows the discharge of the estuary to the sea to be modelled more accurately, and allows for return flow where some of the discharged estuary water may re-enter the estuary on the incoming tide.

The model grid consists of 14265 curvilinear rectangles that vary in size throughout the model domain. In the ocean and in the estuary mouth, the grid cells are nearly square, but in the rest of the estuary they are elongated in the streamwise direction with an aspect ratio between 2 and 5. The coarsest resolution is in the ocean (1 km) and the highest resolution (~2 m) in the estuary mouth. Throughout most of the interior of the estuary, the grid resolution is ~ 8-10 m in the streamwise direction and ~2-3 m in the cross-stream direction.

Depths used in the model grid were derived from

- The bathymetry data within the estuary collected during the field survey 3-4 Feb 2015 (Figure 4-2)
- Coastal depths from LINZ oceanographic charts NZ61, NZ66 and NZ661, downloaded as point data from the LINZ website [4]
- Digitized depths from LINZ oceanographic chart NZ6433 (Approaches to Oamaru)
- Existing LiDAR data for the margins of the Kakanui Estuary

All levels were adjusted to Dunedin Vertical Datum 1958.

[2] http://oss.deltares.nl/web/delft3d

[3] A curvilinear grid consists of curved lines that cross at right angles. The advantages over a rectangular grid (where the lines forming the grid are straight) are that resolution can be increased in areas of interest, and the grid can better follow the shape of the area to be modelled.

[4] https://data.linz.govt.nz/

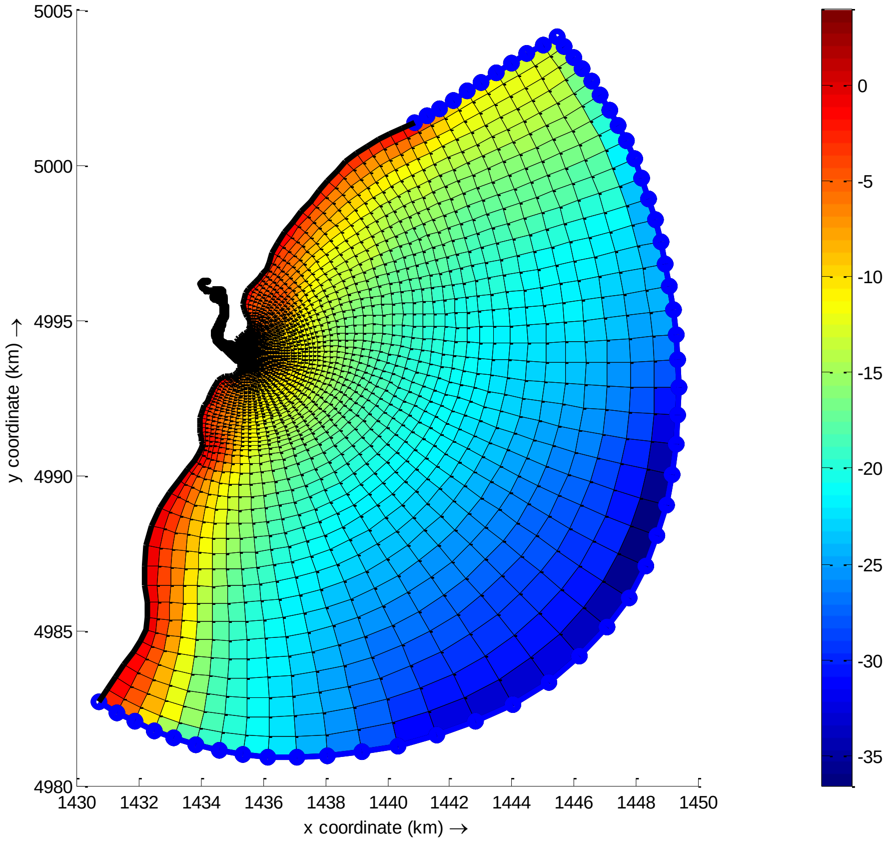

Figure 4-1: Model domain coloured by bed elevation. The blue line and circles show the open boundary points (ocean) and the dark black lines the solid land boundaries.

The Waiareka Creek was included for a considerable distance upstream of its confluence with the estuary. This Creek is deep and low gradient, thus potentially tidally influenced for some distance upstream.

Inflows from the Kakanui River and Waiareka Creek were applied in the model as point discharges at the upper ends of each branch of the estuary. The locations of these discharges are shown in Figure 4-2.

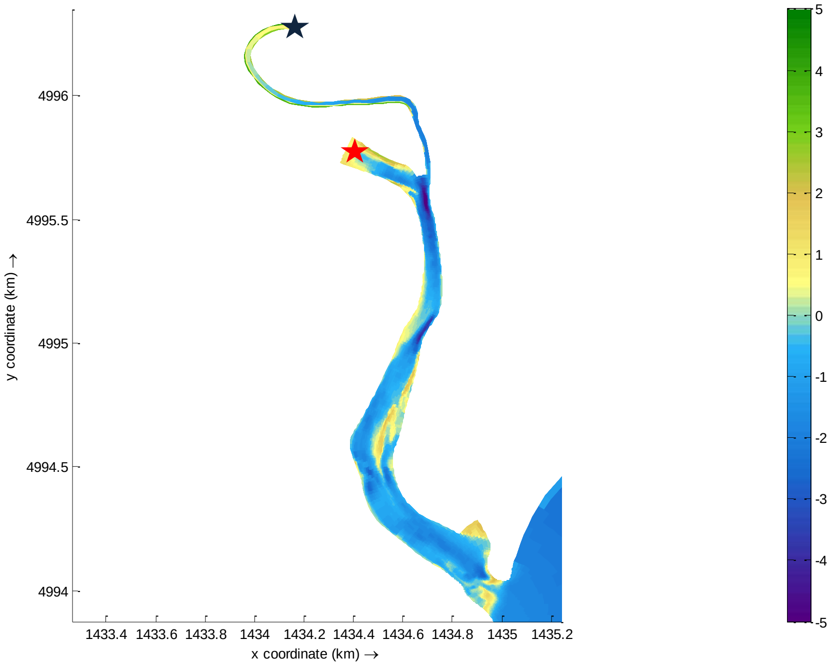

Figure 4-2: Bathymetry within the Kakanui Estuary. The red and blue stars indicate the points where flows from the Kakanui River and Waiareka Creek (respectively) were applied in the model.

4.3 Ocean boundary conditions

Water levels at the open ocean boundaries were specified using the amplitudes and phases of the 13 largest tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, 2N2, MU2, NU2, L2 and T2). These were obtained from NIWA's tide model (Walters, Goring, Bell 2001).

4.4 Mouth configuration

The shape of the mouth of the Kakanui Estuary has a controlling influence on the outflow of water from the estuary, and on the inflow of sea water due to the tide.

Four mouth configurations were modelled in this study (Figure 4-3).

1. **Surveyed mouth**: the estuary is open to the sea such that tidal flow in and out of the estuary occurs, but the entrance is constricted. This scenario is based on the mouth configuration as measured during the 3 February 2015 survey.

2. **Open mouth**: the mouth is assumed to be twice the width of that surveyed in 3 February 2015.

3. **Closed mouth:** the estuary mouth is above the high tide level, and only outflows occur. This is representative of the period in late 2014. The estuary mouth bed level is set at 0.75 m above sea level, and the width approximately 15 m. To ensure that water only exited through the mouth, the elevation of land either side of the mouth was also raised by 1.0 m above the surveyed level.

4. **Narrow mouth:** as results from simulations will show, using the surveyed mouth geometry resulted in higher flows through the mouth than calculated from the water balance. This may have resulted from the mouth widening during a fresh (increased river flow) that occurred about the time of the survey. The narrow mouth configuration is based on the surveyed mouth but with the width reduced from ~18 m to ~8 m (the actual width depending on the state of the tide).

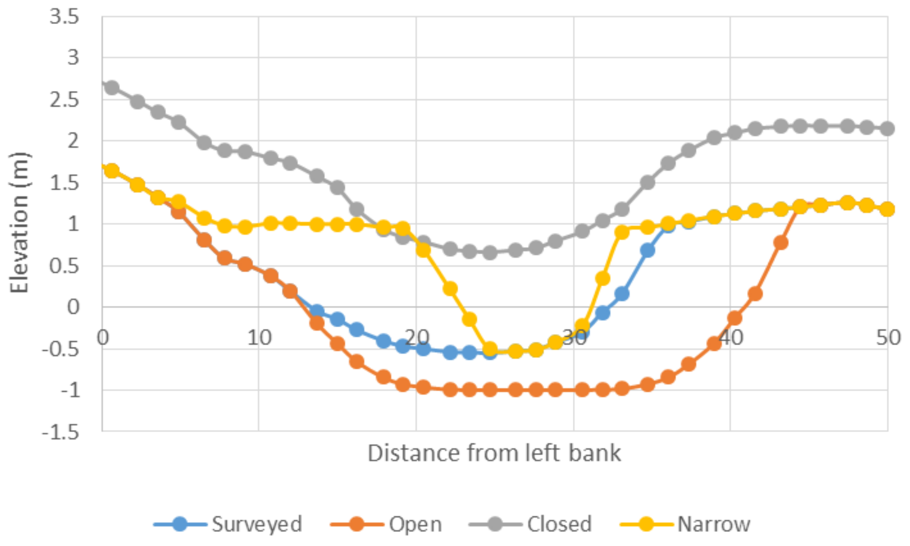

Figure 4-3: Cross-sections of the four estuary mouth configurations. Elevations are relative to MSL. The surveyed configuration shows the mouth as surveyed on 3 Feb 2015.

4.5 Modelling scenarios

Two sets of simulations were conducted.

- **2D (depth-averaged) simulations** using measured river inflows, for the purpose of validating the model. The period modelled covered 20 January 2015 to 4 February 2015.
- **3D simulations** using fixed inflows for the purposes of evaluating the effect of river mouth configuration and calculating dilutions at different flows. The issues with algal growth in the estuary are most pronounced during summer periods and low flows, therefore the flows chosen range between the 7 day mean annual low flow and the mean flow during the period for which flow records were available. These flows are specified in Table 4-1. The model was run with tidal boundary conditions for the period 19 December 2014 00:00 to 29 December 2014 00:00. This was selected as it includes the summer but also had tides that were reasonably consistent in size (i.e. small variation between spring and neap tide) giving a period of "average" tidal range.

River flows used for the 3D simulations are listed in Table 4-1. Flow scenario 1 represents the driest part of summer and can be considered a 'worst case' flow scenario. Scenario 2 uses the mean flows as recorded from 1 Nov 2014 to 31 Jan 2015. In much of the analysis that follows, this scenario will be used to represent “typical summer conditions”. Scenario 5 has the highest flows, using mean flows for each tributary over the total period of flow data as received. The mean flow in the Waiareka Creek is only slightly higher (by 8.5%) than the mean 2014/15 summer flow. In scenarios 3 and 4, the inflow from the Kakanui River is set to values between the mean and mean 2014/15 summer flows to simulate intermediate flows. Other than for scenario 1 (the 7 day MALF), flows in the Waiareka Creek were set to ~ 0.4 $m^3 s^{-1}$. Consequently the modelling focuses on the effects of differences in flows from the Kakanui River and we assume for this study that flows in the Waiareka Creek do not vary significantly over the summer period. This is consistent with observations but the influence of flow changes in the Waiareka Creek could be considered in any future work.

Table 4-1: Flow scenarios used for the modelling of the Kakanui Estuary. 7 day MALF is the average of the lowest flow recorded for a 7 day period each year during the available flow record. It represents the lowest summer flows. The 2014/2015 summer mean flow is the mean flow recorded during the period 1 Nov 2014 to 31 Jan 2015. Mean flow is the average flow over the entire flow record. Flow scenarios 3 and 4 use flows selected as intermediate to scenarios 2 and 5.

Flow scenario	Description	Kakanui ($m^3 s^{-1}$)	Waiareka ($m^3 s^{-1}$)	Total Inflow ($m^3 s^{-1}$)
1	7 day MALF	0.388	0.090	0.478
2	2014/15 summer mean flow	0.70	0.38	1.08
3	Intermediate flow 1	2.0	0.40	2.4
4	Intermediate flow 2	4.0	0.40	4.4
5	Mean flow	6.95	0.413	7.363

The closed and partially-open mouth simulations were started with an initial water level of 0.75 m (high tide) and 34 ppt salinity throughout. The open mouth simulations were started at an initial water level of 0.50 m and 34 ppt throughout.

4.6 Model settings

The 2D (depth-averaged) simulations were run with a time-step of 0.125min, with a constant Chezy bed roughness coefficient of 65. Horizontal eddy viscosities and diffusivities[5] were set to 0 $m^2 s^{-1}$ and a reflection parameter $\alpha = 2000\ s^2$ applied to the ocean boundaries to damp short waves introduced at the start of the simulation (Deltares 2013). While salinity is included in the 2D model, it acts as a tracer only (density driven flows cannot be simulated with a 2D model).

The 3D simulations were run with 7 layers in the vertical. The model uses σ co-ordinates in the vertical, where the layers are a specified proportion of the local water depth. In shallow areas the

[5] Horizontal eddy viscosity is a parameter that relates to how effectively turbulence transports momentum. A low eddy viscosity allows sharp horizontal velocity gradients (differences in velocity) while a high eddy viscosity tends to smooth out velocity gradients. Horizontal eddy diffusivity describes the rate at which turbulence causes a substance to spread between areas of high and low concentrations. In hydrodynamic models, eddy viscosities and diffusivities are used to parameterise turbulent processes that occur at scales smaller than can be resolved by the model grid. While these values have been set to zero in the model input, in practice there is a certain amount of viscosity and diffusivity introduced by the numerical schemes within the model.

layers are thinner than in deeper areas. The thickness of the layers varied over the water depth with thinner layers near the surface to better resolve the interface between the riverine fresh water and the denser sea water. The thickness of the layers from surface to bed specified as a proportion of the total water depth were 5%, 5%, 5%, 10%, 10%, 25% and 45%. The k-L turbulence closure scheme was selected for resolving vertical mixing and transport. A time step of 0.05min was used for the 3D simulations. The effects of salinity on density are included in the 3D simulations, but temperature-induced density effects are not. The reason for this is that salinity has a significantly larger effect on density than temperature does over the range of temperature and salinity differences between the river sources and ocean. Figure 3-8 shows how density variations are caused predominately by salinity with temperature having a comparatively negligible effect. Furthermore, river and oceanic salinities are easily defined (0 and 34 g kg^{-1} respectively, with only small fluctuations expected for oceanic salinity) while temperature will vary seasonally.

4.7 Tracer simulations

Tracer simulations were run using DELWAQ, a water quality model that is part of the Delft3D suite, to to determine the fraction of the estuary volume originating from each fresh water source. While DELWAQ is capable of modelling ecological processes (for example algal growth), for this study it was used only to advect tracers from the Kakanui River, Waiareka Creek and the ocean boundary.

The tracer simulation was run using stored hydrodynamic output from DELFT3D for the period 27 Dec 2014 01:45 to 28 Dec 2014 02:30 (this 24h45min period covers two tidal cycles from the end of the hydrodynamic simulation when the model has stabilised and the influence of the initial conditions is minimised). The hydrodynamic data were repeated 14 times (346.5 hrs) to allow the tracer distributions to reach steady state, and concentrations averaged over the final 24 hr 45mins (two tidal cycles) to obtain a time-averaged spatial distribution of each tracer within the estuary.

Three tracers were used:

1. Kakanui tracer released from the Kakanui River
2. Waiareka tracer released from the Waiareka Creek
3. Ocean tracer released at the ocean boundaries

At model start up, the concentrations of the two river tracers were set to 0 g m^{-3} everywhere, while the ocean tracer was set to an initial value of 1 g m^{-3} everywhere. All 3 tracers were added at a concentration of 1 g m^{-3} with an inflow rate (m^3 s^{-1}) matching that of the flow in the hydrodynamic model. The resulting concentration distributions in the estuary represent the proportion of the tracer from each source. Nutrient concentrations in the estuary can then be determined by scaling the concentration of each tracer by the nutrient concentration in each source, and then adding these together.

5 Model results

5.1 2D simulations with time-varying river discharge

Figure 5-1a shows time-series of water levels predicted by the model compared with measurements at the Kakanui Bridge over the period 20 Jan to 4 Jan 2015. Water levels are shown for simulations using the surveyed mouth (based on that measured on the 3 Feb 2015) and the narrow mouth. The model includes measured time-varying river discharges, and astronomic tides. It does not include the effects or wind or atmospheric pressure on sea level.

The timing of the peaks and troughs in water level for both model configurations agree with measurement. However there are differences in the water levels, particularly at high tide where the model generally over-predicts water level fluctuations. The agreement between model and measured data varies over time, and this is likely to be due to changing mouth geometry. Over most of the simulation period, the modelled water level for the surveyed mouth simulation is close to the observed level at low tide. This indicates that the elevation of the mouth in the model was likely close to that of the actual mouth. The over-prediction of water levels at high tide indicates that the model allowed more tidal flow through the mouth than predicted by the water balance, suggesting that the mouth at the time of the survey was wider than that occurring over the previous ~10 days. A comparison of discharge through the mouth as predicted by the model and estimated from the water balance is shown in Figure 5-1b, confirming that modelled flows through the mouth were higher than actually occurred.

The agreement between the simulation with the surveyed mouth and the observed water levels and derived mouth discharge is quite good during the period that the mouth was surveyed 3-4 Feb 2015. This suggests that the model is capable of giving good results if the mouth geometry is correct for the period simulated.

In contrast, the narrow mouth configuration gives much better agreement between simulated and estimated discharge through the mouth (Figure 5-1b), although still over-predicts water level at high tides (Figure 5-1a). The tidal range (the difference between high and low tides) is closer to the observed. This simulation also shows a gradual increase in water level over time. A careful inspection of the two graphs shows that this increase in modelled water level occurred in steps and that these steps occur at similar times that small increases in river inflow occurred. During the field survey it was noted that the gravel bed of the mouth was mobile, thus it is likely that the mouth changed shape continuously. Small increases in flow could result in temporary increase in the width or depth of the mouth which allowed the extra inflow to drain from the estuary, a process that the model is unable to capture. The photographs (Figure 3-10) also illustrate that the estuary mouth continually changes. The large tidal flows through the mouth will cause continual reshaping of the mouth geometry. Even during periods when the mouth is effectively “closed” to the sea, allowing only outflows (see for example the first 4 sets of photos in Figure 3-10) the channel changes shape.

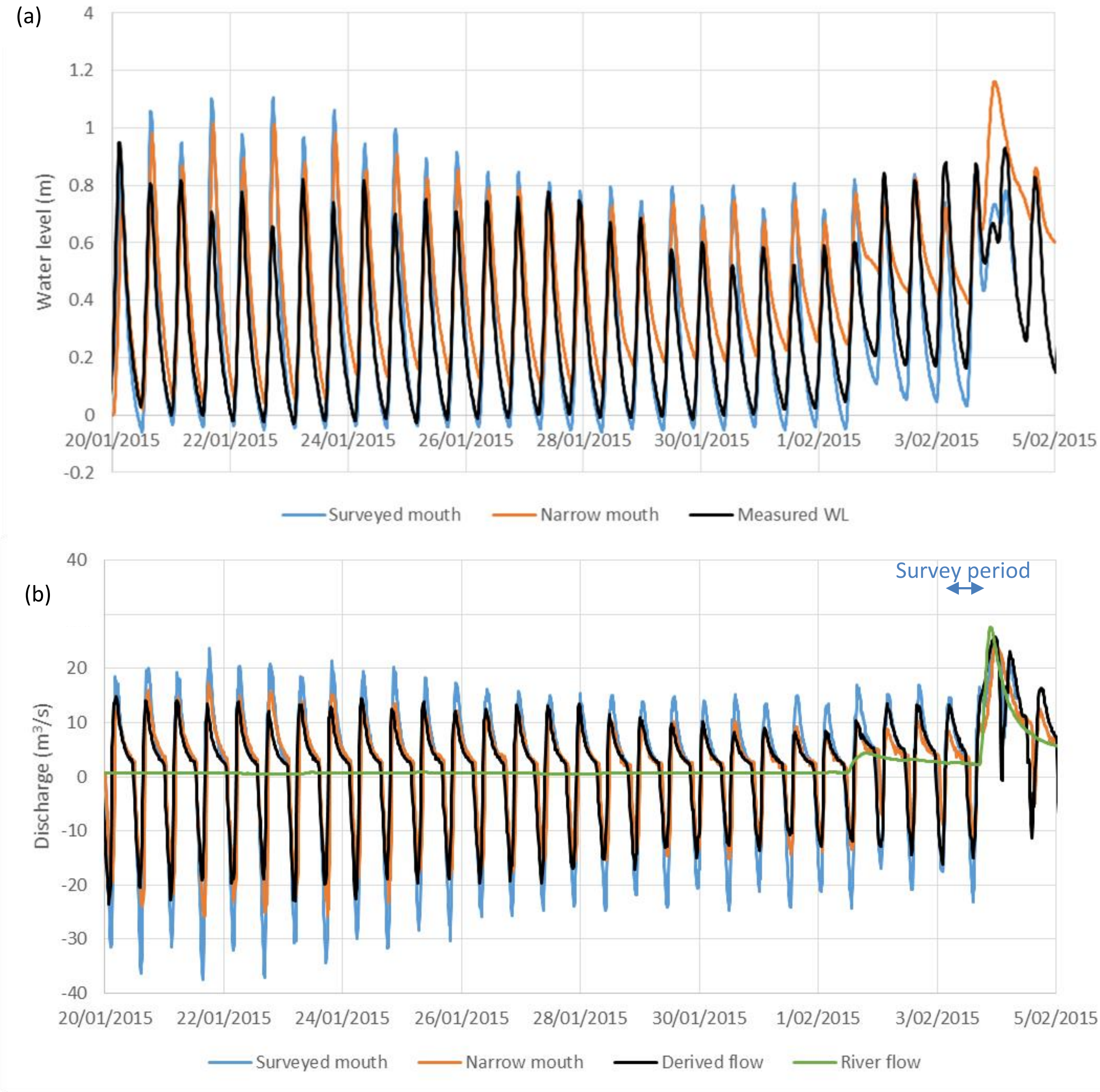

Figure 5-1: (a) Modelled and measured water levels at the Kakanui Bridge, and (b) discharge through the estuary mouth over the period 20 Jan 2015 to 4 Feb 2015. The model assumes a fixed mouth geometry, with the "surveyed mouth" that as measured 3 Feb 2015, and the "narrow mouth" based on the same elevations but with the width of the mouth reduced to ~8 m. In reality the mouth was mobile and likely to have changed geometry throughout this period. The combined river inflow is also shown in (b).

These simulations demonstrate the greatest challenge in modelling the Kakanui Estuary – the effect of the constantly changing mouth on the tidal exchange with the sea. With regard to determining the dilution of incoming riverine nutrients with oceanic water, it is more important that the model correctly predicts the tidal exchange than water levels. The simulations also demonstrate that both mouth geometries are realistic: the narrow mouth geometry likely represents the condition of the mouth over much of January, while the surveyed mouth shows a more open condition as a response to increased river flow.

5.2 3D simulations with constant river discharge

A large number of 3D simulations were conducted (5 flows for each of 4 mouth geometries) and only a summary of these results can be presented here.

The concentrations of salinity and the river tracers vary in both space (horizontally and vertically) and time within the estuary. This is illustrated in Figure 5-2 which shows distributions of salinity in the upper layer (top 5%) and lower layer (bottom 40%) at low and high tide for the surveyed mouth geometry. The results presented here are for the simulation using constant river flows set at the 2014/2015 mean summer flow (Table 4-1). The times of high and low tide are based on the time of highest and lowest water level at the bridge. The tide is asymmetrical with the flood tide much shorter in duration than the ebb tide. The vertical stratification is evident when comparing the upper and lower plots of Figure 5-2. The denser salty water sits beneath the fresh riverine water, but the two sources also mix forming regions of intermediate salinity. Stratification also occurs offshore of the estuary where the discharge plume from the estuary mixes with the coastal waters. For this mouth configuration, the model shows that at low tide, the surface waters are fresh upstream of the bridge, becoming brackish towards the mouth (5-6 ppt). However bottom waters are brackish all through the estuary as far as the confluence with the Waiareka Creek. In the deep region near the mouth, salinities > 20 ppt are predicted.

The flood tide brings more sea water into the estuary, and essentially sea water salinities (>30ppt) can be seen at the surface to about halfway between the mouth and sea. Brackish water travels upstream of the bridge at the surface. In the lower water column, salinities > 25ppt extend north of the bridge, and brackish water can be seen in the Kakanui and Waiareka arms of the upper estuary. It is worth noting that at the bridge the estuary is only ~2-2.5 m deep and the vertical salinity gradients are strong.

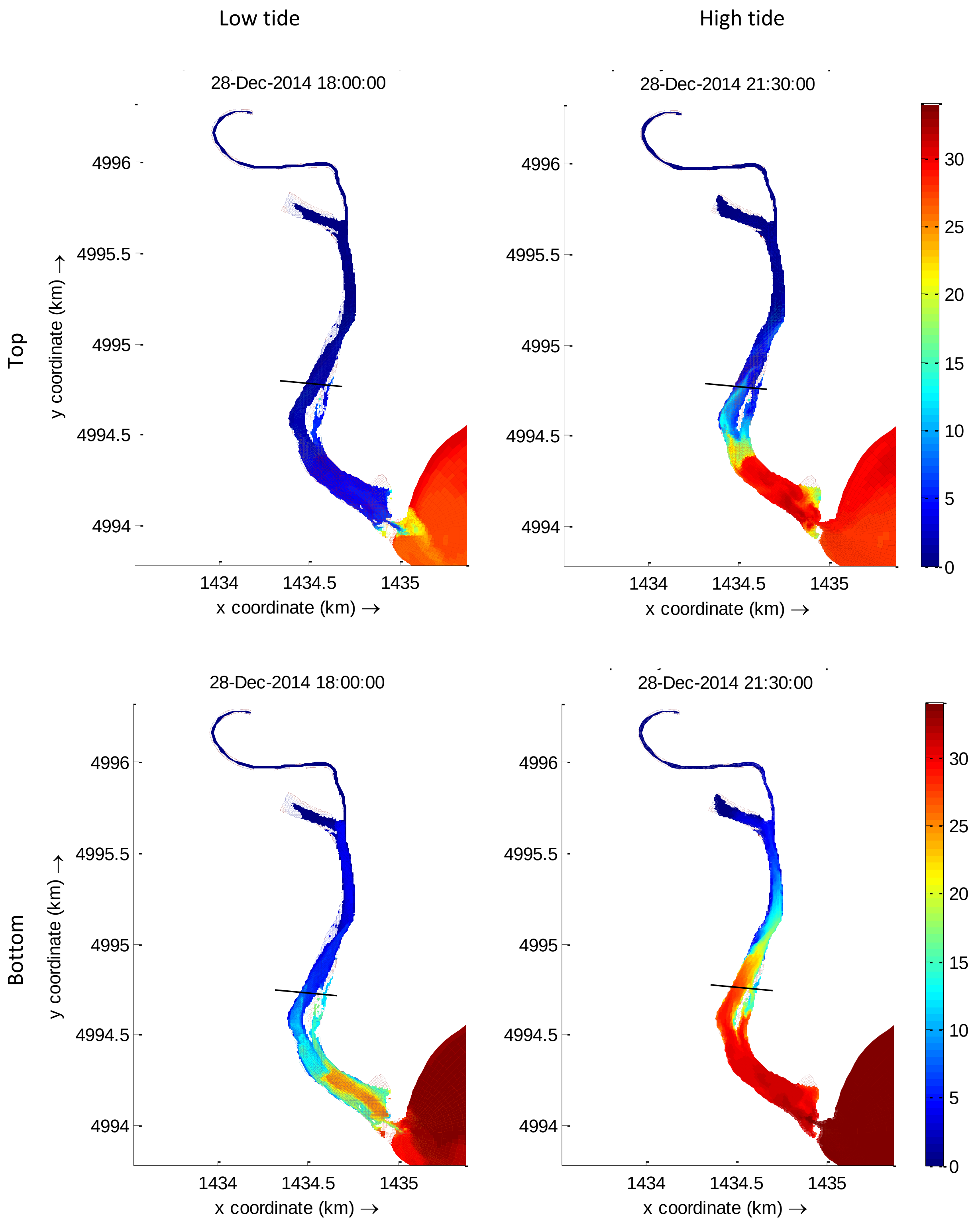

Figure 5-2: Simulated salinity distributions in the Kakanui Estuary at (left) low tide and (right) high tide for the surveyed mouth opening geometry for 2014-2015 mean summer flows. The upper two plots show salinity in the uppermost 5% of the water column, and the lower two plots show salinity in the bottom 40% of the water column. The location of the bridge is indicated by the black line crossing the estuary.

Some indication of the model performance with respect to stratification is obtained by plotting salinity profiles from a point near the bridge for the three open mouth configurations at high tide, and comparing to salinity measured from the bridge at high tide on the 3 Feb 2015 (Figure 5-3). The model does capture the vertical stratification, but the lower near-bed salinities of the narrow mouth and surveyed mouth configurations and the more diffuse interface between upper and lower layers suggest that the model has too much vertical mixing. The amount of vertical mixing could potentially be reduced by adding more vertical layers (at the cost of increased computation time) or modifying the vertical turbulence closure scheme. However, the constantly changing mouth during the period of the field survey (as observed and indicated by the water balance) cannot be easily replicated in the model, and this would have a large influence on the influx of sea water and the amount of vertical mixing. It is highly likely that the flow increase on 1-2 Feb 2015 opened the mouth allowing more sea water to enter, raising the salinity within the estuary. This high salinity/high density water would have travelled far upstream into the estuary, and formed a stable, dense underlying layer that would take some time to mix. The model predictions show conditions after a period of several days of constant flow when mixing would result in a steady state (when averaged over the tidal period) vertical profile. Because of these factors, we elected not to add additional vertical layers or modify the parameters of the turbulence closure schemes as there was not enough data to confirm that any changes were truly improving the performance of the model.

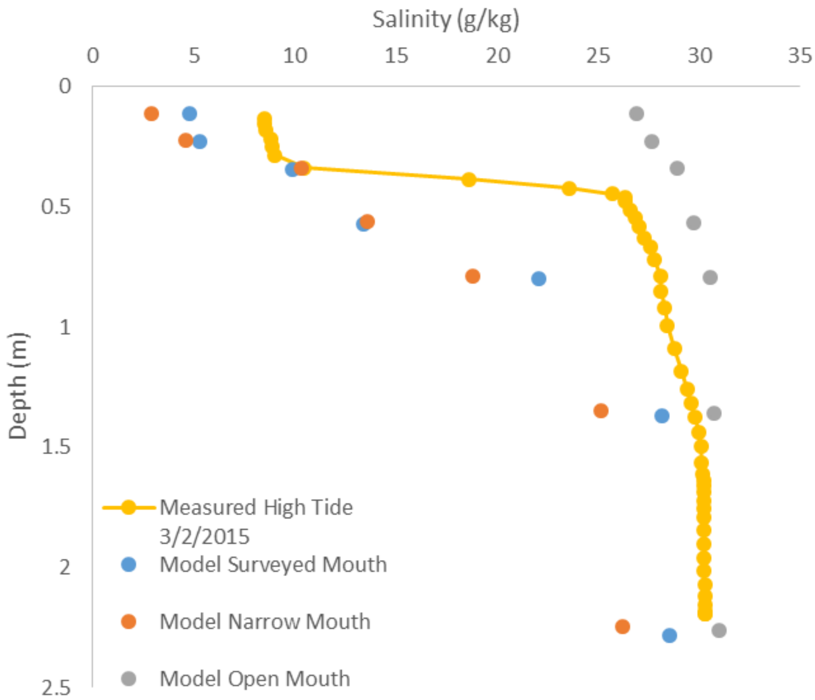

Figure 5-3: Vertical profiles of salinity at the Kakanui Bridge at high tide for the three simulated mouth openings and measured on 3 Feb 2015.

The water in the estuary is a mix of water sourced from the Kakanui River, the Waiareka Creek and the ocean. The proportion of water from these three sources will vary in time as well as horizontally and vertically. Figure 5-4 shows the time- and depth-averaged ratios of water from each source for the surveyed mouth opening at 2014-2015 mean summer flows. Plots of the tracer distributions from all 20 simulations are given in Appendix A. Although this time- and depth- averaging does obscure the variability that occurs at any point in the estuary, it does provide a means by which different flows and mouth configurations can be compared. Figure 5-4 illustrates that for this mouth and flow configuration, the river upstream of the bridge mostly originates from the Kakanui River, with the Waiareka Creek providing of 30-40% of the water. Ocean-sourced water dominates (on average) between the estuary mouth and the downstream end of the island below the bridge. Time- and depth-averaged salinities can be estimated by multiplying the ocean-sourced fraction by the salinity of coastal sea water (~34ppt).

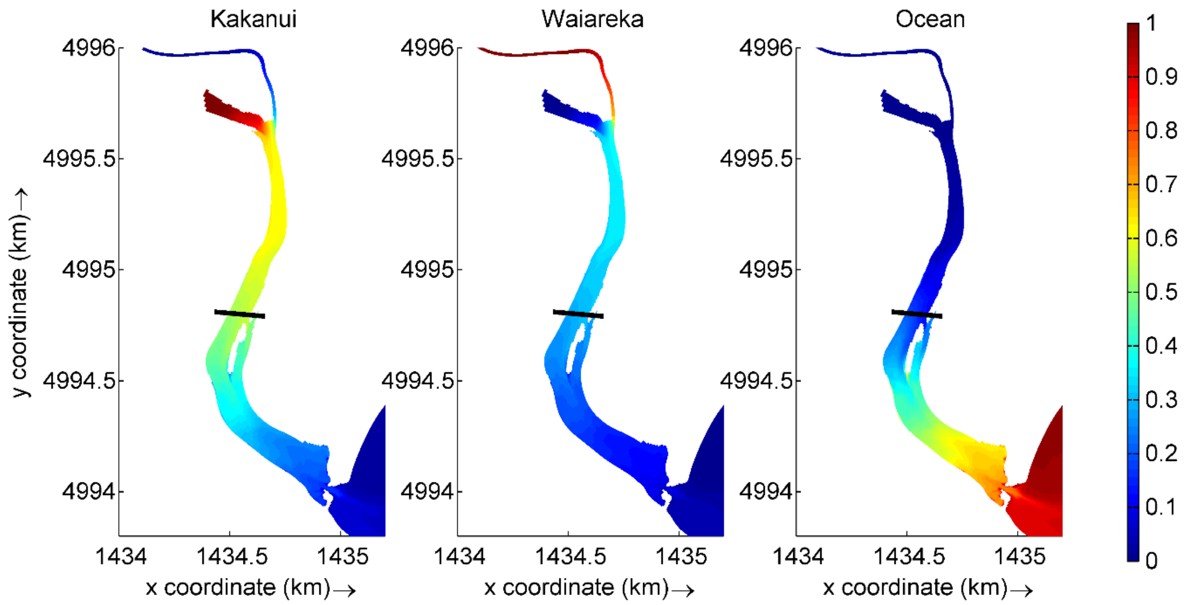

Figure 5-4: Depth- and time-averaged distributions of the fractions of water originating from Kakanui River, Waiareka Creek and the ocean. The distributions are calculated as averages over two tidal periods (24hr45min) for the surveyed mouth configuration with mean 2014-2015 summer flows (flow scenario 2).

Distribution of nutrient concentrations in the estuary can be derived by simply multiplying the nutrient concentration in each source (if known) by the fraction of the water originating from that source, and then adding these values together. This process will be demonstrated later.

A further simplification can be made by calculating volumetric- and time-averaged tracer concentrations. This more readily allows a comparison between different flow scenarios and mouth configurations on an estuary wide basis. Volume averages have been calculated over the area between the mouth and the confluence of the Kakanui River and Waiareka Stream. Figure 5-5 shows the time- and volume-averaged tracer concentrations for all of the model simulations. The figure shows the averaged fraction of water from each source (Kakanui River, Waiareka Creek, and the ocean) plotted against the discharge from the Kakanui River. We have plotted the data points corresponding to the lowest flow (7 day MALF) using a different symbol because a lower discharge from the Waiareka Creek was used for those simulations. Thus the concentrations at the lower flow are affected by the lower Waiareka Creek and should not be directly compared to the other flow scenarios. Figure 5-5 shows two significant trends:

- The fraction of the estuary volume originating from the Kakanui River increases as the discharge from the Kakanui River increases. The fractions originating from the Waiareka Creek and the ocean decrease.
- The fraction of water originating from the ocean increases as the mouth is widened.

There is little difference between the 'narrow' and 'surveyed' mouth configurations. If we may consider these to be "typical" mouth configurations, then the estuary consists of >50% Kakanui River sourced water at discharges above ~1.2 $m^3 s^{-1}$.

The ocean-sourced fraction is negligible when the mouth is closed. It is important to note that the simulations represent conditions that will be obtained after a sustained 14 day period. When the mouth changes from an open to closed configuration the ocean fraction (and salinity) gradually drops as the sea water is flushed from the estuary. The oceanic fraction shown at the lowest flow is 0.18. This non-zero value is caused by two factors: firstly at this lowest river discharge the residence time of the estuary is long (Q/V ~ 9.7 days). Secondly the low flows result in low turbulence and vertical mixing and oceanic water can be retained in deeper parts of the estuary for long periods of time.

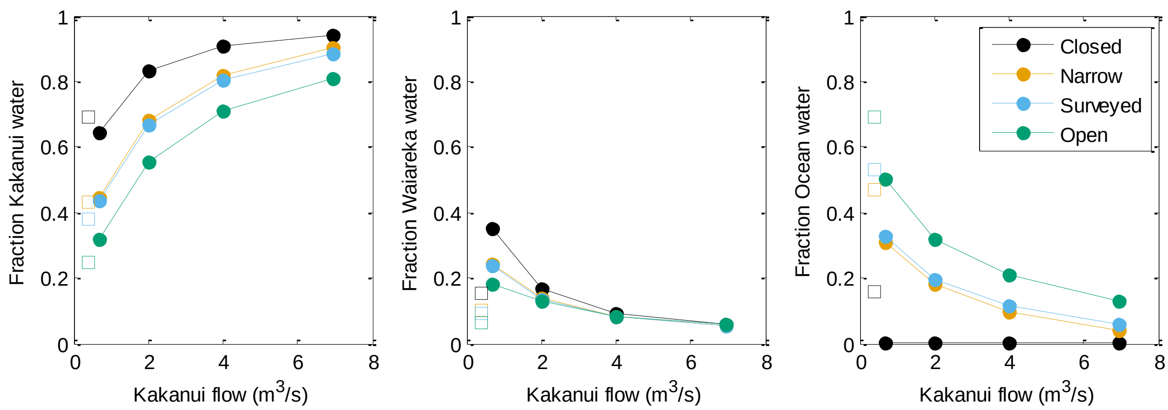

Figure 5-5: Time and spatially averaged fraction of water from each source in the estuary as a function of flow in the Kakanui River. Discharge from the Waiareka Creek was ~0.4 $m^3 s^{-1}$ for all scenarios except for the lowest flow, plotted using open squares, where a discharge of 0.09 $m^3 s^{-1}$ was used.

5.3 Estuary nutrient concentrations

The water volume fractions shown in Figure 5-5 can be used to estimate nutrient concentrations in the estuary by multiplying the fractions by the corresponding concentrations in the inflows and ocean. We use the sum of the mean values of NNN[6] (almost entirely nitrate (NO_3^-) but including small amounts of nitrite (NO_2^-)) and ammonium (NH_4^+) to represent Dissolved Inorganic Nitrogen (DIN) for the Waiareka Creek (299 mg m^{-3}) and Kakanui River (139 mg m^{-3}) from a summary of water quality published by the Otago Regional Council (Ozanne and Wilson 2013, Table 4.2). No measurements of

[6] NNN is the biologically available component of total nitrogen, an excess of which may cause nuisance algal growths.

coastal nutrient concentrations were available, so we use a value of 44 mg m^{-3} DIN based on measurements from coastal Canterbury 2012-2014 (Environment Canterbury unpublished data). These values are also consistent with estimates of 50 mg m^{-3} NO_3^- obtained from CARS[7] for the data point closest to the Kakanui Estuary during summer (averaged from December to March).

Results from this analysis are shown in Figure 5-6. DIN concentrations are a function of both river discharge and mouth configuration. Concentrations in the estuary decrease as the mouth opening increases. For the closed mouth configuration, the DIN concentration decreases with river flow (except at the lowest discharge, which will be discussed latter). For the open mouth, concentrations increase with Kakanui River discharge, reaching a concentration close to but slightly lower than the concentration in the Kakanui River. For the narrow and surveyed mouths, concentrations initially decrease, then slightly increase with river flow, with concentrations slightly higher than those in the Kakanui River.

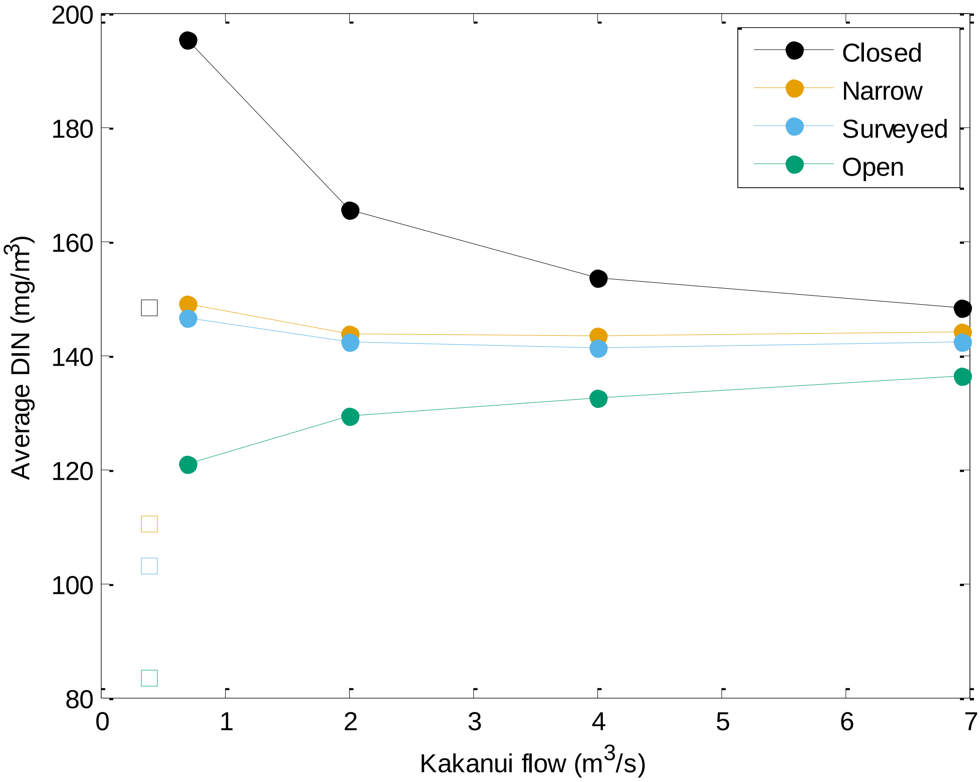

Figure 5-6: Spatially and time-averaged nitrogen concentrations in the Kakanui Estuary plotted against discharge from the Kakanui River for each simulated mouth configuration. As in previous figures, a different symbol is used for data points corresponding to the lowest river discharge due to a lower discharge used for the Waiareka Creek.

The concentrations predicted in Figure 5-6 are higher than measured DIN concentrations (see Figure 3-9 and Table 3-2) and represent the 'potential' supply of DIN arising from river and ocean loading, and fluxing. This discrepancy could be due to a combination of factors:

7 CARS (CSIRO Atlas of Regional Seas) is a digital climatology of seasonal ocean water properties http://www.marine.csiro.au/~dunn/cars2009/

- The predicted values are time (tidally) and volume averaged, whereas the field data are for surface samples collected at the Kakanui Bridge at a particular point in time
- The model-derived predictions do not account for any uptake of nitrogen by algae in the estuary. This would reduce DIN concentrations
- The model-derived predictions do not account for any loss of N via release of N_2 gas (denitrification) by estuary sediments. This would also reduce DIN concentrations
- The mean values of DIN used for the river inflows may be high for summer conditions.

Further insight can be obtained by comparing how much of the N concentration can be attributed to each end-member source. Figure 5-7 shows the total DIN concentration as a function of Kakanui River flow for each mouth configuration, as well as the portion of the total concentration originating from each source. It becomes apparent that at low flows, particularly the mean summer 2014/15 flow, the Waiareka Creek contributes a significant proportion of the N-loading even though the flows from this source are lower than in the Kakanui. This due to the higher concentrations of DIN in the Waiareka Creek. At the lowest flow modelled (7 day MALF, shown as open squares), the DIN concentration resulting from the Waiareka Creek is substantially reduced because the discharge is reduced to 0.09 $m^3 s^{-1}$ while no changes were made to concentration. Thus the loading (flow × concentration) is reduced compared to the other scenarios. For most mouth configurations the decrease in concentration with increasing Kakanui River discharge is due to a combination of greater dilution of the more concentrated Waiareka-derived nutrients, and because water is more rapidly flushed from the estuary at higher flows.

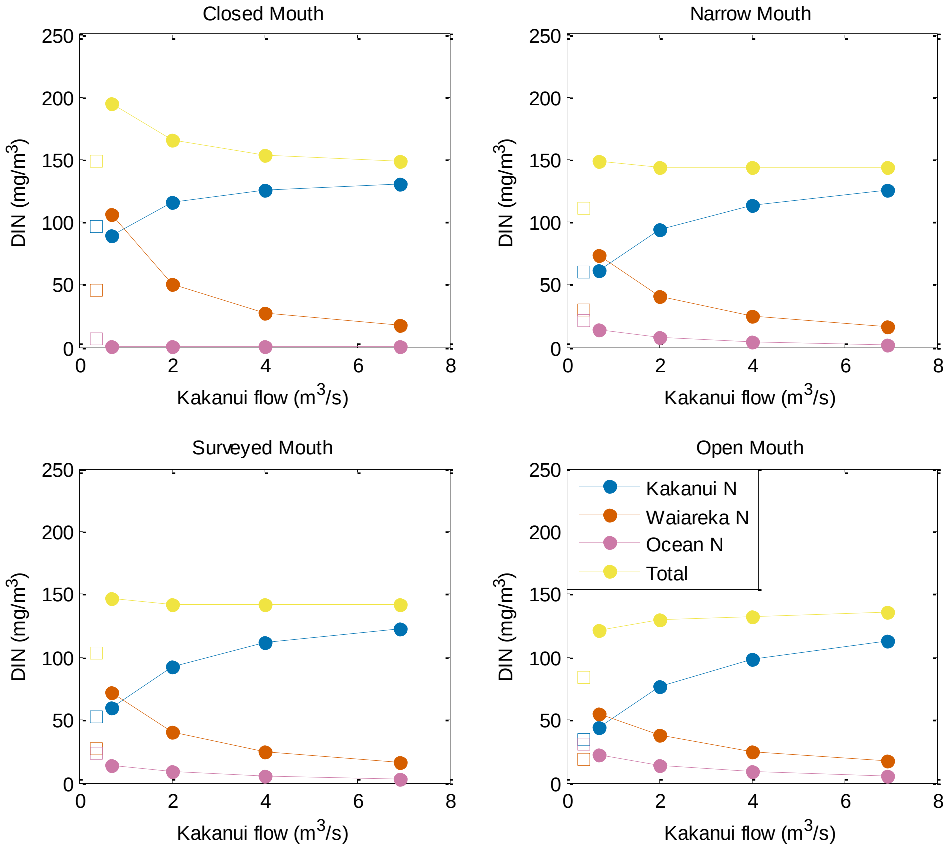

Figure 5-7: Spatially and time-averaged concentrations of DIN in the Kakanui Estuary for each mouth configuration as a function of discharge from the Kakanui River. Each plot shows the contribution of DIN from each source (Kakanui River, Waiareka Creek, and ocean) and the total concentration. The data points for the lowest discharge are shown with a different symbol because this simulations used a lower discharge in the Waiareka Creek.

The above graphs show spatially and time-averaged results. When the mouth is open, there are longitudinal gradients in tracer and hence nutrient concentrations. Taking the mean summer 2014/15 flow scenario as representing typical summer conditions in the estuary, the spatial distributions of nitrogen can be compared between the modelled mouth configurations (Figure 5-8). Concentrations are near uniform throughout the estuary when the mouth is closed. When the mouth is open to the sea, nutrients concentrations are highest in the upper reaches of the estuary, and decrease towards the mouth. The influence of the high concentrations of DIN in the Waiareka Creek also are apparent.

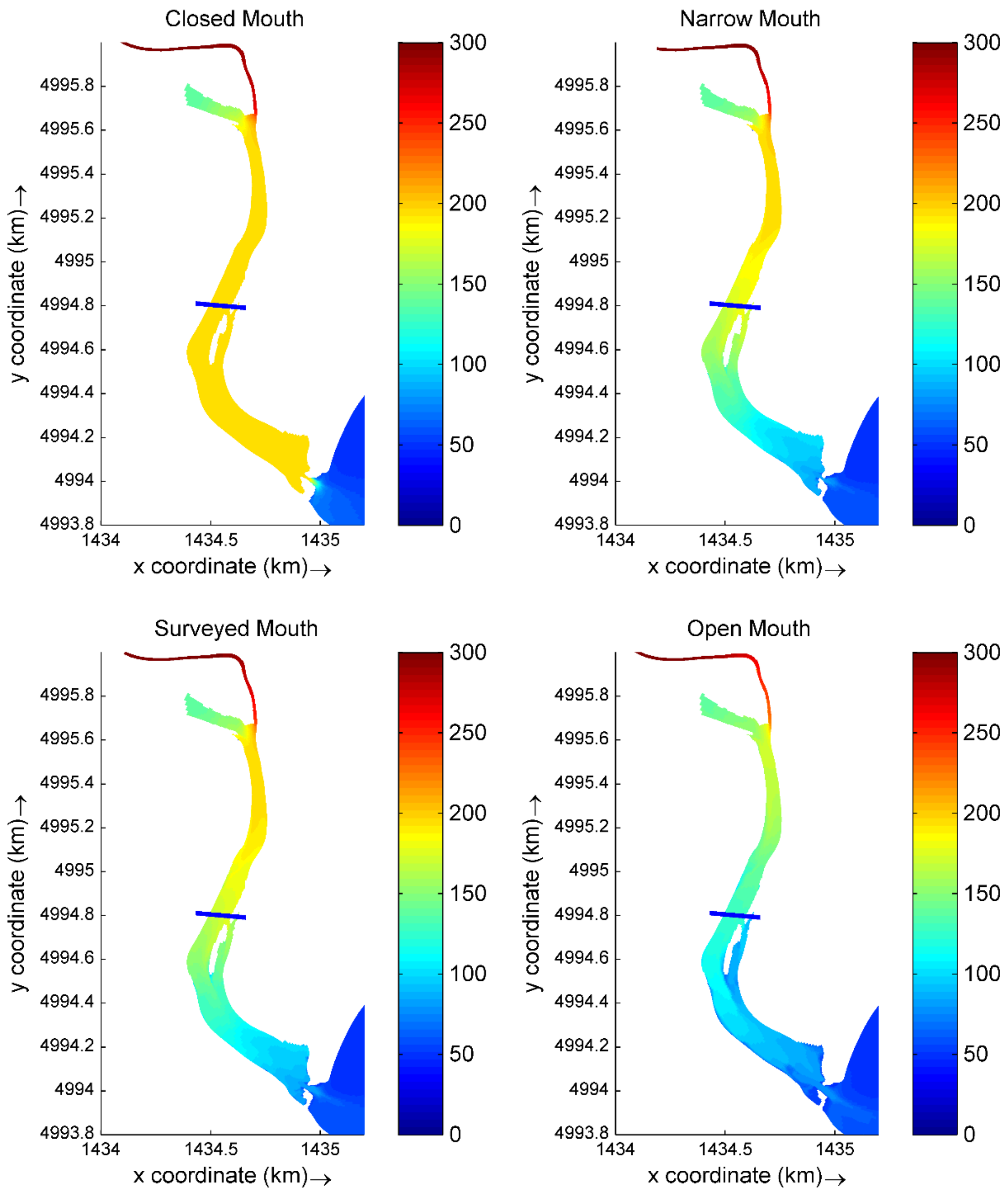

Figure 5-8: Modelled time- and depth-averaged DIN concentrations under summer 2014/15 mean flow conditions for each mouth configuration. Concentrations are indicated by the colour scale with units of mg m^{-3}. Concentrations used for the Kakanui River and Waiareka Creek were 139 mg m^{-3} and 299 mg m^{-3} respectively, with 44 mg m^{-3} applied to the ocean boundary.

6 Implications for estuary trophic state

Ulva samples collected from the Kakanui Estuary indicated moderate (to high in some cases) levels of nitrogen availability with mean tissue-N levels of 2.65%. *Ulva* is well known to thrive on high concentrations of nitrogen in water (Björnsäter and Wheeler, 1990; Morand and Briand, 1996; Barr *et al*., 2013), attaining high growth rates often in excess of 40% day^{-1} especially when other nutrients and conditions are also optimal for growth. There is a very strong but non-linear relationship between tissue-N content in *Ulva* and its potential growth rate (Björnsäter and Wheeler, 1990). However there are also other factors that affect growth, in particular light and temperature. Because of the uncertainty around the other factors affecting *Ulva* growth in the Kakanui Estuary we suggest draft target ranges of both *Ulva* tissue-N content and potential water nitrogen concentrations for controlling potential growth rather than single trigger values (Table 6-1, informed from Morand and Briand, 1996 and Barr *et al*., 2013). These draft values will need verification, based on further work to fully evaluate all the factors that contribute to *Ulva* biomass in the estuary and attendant ecological effects. These target ranges correspond to the following levels of *Ulva* potential growth and environmental effect:

Low: 'natural' levels of biochemical constituents (tissue N%) and biomass levels in the field inconspicuous, 'sustenance level'. Ecological communities are healthy and resilient.

Low to moderate: Detectable eutrophic conditions, including moderate percentage cover and biomass (at transition from reference threshold). Detectable signals of anthropogenic nutrient loading are present in algal biochemical indicators. Human amenity values are affected. Increased growth apparent in algal composition and environmental effect.

Moderate to high: Macroalgal coverage and biomass have exceeded reference threshold and algal biochemical indicators indicate the estuary is receiving significant loads of anthropogenic, catchment derived nitrogen. Seagrasses are seriously impacted and/or lost, invertebrate communities are impacted, but at levels that have not altered overall ecological integrity, with invertebrate communities reduced and fragmented. Impacts are persistent: eutrophication effects are present after seasonal algal senescence. Human amenity values are impaired.

High: Saturated maximal growth. There is extensive, seasonally persistent cover and biomass of algal mats, and very strong algal biochemical signals of anthropogenic terrestrial nutrient loading. Seagrasses lost, nearly complete loss of macrobenthic biodiversity. Impacts are quasi-permanent: good ecological function does not recover upon seasonal algal senescence or with remediation. Human amenity values are eliminated.

Table 6-1: Guide for potential growth rate in *Ulva* based its tissue-N content and potential water nutrient concentrations.

Potential growth rate	Low	Low to moderate	Moderate to high	High
Ulva tissue-N (%)	< 1	1 - 2	2 - 3	> 3
DIN (μmol/L)	< 2	2 - 5	5 - 15	> 15
DIN (mg/m^3)	< 28	28 - 70	70 - 210	> 210

7 Summary

The modelling and field data show that nutrient concentrations within the estuary are governed by river flow, nutrient concentrations in the Kakanui River and Waiareka Creek, and the state of the estuary mouth. It is important to consider that the model treats nutrients as passive tracers. Any uptake or release of nutrients (or changes in their form) are not considered. Consequently we might expect the model to overestimate dissolved nitrogen concentrations compared to field measurements as high biomass of *Ulva* will draw down nutrients (the measured nutrient concentrations would likely be higher if the algae were not present). However high biomass in the estuary is a function of the nutrient availability. The 'potential nutrient concentrations' predicted by the model are a useful predictor of the availability of nutrients for algae growth.

7.1 Estuary mouth

Because nitrogen concentration are higher in the rivers than in the ocean, nutrient concentrations in the estuary reduce as the mouth opening increases. An open mouth allows greater tidal flows into and from the estuary, resulting in greater exchange between the estuary and the sea, and increased dilution of the riverine water by sea water. This dilution and the associated reduction in nutrient concentrations is greatest close to the mouth. As the mouth opening increases in size, the extent of dilution with sea water increases upstream. Increasing the exchange between the estuary and ocean also results in a reduction of residence time within the estuary. Figure 5-6 illustrates how opening the mouth can reduce the average dissolved inorganic concentration within the estuary. At mean 2014/15 summer flows, DIN concentrations were reduced by 25-40% compared to the closed mouth scenario.

A possible method of reducing nutrient concentrations in the estuary may be to maintain an open mouth over summer months. The gravel bar at the mouth of the Kakanui Estuary is highly mobile, and maintaining an open mouth would likely present some engineering challenges. Whilst maintaining an open mouth would reduce nutrient concentrations, it can only reduce them so far. When using mean riverine DIN concentrations derived from Ozanne and Wilson (2013), the DIN concentrations predicted for an open or partially open mouth (Figure 5-6) are still within the range that would result in moderate to high growth rates (Table 6-1). The in-estuary DIN concentrations estimated from mean riverine DIN concentrations are higher than observed for reasons discussed previously. But the tissue-N samples were collected following a period of partial mouth opening and the tissue-N concentrations indicate that moderate to high growth rates are likely.

The total biomass in the estuary also reflects growth that occurred earlier in the season when the mouth was closed. It is likely that DIN concentrations would have been towards the upper end of the moderate to high range of potential *Ulva* growth rates (Table 6-1) when the mouth was closed.

Opening the mouth may give some reduction in *Ulva* growth rates, but is not likely to cause significant reduction in algae growth without reductions in nutrient inputs from the Kakanui River and Waiareka Creek. The concentration in the estuary will be intermediate that of the inflows and the ocean, but closer to that of the inflows, particularly as the mouth becomes increasingly constricted.

Further model assessment of the likely reduction in estuary nutrient concentrations should be made using a range of river nutrient concentrations, and measurements of coastal nutrient concentrations would also be useful for setting the oceanic boundary condition. The oceanic DIN concentration assumed when demonstrating how the model can be used to predict concentrations in the estuary (see Figure 5-6 to Figure 5-8) were taken from coastal Canterbury and there may be some differences to concentrations offshore from the Kakanui Estuary. However it is unlikely that coastal DIN would be significantly higher than the value used here.

7.2 River nutrient loads

Nutrient concentrations in the estuary can also be controlled if the nutrient loadings from the two river inflows can be managed. The loading (kg yr^{-1}) to the estuary is a product of both flow and concentration, which may be related. We have assumed constant inflow concentrations in our simulations (we have neither increased nor decreased concentrations when changing river flows). At low flows the Waiareka Creek contributes a large proportion (>50% at mean 2014/15 summer flows) of the nitrogen loading to the estuary due to the high concentrations in this source. It would be useful to determine the relationship between flow rate and nutrient loading from the Waiareka Creek and the Kakanui River . In the model, the Kakanui River became the dominant source of nitrogen in the estuary as the discharge from this river was increased (due to the assumption of fixed nitrogen concentrations). Similarly, concentrations of nutrients in the Kakanui River could either decrease with increasing flow (greater dilution) or increase due to more runoff. As Kakanui River discharge was increased, concentrations in the estuary trended towards the raw riverine values. Ultimately, nutrient concentrations in the estuary will be determined by those in the river.

To reach values of the critical threshold (N_{crit}) for *Ulva* tissue N would require reducing potential DIN concentrations in the estuary to <70 mg m^{-3}. For the mouth configurations modelled here at mean summer flows, this implies reducing the concentrations of the inflows to <96 mg m^{-3} DIN for the open mouth, <84 mg m^{-3} for the surveyed and narrow mouth, and <70 mg m^{-3} when the mouth is closed. This compares to current mean DIN concentrations of 139 mg m^{-3} in the Kakanui River and 299 mg m^{-3} in the Waiareka Stream.

7.3 Recommendations for further work

The current study was intended to provide information about the likely nutrient concentrations in the estuary as a function of river flow and nutrient loading. We have addressed this by conducting simulations and using tracers to determine the distributions within the estuary of material from the two freshwater inflows and the ocean. The resulting tracer concentrations can be scaled by nutrient concentrations appropriate to each source to estimate the resulting estuary concentration. There are however a number of areas which could not be considered within the current study that might be worthy of future consideration:

- Further model calibration: while some field data were collected (water levels), attempts to monitor salinity proved unsuccessful due to instrument failure. Profiles of salinity and temperature were collected on the 4th Feb 2014, but the timing was unfortunate because a small flood in the Kakanui River occurred overnight. This altered the mouth opening and also meant that conditions were not the same as those simulated. This means that there was insufficient data against which to calibrate or validate the mixing routines within the model. A more robust model calibration would require time-series of salinity (preferably at two depths, as attempted here) and vertical profiles taken after a period of stable flows and mouth configuration, at different stages of the tide. We suspect that the model may allow too much vertical mixing, which would result in the model results showing less upstream intrusion of seawater.

- Additional simulations could be run to investigate the influence of discharge from the Waiareka Creek. There is a minimum flow imposed on this Creek of 100 $l\ s^{-1}$, although summer flows are typically in the range 300-400 $l\ s^{-1}$ (according to the flow data received). Apart from in the lowest flow scenario, the discharge of the Waiareka Creek was not varied significant in our study. In view of the possibility of controlling the flow from this Creek (e.g. via consents on water takes/discharges), a wider range of flow scenarios could be modelled.
- Implement a monitoring programme of the estuary mouth and where possible survey different mouth openings. Maintaining a water level recorder in the estuary (for example at the Kakanui Bridge) would also provide much insight into the extent of tidal influence on water levels in the estuary and provide indications of the state of the estuary mouth, potentially informing decisions regarding management intervention to open a closed mouth.
- Dynamic response to flow changes or mouth openings: the 3D models were run with fixed river flows and mouth configurations to simulate steady flow summer conditions. Further analysis of existing simulations or rerunning with modified input conditions could provide information on how rapidly tracer (and therefore nutrient) concentrations respond to floods, or to mouth openings/closures.

8 Acknowledgements

Thank you to Rachel Ozanne, Paul Hannah, Pete Stevenson (Otago Regional Council) for providing flow and water level data, site photographs, and for installation of instruments at the estuary. Thanks also to Jo Hoyle, Andrew Willsman and Jo Bind (NIWA) for conducting the bathymetry survey of the Kakanui Estuary.

9 Glossary of abbreviations and terms

7 day MALF	7 day Mean Annual Low Flow. The average of the lowest mean flow over 7 consequitive days in a calendar year
CTD	An instrument for recording vertical profiles of water column properties. CTD stands for Conductivity, Temperature, Depth, which are the three primary parameters recorded. Other sensors are added to measure other properties such as dissolved oxygen, fluoresence or light.
DIN	Dissolved Inorganic Nitrogen, consisting of Nitrate, Nitrite and Ammonia
MALF	Mean Annual Low Flow. The average of the lowest daily flow occuring in a calendar year.

10 References

Barr, N.G.; Dudley, B.D.; Rogers, K.R. and Cornelisen, C.D. (2013). Broad-scale patterns of tissue-δ^{15}N and tissue-N indices in *Ulva*; Developing a national baseline indicator of nitrogen-loading for coastal New Zealand. Marine Pollution Bulletin Baseline, Marine Pollution Bulletin 67, 203-216. [Scopus record]

Björnsäter, B.R., Wheeler, P.A., 1990. Effect of nitrogen and phosphorus supply on growth and tissue composition of *Ulva fenestrata* and *Enteromorpha intestinalis* (Ulvales, Chlorophyta). Journal of Phycology 26, 603-611.

Deltares (2013) Delft3D-FLOW. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. User Manual. Hydro-Morphodynamics. *Deltares systems*: 702.

Morand, P. and Briand, X. (1996). Excessive growth of macroalage: a symptom of environmental disturbance. *Botanica Marina* 39, 491-516.

Ozanne, R., Wilson, S. (2013) Kakanui River Water Quality Report: 95. http://www.orc.govt.nz/Documents/Publications/Research%20And%20Technical/surface-water-quality/Kakanui-river-water-quality-report.pdf

Pedersen, M.F., Borum, J. (1996). Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae. *Marine Ecology Progress Series* 142, 261-272.

Walters, R.A., Goring, D.G., Bell, R.G. (2001) Ocean tides around New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 35: 567-579.

Appendix A Maps of time- and depth-averaged tracer distributions

Closed Mouth

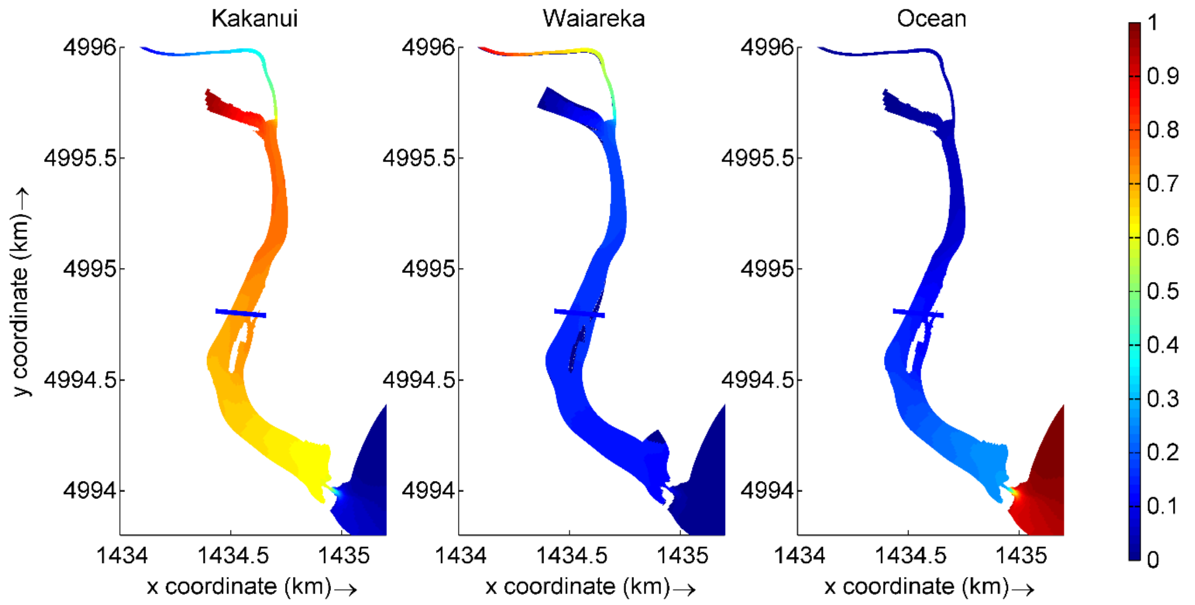

Figure A-1: Time and depth-averaged tracer concentrations for the Closed Mouth, Kakanui fow = 0.388 $m^3 s^{-1}$, Waiareka flow = 0.090 $m^3 s^{-1}$.

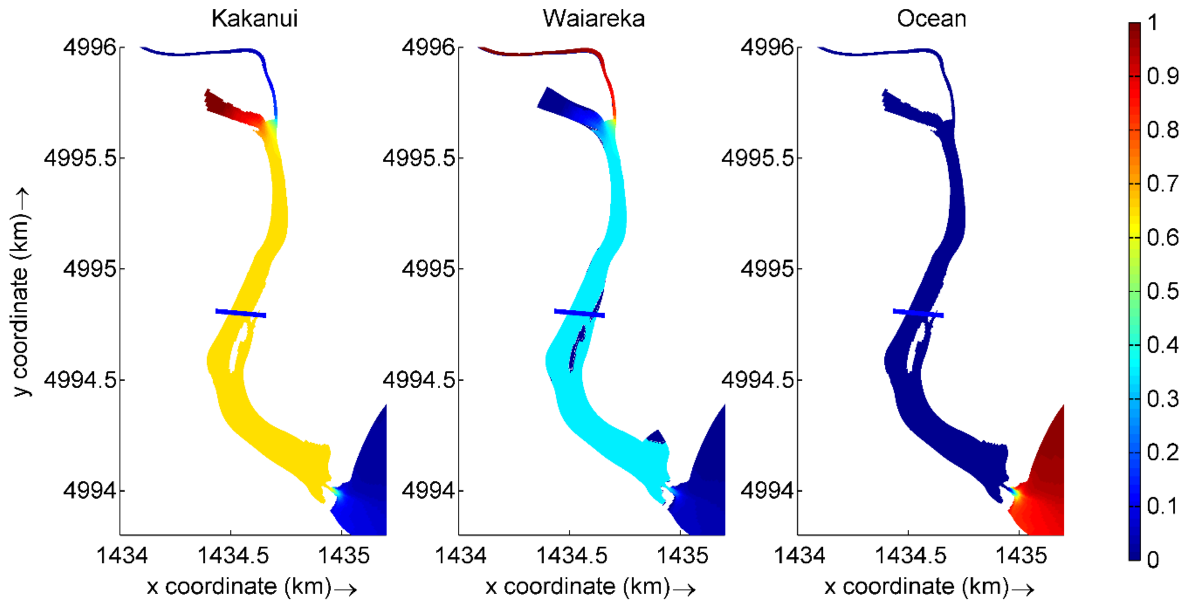

Figure A-2: Time and depth-averaged tracer concentrations for the Closed Mouth, Kakanui fow = 0.70 $m^3 s^{-1}$, Waiareka flow = 0.38 $m^3 s^{-1}$.

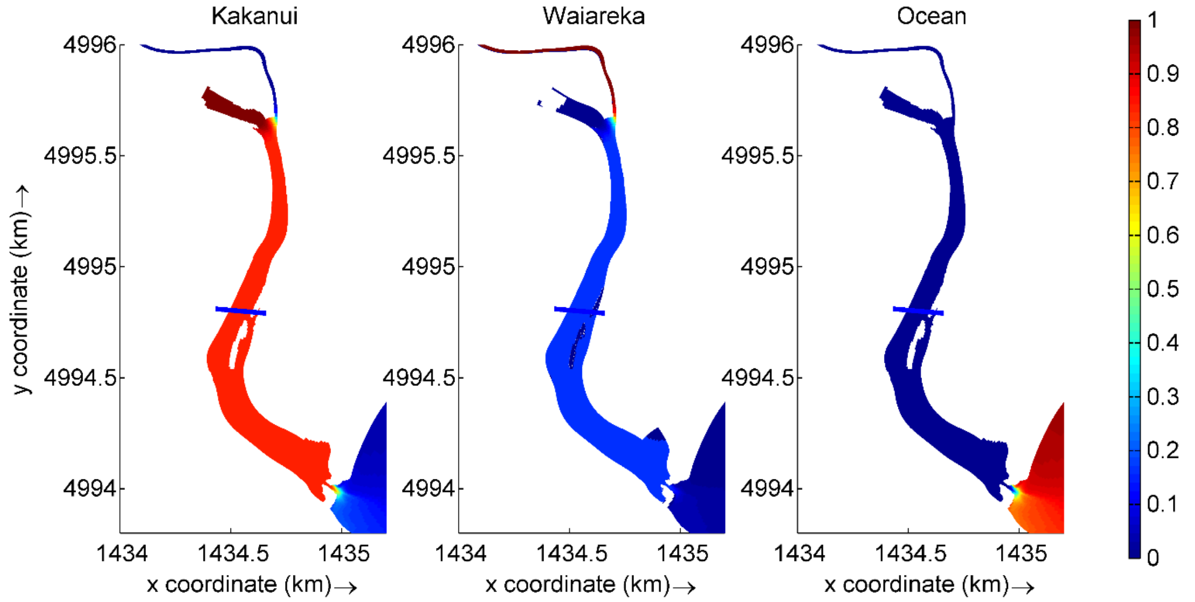

Figure A-3: **Time and depth-averaged tracer concentrations for the Closed Mouth, Kakanui fow = 2.0 $m^3 s^{-1}$, Waiareka flow = 0.40 $m^3 s^{-1}$.**

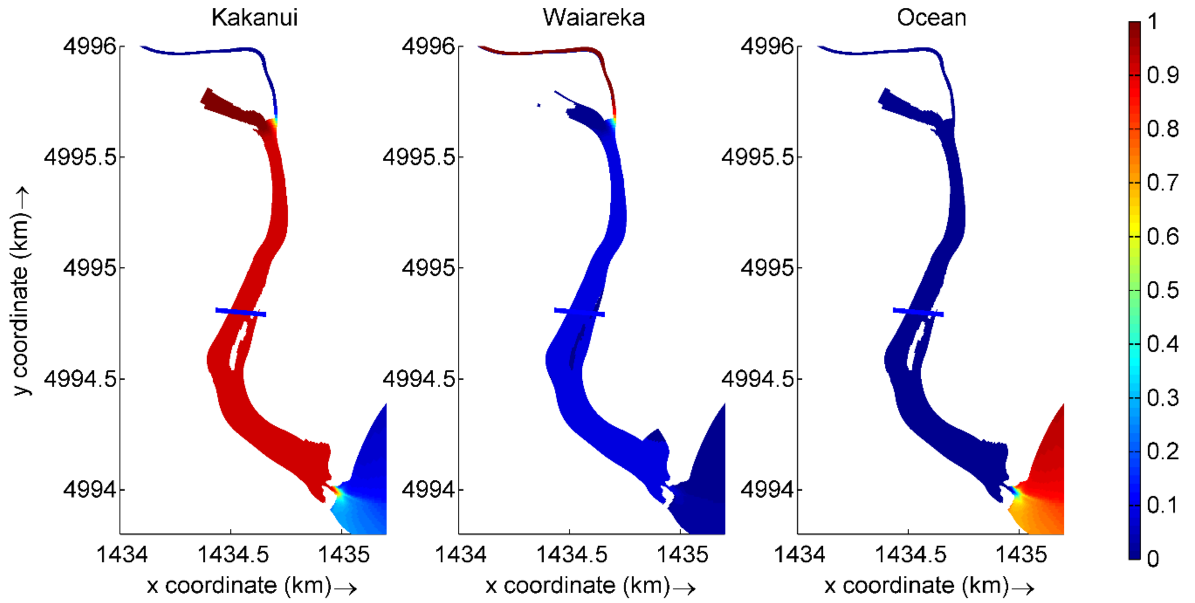

Figure A-4: **Time and depth-averaged tracer concentrations for the Closed Mouth, Kakanui fow = 4.0 $m^3 s^{-1}$, Waiareka flow = 0.40 $m^3 s^{-1}$.**

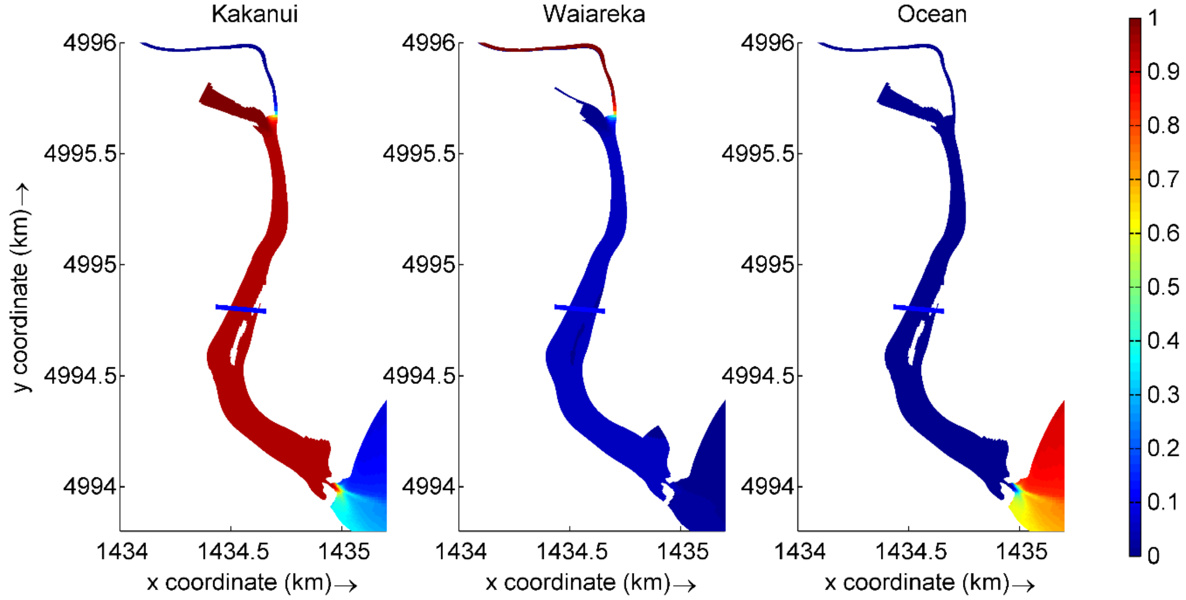

Figure A-5: Time and depth-averaged tracer concentrations for the Closed Mouth, Kakanui fow = 6.95 m^3 s^{-1}, Waiareka flow = 0.413 m^3 s^{-1}.

Narrow Mouth

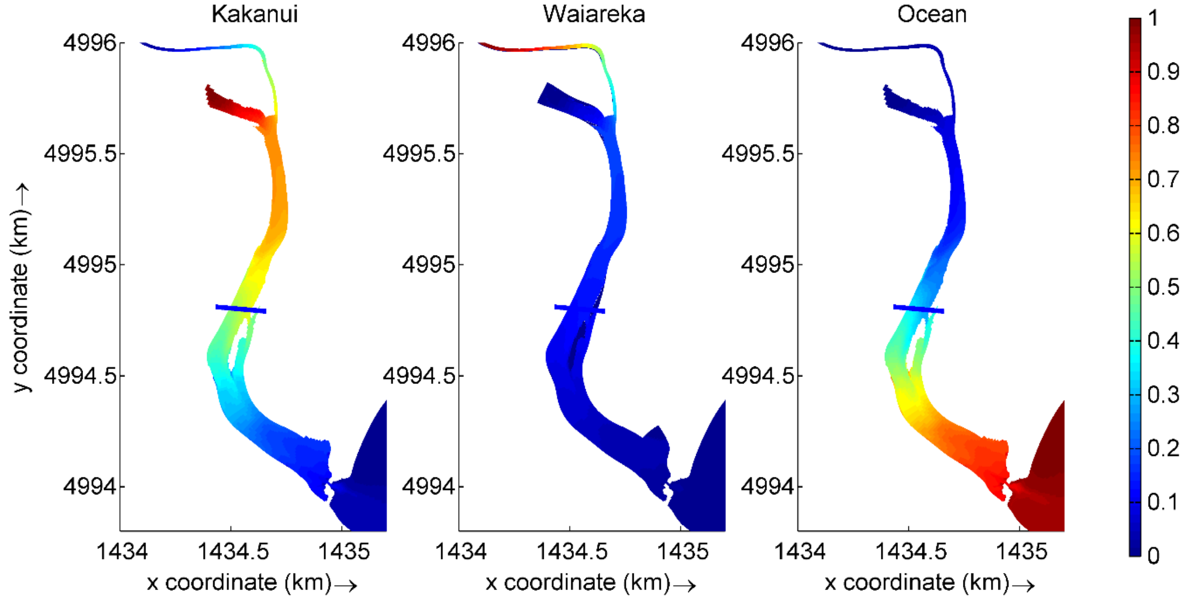

Figure A-1: Time and depth-averaged tracer concentrations for the Narrow Mouth, Kakanui fow = 0.388 m^3 s^{-1}, Waiareka flow = 0.090 m^3 s^{-1}.

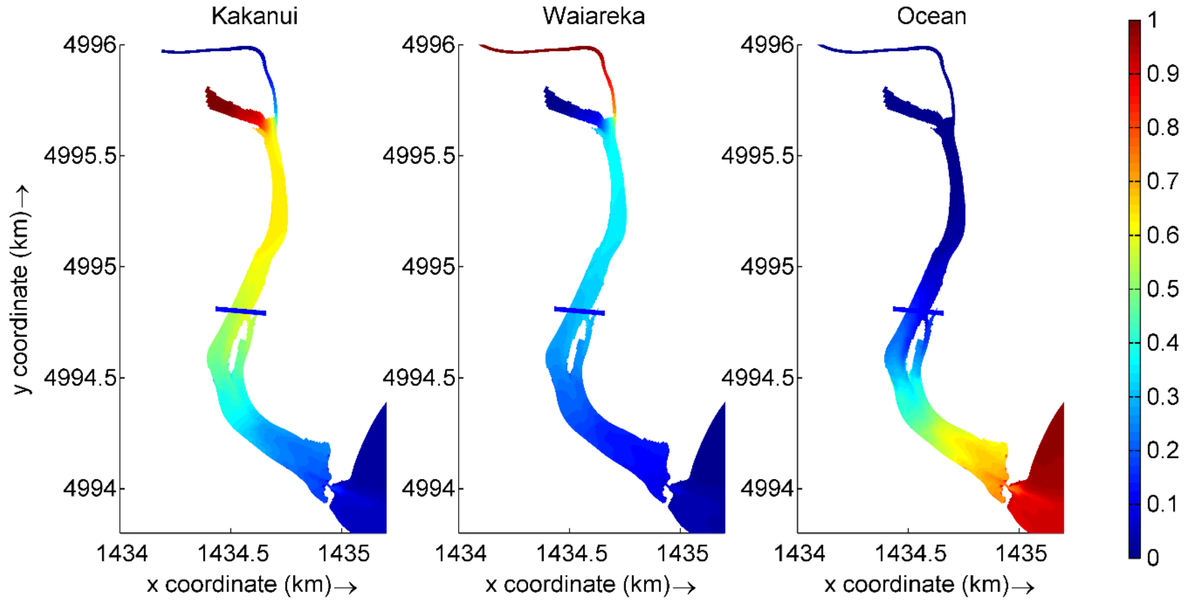

Figure A-2: Time and depth-averaged tracer concentrations for the Narrow Mouth, Kakanui fow = 0.70 m^3 s^{-1}, Waiareka flow = 0.38 m^3 s^{-1}.

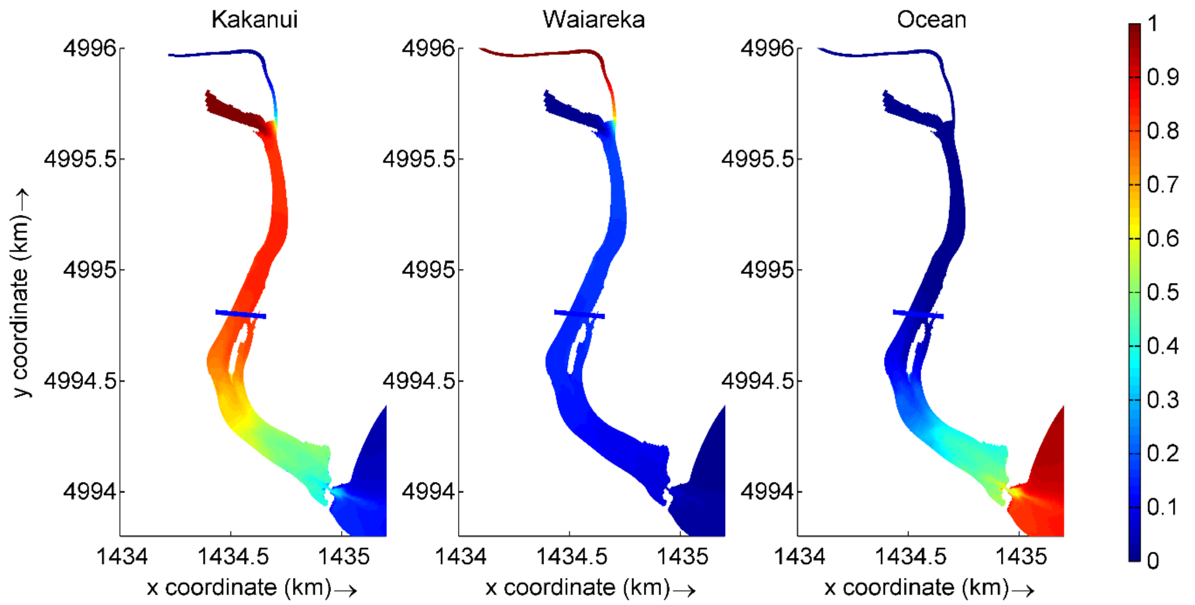

Figure A-3: Time and depth-averaged tracer concentrations for the Narrow Mouth, Kakanui fow = 2.0 m^3 s^{-1}, Waiareka flow = 0.40 m^3 s^{-1}.

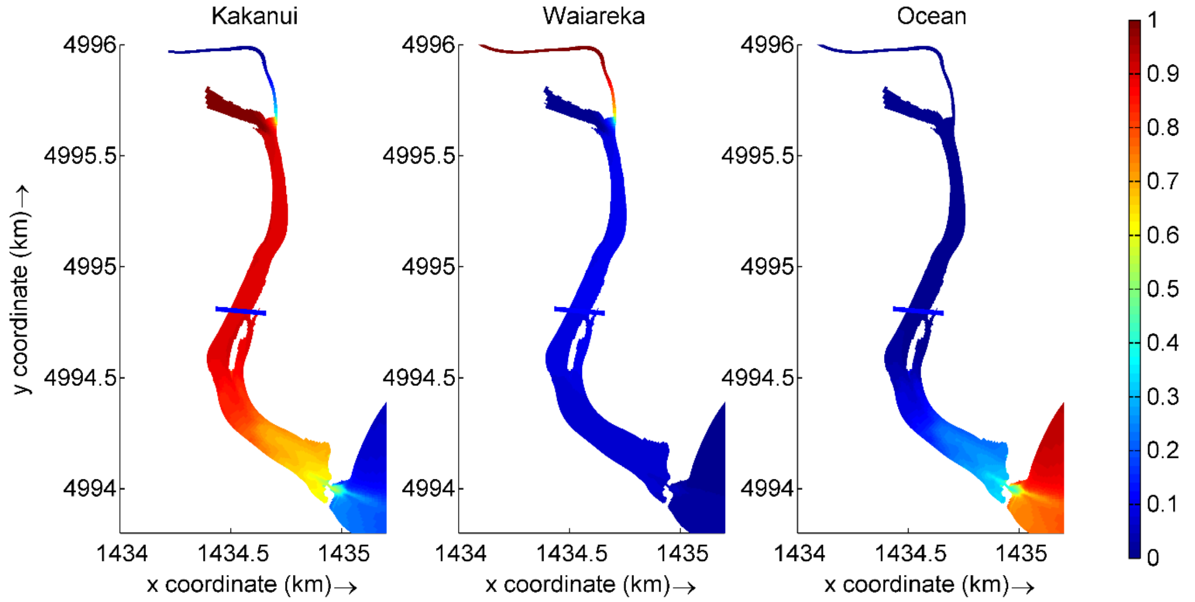

Figure A-4: Time and depth-averaged tracer concentrations for the Narrow Mouth, Kakanui fow = 4.0 m^3 s^{-1}, Waiareka flow = 0.40 m^3 s^{-1}.

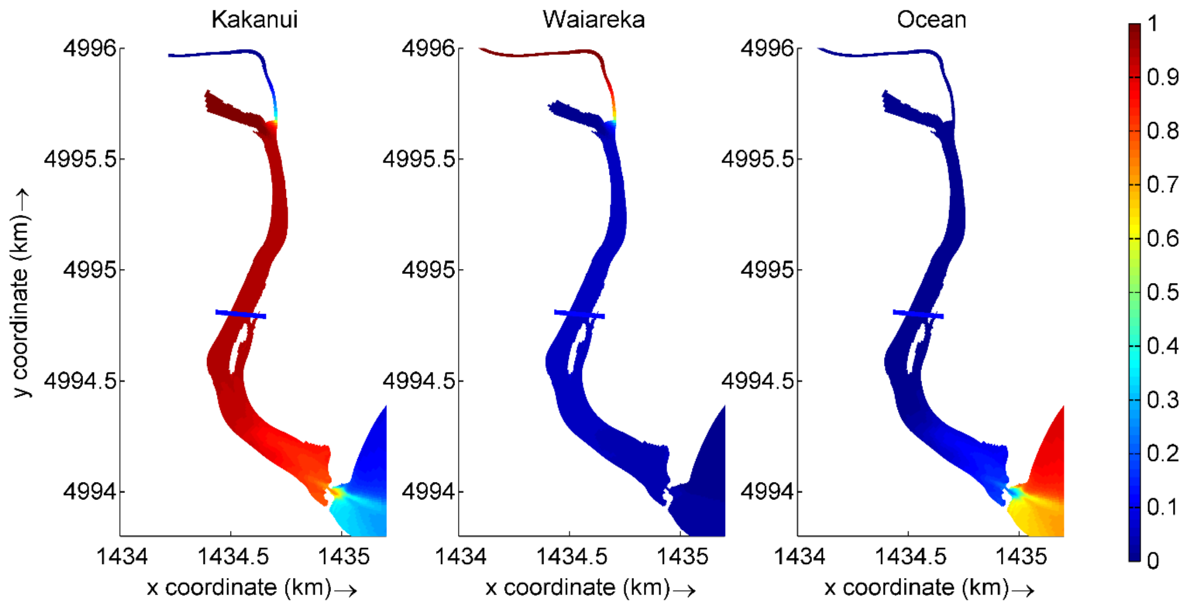

Figure A-5: Time and depth-averaged tracer concentrations for the Narrow Mouth, Kakanui fow = 6.95 m^3 s^{-1}, Waiareka flow = 0.413 m^3 s^{-1}.

Surveyed Mouth

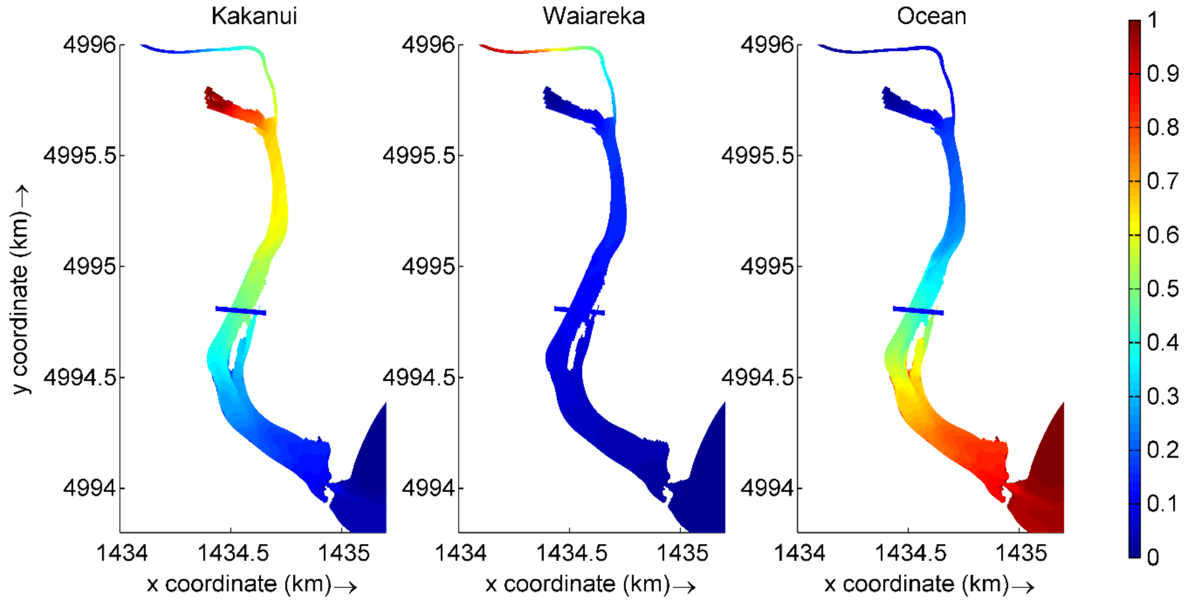

Figure A-1: Time and depth-averaged tracer concentrations for the Surveyed Mouth, Kakanui fow = 0.388 $m^3 s^{-1}$, Waiareka flow = 0.090 $m^3 s^{-1}$.

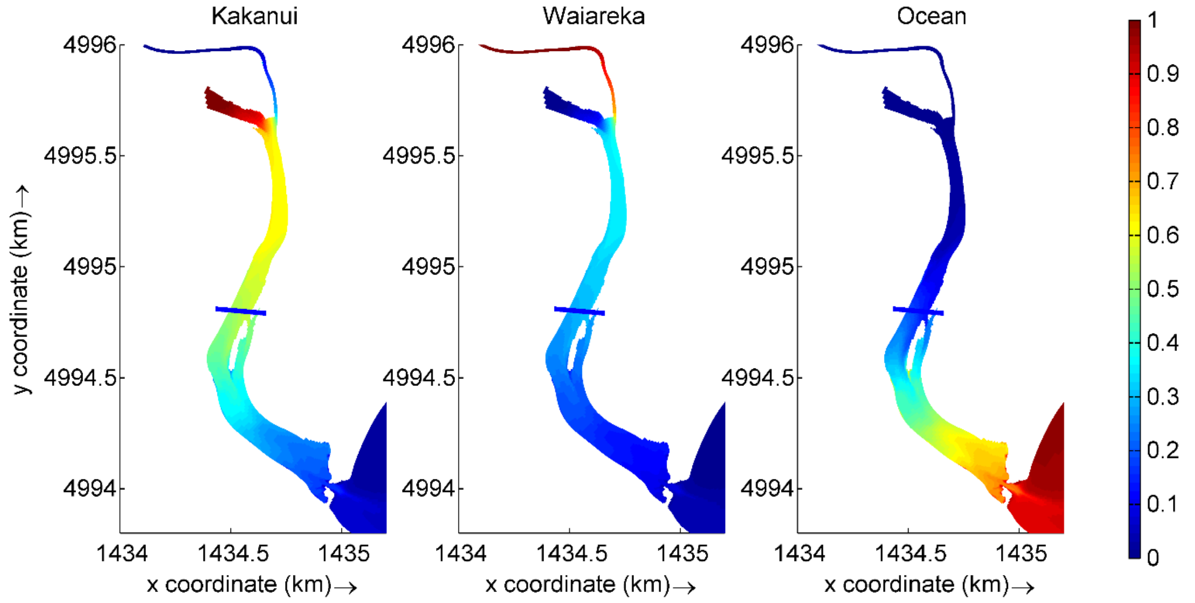

Figure A-2: Time and depth-averaged tracer concentrations for the Surveyed Mouth, Kakanui fow = 0.70 $m^3 s^{-1}$, Waiareka flow = 0.38 $m^3 s^{-1}$.

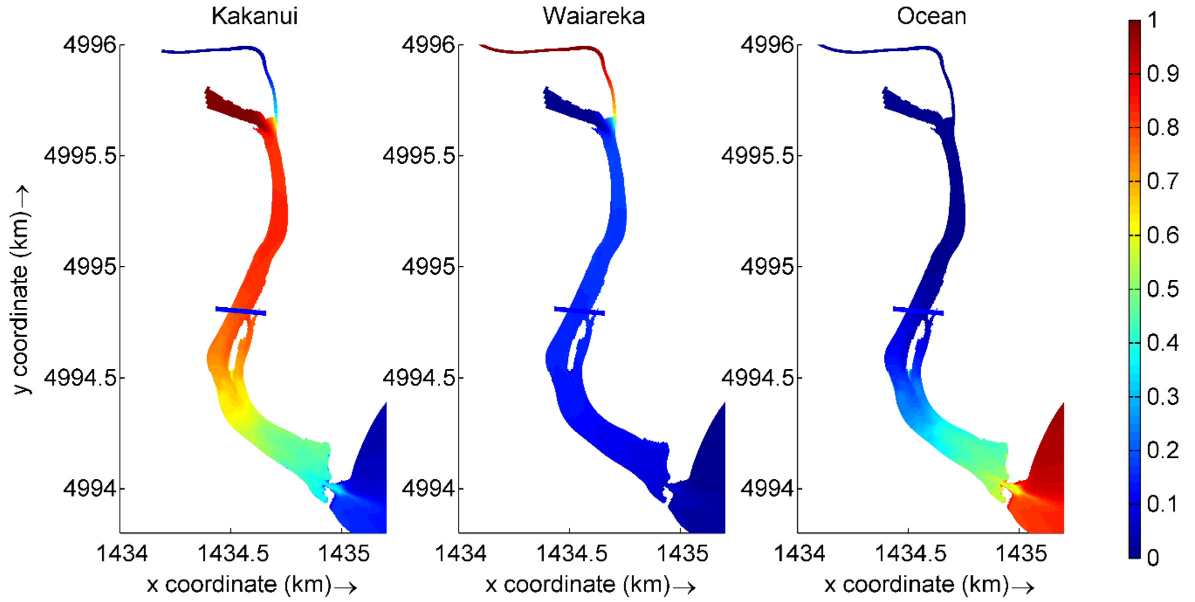

Figure A-3: Time and depth-averaged tracer concentrations for the Surveyed Mouth, Kakanui fow = 2.0 m^3 s^{-1}, Waiareka flow = 0.40 m^3 s^{-1}.

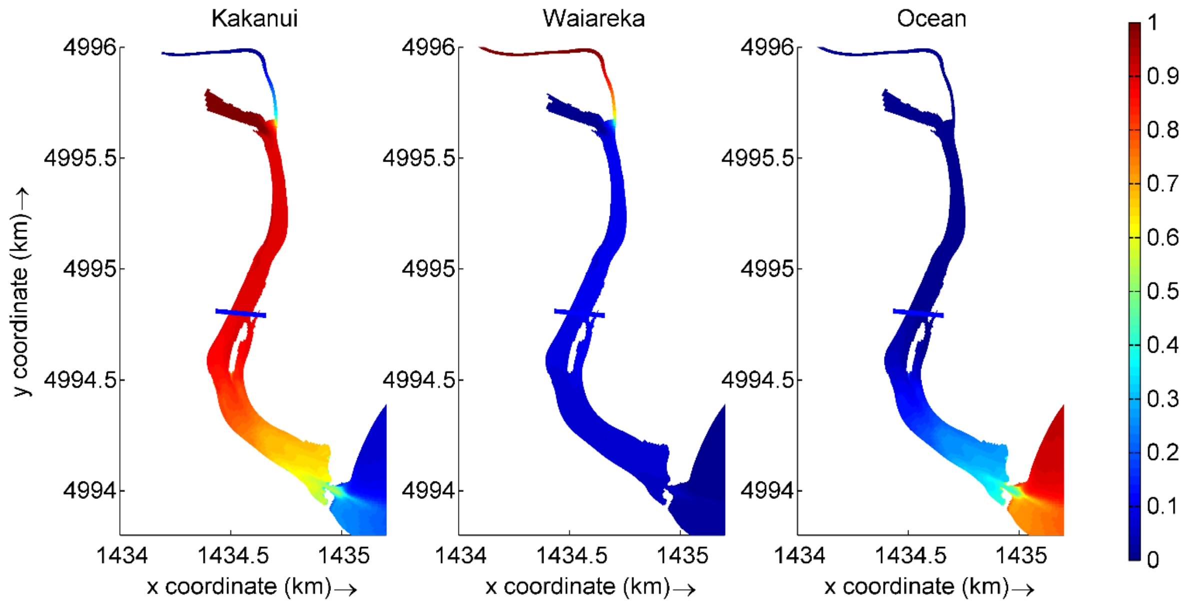

Figure A-4: Time and depth-averaged tracer concentrations for the Surveyed Mouth, Kakanui fow = 4.0 m^3 s^{-1}, Waiareka flow = 0.40 m^3 s^{-1}

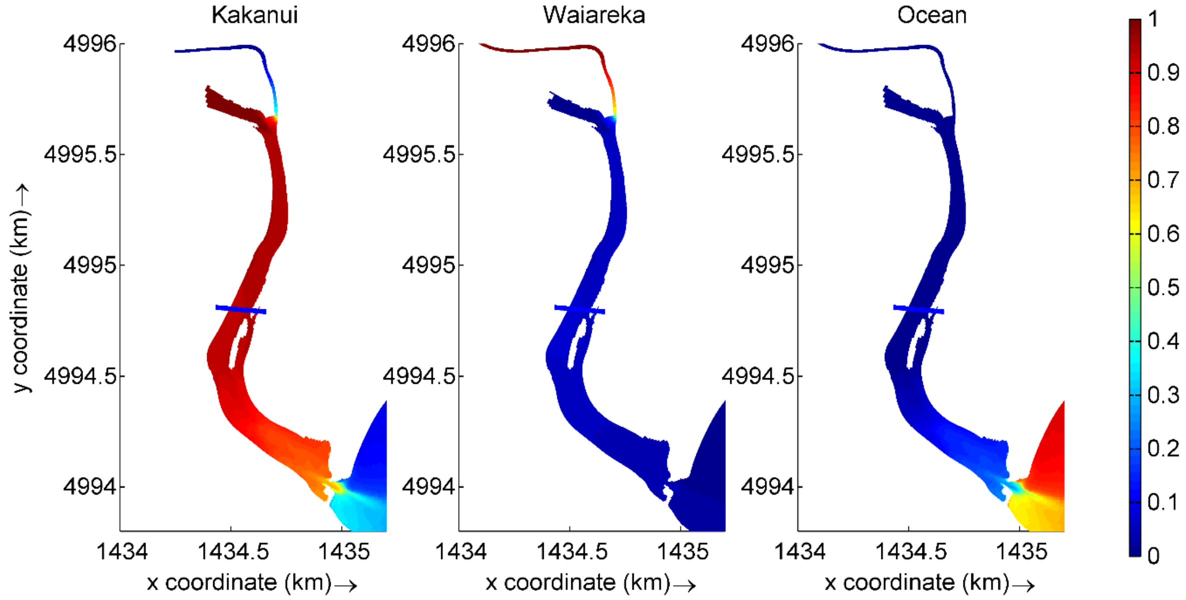

Figure A-5: Time and depth-averaged tracer concentrations for the Surveyed Mouth, Kakanui fow = 6.95 $m^3\ s^{-1}$, Waiareka flow = 0.413 $m^3\ s^{-1}$.

Open Mouth

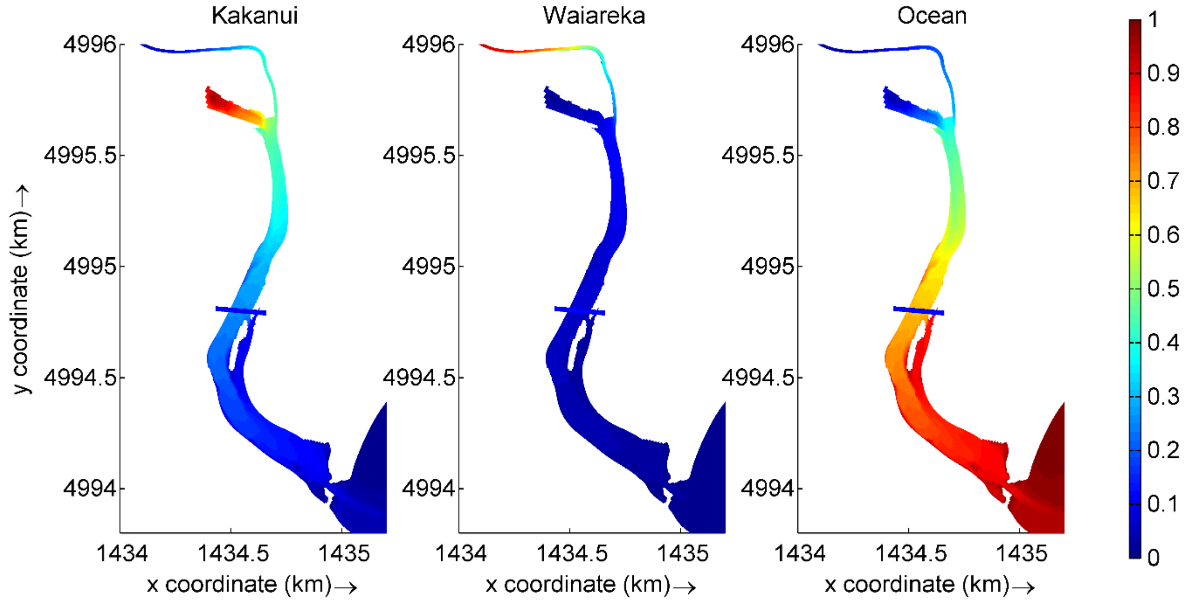

Figure A-1: Time and depth-averaged tracer concentrations for the Open Mouth, Kakanui fow = 0.388 $m^3\ s^{-1}$, Waiareka flow = 0.090 $m^3\ s^{-1}$.

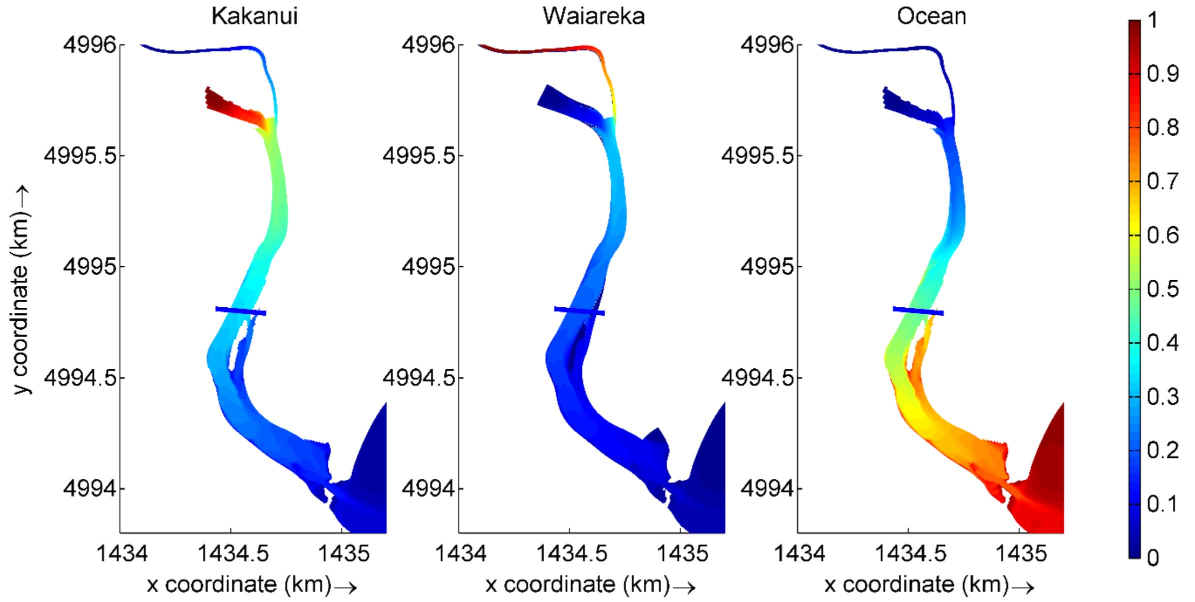

Figure A-2: Time and depth-averaged tracer concentrations for the Open Mouth, Kakanui fow = 0.70 $m^3 s^{-1}$, Waiareka flow = 0.38 $m^3 s^{-1}$.

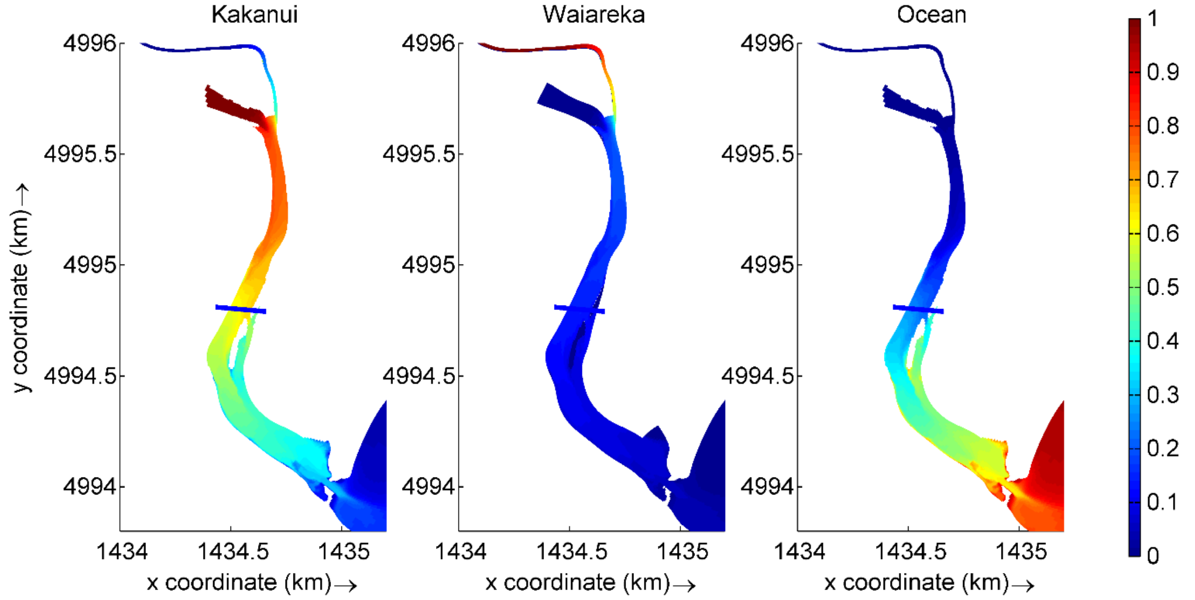

Figure A-3: Time and depth-averaged tracer concentrations for the Open Mouth, Kakanui fow = 2.0 $m^3 s^{-1}$, Waiareka flow = 0.40 $m^3 s^{-1}$.

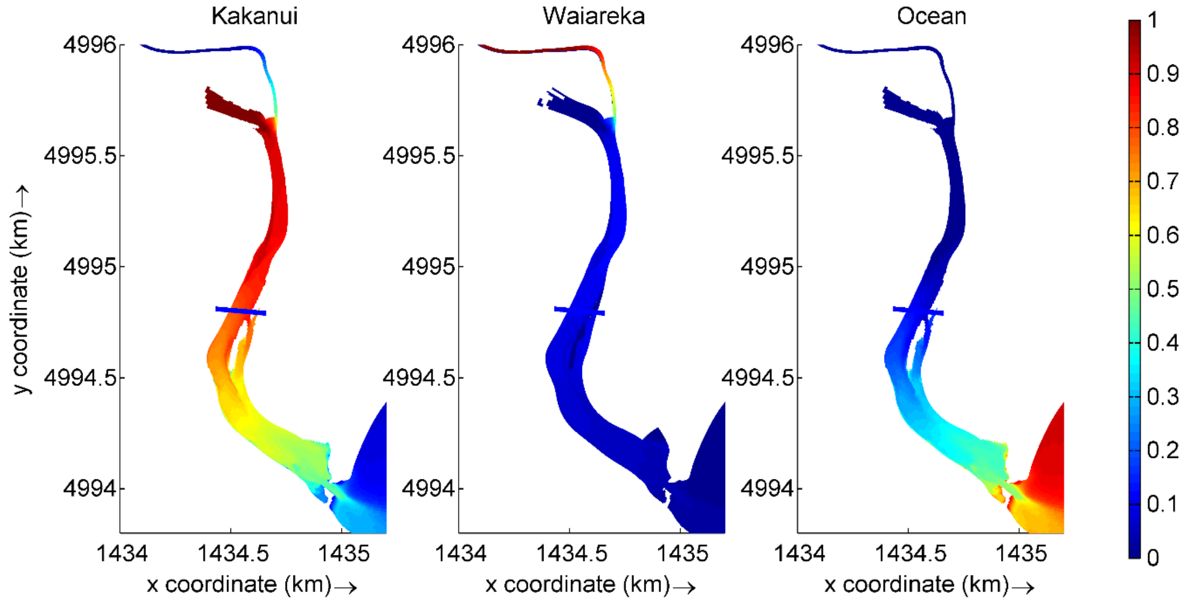

Figure A-4: Time and depth-averaged tracer concentrations for the Open Mouth, Kakanui fow = 4.0 $m^3 s^{-1}$, Waiareka flow = 0.40 $m^3 s^{-1}$.

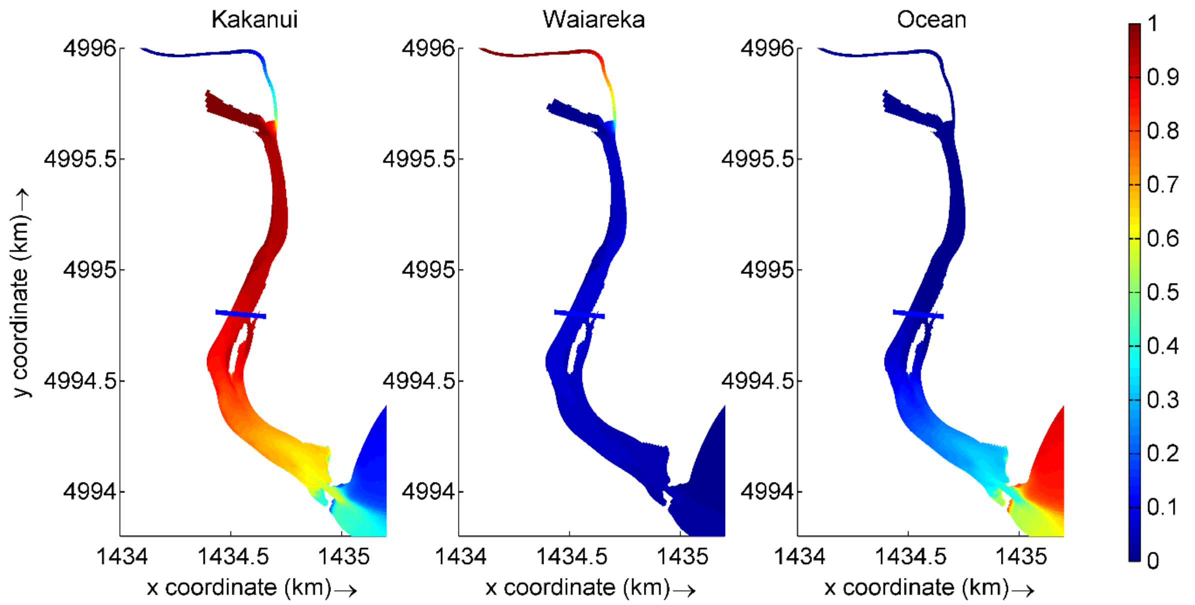

Figure A-5: Time and depth-averaged tracer concentrations for the Open Mouth, Kakanui fow = 6.95 $m^3 s^{-1}$, Waiareka flow = 0.413 $m^3 s^{-1}$.