Modelling the effect of river inputs on coastal water quality in Hawke Bay

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(06) 835 9200
0800 108 838
Private Bag 6006 Napier 4142
159 Dalton Street . Napier 4110

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Prepared By:
Charine Collins - ROMS Modeller
David Plew - Group Manager Hydrodynamics

National Institute of Water and Atmospheric Research Ltd

Reviewed By:
Helen Macdonald – ROMS Modeller Coasts and Oceans

Signed:

Approved By:
Helen Rouse – Regional Manager, Christchurch

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Executive summary

Hawke's Bay Regional Council (HBRC) is seeking a better understanding on the influence of nutrient inputs from different rivers and ocean outfalls on the water quality in Hawke Bay. This information will assist HBRC in managing coastal water quality.

An ocean and coastal hydrodynamic model was set up to simulate freshwater transport in Hawke Bay. A three-dimensional Regional Ocean Modelling System (ROMS) model of the east coast of the North Island at 2 km resolution was run for a period of one year (January 2017-December 2017). The model was forced with winds, ocean currents, tides and freshwater inputs from 13 rivers in Hawke Bay along with two wastewater outfalls. Ten of the rivers in Hawke Bay as well as the wastewater outfalls were each labelled with a separate tracer, allowing the concentration of river- and wastewater-derived freshwater to be evaluated and attributed to a specific source.

The model produces freshwater plumes with behaviour that is physically plausible and in agreement with historical studies of the circulation in Hawke Bay. High surface freshwater concentrations are confined close to the coast with distinct plumes of elevated concentrations associated with the three main freshwater sources, the Wairoa River, Mohaka River and the Ngaruroro, Tutaekuri and Clive confluence (referred to as the combined NTC rivers). Freshwater advection from point sources in Hawke Bay occur mainly along the coast inshore of the 50 m isobath. This advection is facilitated by along-shore currents flowing north- and southward with outflow around Mahia Peninsula and Cape Kidnappers.

Freshwater plumes from the two largest rivers discharging into Hawke Bay show markedly different advection patterns. Freshwater from the Mohaka River is advected throughout Hawke Bay with the highest concentration being transported north- and southward by the along-shore currents. Freshwater from the Wairoa River is confined to the northern half of Hawke Bay and is advected mainly northward into Opoutama Bay and past Mahia Peninsula.

The biggest contributors of freshwater to Hawke Bay are, in descending order, the Mohaka River, Wairoa River, the combined NTC, and the Tukituki River. The Napier and Hastings wastewater outfalls contribute minimally to the freshwater in Hawke Bay.

The influence of river and wastewater inputs on nutrient concentrations in Hawke Bay were approximated by treating nutrients as passive tracers to predict "potential nutrient concentrations". At the bay scale, the offshore ocean is the largest contributor of nitrogen (49%) and phosphorus (84%). The Tukituki River is the next largest source of nitrogen, while the Mohaka, Wairoa and combined NTC Rivers, and the two wastewater outfalls from Napier and Hastings, contribute most of the remaining nitrogen. Land-derived inputs of phosphorus are roughly evenly split between the same sources.

The largest increases in nitrogen are seen in the south-east of Hawke Bay between Napier and Cape Kidnappers, where the Tukituki River, combined NTC rivers, Napier and Hastings wastewater treatment plants (WWTP) all discharge. Annually averaged dissolved inorganic nitrogen concentrations close to three times those of background values are predicted in this area. Increases in phosphorus are small in comparison (<50% compared to background). Elsewhere, increases in nitrogen and phosphorus concentrations align with the distribution of freshwater plumes.

1 Introduction

1.1 Motivation

Hawke's Bay Regional Council (HBRC) requires a deeper understanding of how much influence inputs of nutrients from different rivers and ocean outfalls have on water quality in Hawke Bay. This information will assist HBRC in managing coastal water quality.

The objective of this project was to use hydrodynamic modelling to simulate coastal hydrodynamic processes including the advection, mixing and dilution of freshwater plumes from rivers and outfalls that discharge into Hawke Bay. An existing three-dimensional Regional Ocean Modelling System (ROMS) model spanning the east coast of the North Island at ~2 km horizontal resolution was used to simulate the freshwater plumes.

HBRC are particularly interested in the fate of freshwater plumes from the Mohaka and Wairoa Rivers. Also of interest are the contribution and influence of nutrient inputs from the different sources to Opoutama Bay, and the coasts off Awatoto and Cape Kidnappers.

1.2 Oceanographic conditions

Hawke Bay is a large semi-circular bay on the east coast of the North Island. Its ~80 km wide entrance, extending from Mahia Peninsula in the north to Cape Kidnappers in the south, is entirely open to the south-east. The bottom topography is smooth, and isobaths tend to run parallel to the shoreline conforming to the shape of the bay.

The large-scale circulation on the east coast of the North Island is dominated by the East Cape Current (ECC) and the Wairarapa Coastal Current (WCC) as well as numerous mesoscale eddies (Figure 1-1: Schematic of the circulation along the east coast of the North Island.; Chiswell et al. 2015; Stevens et al. 2019). The ECC, an extension of the East Auckland Current, carries warm, saline subtropical water southward offshore of the east coast of the North Island (Chiswell and Roemmich 1998). At ~42°S it turns away from the coast to flow eastward along the ridge line of Chatham Rise (Chiswell 1996). The retroflection of the ECC has been proposed as a likely formation mechanism for the Wairarapa Eddy (WE; Chiswell 2005) which is located over the Hikurangi Trough at ~41° S, 178.5° E.

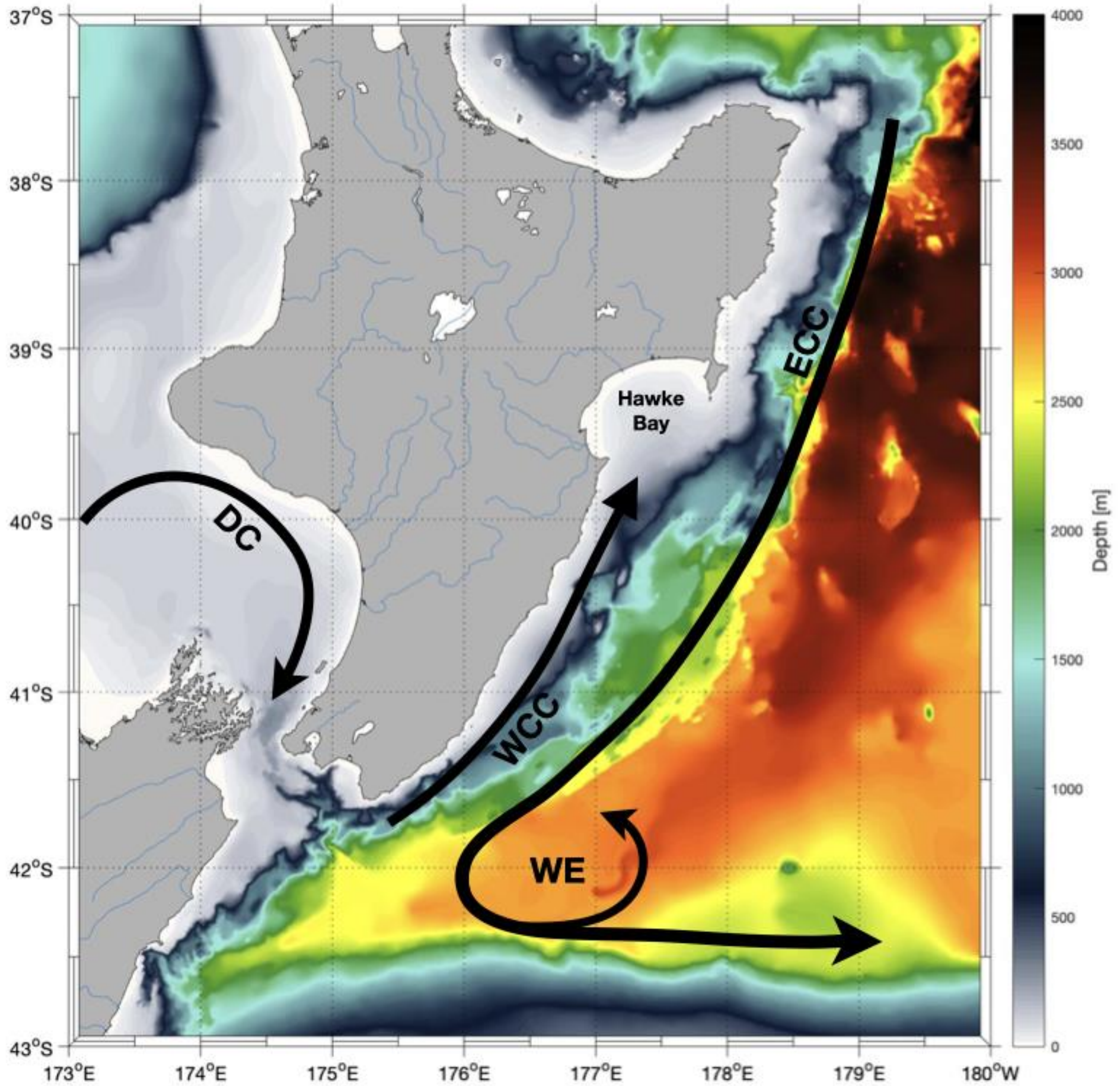


Figure 1-1: Schematic of the circulation along the east coast of the North Island. The following circulation features are indicated by the black arrows: the East Cape Current (ECC), the Wairarapa Coastal Current (WCC), the Wairarapa Eddy (WE), and the D'Urville Current (DC) in Cook Strait.

The WCC, transporting cool, fresh water northward along the east coast of the North Island, flows inshore of the warmer more saline southward flowing ECC (Figure 1-1: Schematic of the circulation along the east coast of the North Island.). Historically, the WCC was regarded as an extension of the Southland Current, however Chiswell (2000) showed that the water within the WCC is too warm and saline to have originated purely from the Southland Current. Instead it consists of a mix of water from the Southland and D'Urville Currents. The WCC occurs within 40-50 km from the coast and extends as far north as Mahia Peninsula. Subtropical water from the offshore ECC is entrained into the WCC along its entire length. This results in an increase in temperature and salinity and a decrease in transport as the current moves northward (Chiswell 2000).

The WCC has a pronounced effect on sea surface temperature (SST) along the east coast of the North Island. A cold-water tongue adjacent to the east coast is often observed in satellite sea surface temperature (SST) (Figure 1-2: A snapshot of satellite derived sea surface temperature (SST) for 25 October 2017.). There is also evidence that the WCC has an influence on water within Hawke Bay. A one-week survey of Hawke Bay in

1976 revealed water within the bay had temperature and salinity properties comparable to those of offshore water (Bradford et al. 1980). From this, Bradford et al. (1980) deduced that the waters in the bay came from the WCC.

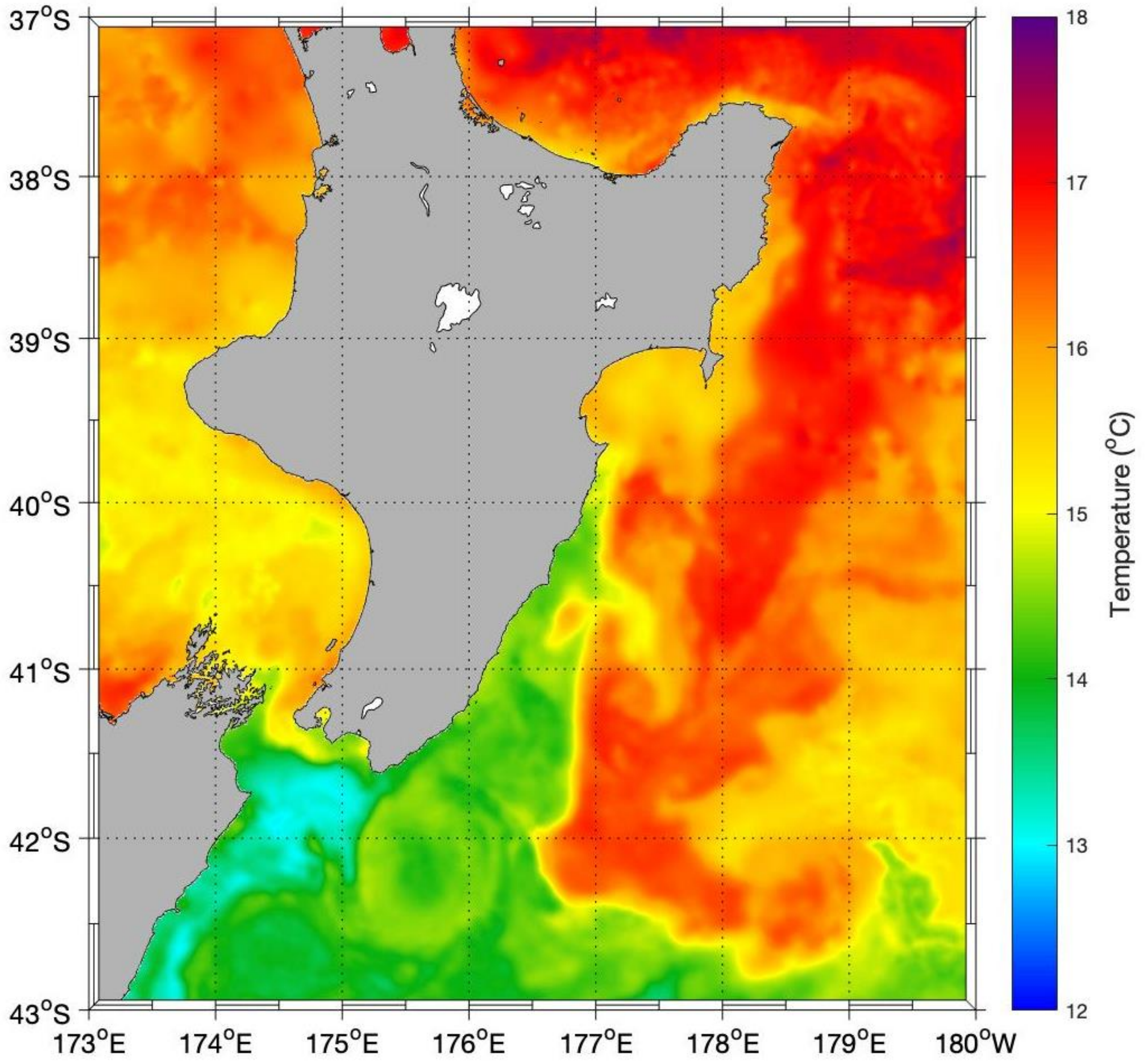


Figure 1-2: A snapshot of satellite derived sea surface temperature (SST) for 25 October 2017. The colder temperature along the east coast of the North Island is indicative of the WCC. Data source: MUR-JPL-L4-GLOB-v4.1 sourced from https://podacc.jpl.nasa.gov.

Detailed studies of the physical oceanography of Hawke Bay are limited. Water circulation in the bay is driven by a range of environmental conditions including winds, tides, river inflow from the main rivers, the WCC and the ECC. Historical studies based on drift card movements as well as temperature and salinity observations describe the surface circulation in Hawke Bay as consisting of a strong inflow along the midline of the bay which bifurcates into northward and southward along-shore currents (Ridgeway 1960; Ridgeway and Stanton 1969). The two along-shore currents together with the inflow results in two circulation cells in the bay with outflow around Mahia Peninsula in the north and Cape Kidnappers in the south.

Ridgeway and Stanton (1969) used temperature and salinity measurements throughout Hawke Bay, on the continental shelf outside, and to the south of the bay, to show that temperature and salinity in the bay are lower compared to the shelf water along the open coast. Based on these measurements, they concluded that water in Hawke Bay is a mixture of oceanic water entering the bay from south of Cape Kidnappers and fresh water from river run-off. More recently, Chiswell (2002), using eight years of coastal SST observations from Napier, found that the temperature at Napier wharf is controlled by alongshore advection of the WCC which is wind stress driven.

1.3 Nutrients in the coastal zone

Primary production in Hawke Bay, forming the base of the food web, is controlled by nutrient supply. The bioavailability of two key nutrients, nitrogen (N) and phosphorous (P), often limit primary production which, in the coastal zone, is dominated by photosynthetic bacteria, phytoplankton and macroalgae. In temperate coastal waters, including New Zealand, N is the most important limiting factor for primary production (National Research Council 1993).

A moderate supply of nutrients can be beneficial, resulting in increased primary production which, in turn, will propagate up the food-web. However, elevated nutrient levels lead to excessive primary production which causes oxygen depletion and a resultant negative impact on higher trophic levels. Excess nutrient enrichment can also result in dense, foul-smelling phytoplankton blooms that reduce water clarity, deteriorate water quality and may be toxic to consumers including humans (GESAMP 2001). Thus, eutrophication can degrade coastal habitats turning them into wastelands, while large reductions in nutrients can also adversely affect coastal productivity.

In this study, we focus on dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) as these are the forms of nitrogen and phosphorus that are most bioavailable and drive primary productivity. Dissolved inorganic nitrogen consists mostly of nitrate and ammoniacal nitrogen. Other forms of nitrogen include particulate and dissolved organic nitrogen; however, these are largely refractory forms of nitrogen with slow remineralisation times (and only slowly remineralise to bio-available form for primary producers). Similarly, other forms of phosphorus are mostly associated with organic matter or in particulate form, and not directly available to primary producers.

2 Model setup

The hydrodynamic model used in this project is the Regional Ocean Modelling System[1] (ROMS; Haidvogel et al. 2008), an open-source ocean model that has been applied to a variety of problems on ocean-basin to coastal scales (e.g., Moriarty et al. 2015, Malauene et al. 2018). ROMS is a free-surface ocean model capable of simulating the three-dimensional ocean currents forced by winds and tides. It is also able to simulate the effects of density differences caused by variations in water temperature and salinity.

In the vertical, ROMS uses a terrain-following coordinate system, i.e., a fixed number of vertical levels are distributed throughout the water column between the surface and the bottom; this system is well-suited to coastal situations and copes well with large tidal variations in sea level. In the horizontal, ROMS uses a structured rectangular grid.

2.1 Model grid

The model domain used in this project covers the continental shelf of the eastern North Island extending from Cook Strait in the south to East Cape in the north (Figure 2-1: Model domain showing bathymetry in meters (m).). It has a horizontal resolution of ~2 km with 30 terrain-following vertical levels resulting in a vertical resolution of 0.5-3 m in Hawke Bay and 3-90 m offshore.

The model bathymetry was constructed from various sources including the NIWA bathymetry database, land elevation data, regional coastline data, and the General Bathymetric Chart of the Oceans[2] (GEBCO) gridded ocean bathymetry.

[1] http://www.myroms.org
[2] https://www.gebco.net

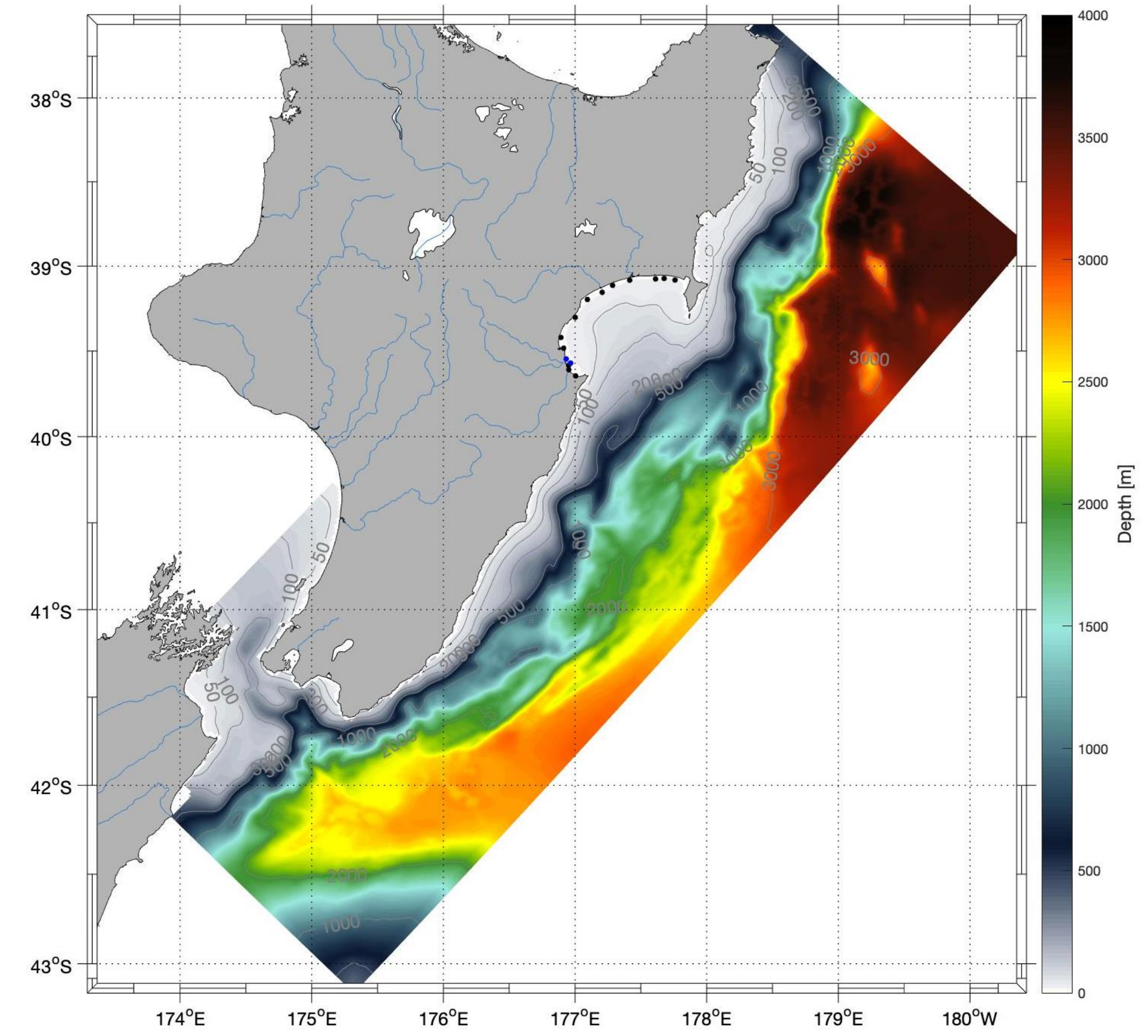


Figure 2-1: Model domain showing bathymetry in meters (m). The black dots indicate the rivers terminating along the Hawke Bay coast that were included in the model as freshwater point sources. These rivers are listed in order from North to south in Table 2-1. The blue dots indicate the two wastewater treatment plant outfalls that were also included as freshwater point sources.

2.2 Initial and boundary conditions

The ROMS simulation used in this project was carried out in forward mode, i.e., the model variables (water temperature, salinity, velocity and sea surface height) were set to a plausible initial state and then stepped forward in time subject to various forcings from the surface (wind stress, heat flux, freshwater flux), the bottom (bottom drag), the open ocean lateral boundaries (specified temperature, salinity, velocity etc.) and inflows from point sources like rivers.

The initial and lateral boundary conditions for the hydrodynamic variables (velocity, temperature, salinity and sea surface height) were derived from a global ocean analysis and prediction system based on the Hybrid Coordinate Ocean Model[3] (HYCOM; Chassignet et al. 2009). The HYCOM product used here provides daily snapshots of the 3-dimensional state of the global ocean on a 1/12° grid.

Tides were imposed at the boundaries of the model domain in terms of the amplitude and phase of 13 tidal constituents derived from the NIWA EEZ (Exclusive Economic Zone) tidal model (Walters et al. 2001). The

[3] https://www.hycom.org

ROMS tidal forcing scheme uses the amplitude and phase of the tidal constituents to calculate the tidal sea surface height and depth-averaged velocity at each time step and adds them to the lateral boundary data.

2.3 Forcing

Surface stresses generated by the wind are an important factor forcing ocean currents. For this simulation, surface wind stress was calculated from 3-hourly winds obtained from the 12 km New Zealand Limited Area Model (NZLAM; Lane et al. 2009).

The heat, momentum and freshwater fluxes through the sea surface were calculated from six-hourly NCEP/NCAR reanalysis data (Kalnay et al. 1996). The NCEP/NCAR reanalysis product provides global atmospheric fields at a 2.5° resolution. A heat flux correction term was applied to the SST, nudging the model SST towards observed SST from the 1⁄4° daily National Oceanic and Atmospheric Administration (NOAA) optimum interpolation SST analysis (Reynolds et al. 2002). The heat flux correction prevents the modelled SST from drifting too far from reality due to any biases in the surface fluxes but has a negligible effect on the day-to-day variability. Freshwater sources representing the main rivers are also included, as described in more detail in section 2.4.

2.4 Freshwater input

The major rivers draining into Hawke Bay were represented in the model as point sources of freshwater and labelled with passive tracers, or “dyes”, as explained below. The freshwater sources along with their input locations are listed in Table 2-1: Model freshwater point sources.. The input locations for each of the rivers were obtained from the New Zealand River Environment Classification (REC; Biggs et al. 1990; Snelder et al. 2004) and then converted into model grid locations, with adjustments to ensure each freshwater input is located on the model’s land-sea boundary. Flow-rate time series for the year 2017 (Figure 2-2: Freshwater flow rate timeseries for 10 of the rivers terminating in Hawke Bay.), considered to be an average flow year, were provided by HBRC for nine of the rivers listed in Table 2-1: Model freshwater point sources.. HBRC also provided data for the Karamu Stream (which becomes the Clive River downstream), and the Tutaekuri River. These two freshwater sources, along with the Ngaruroro River merge before flowing into Hawke Bay (here combined NTC is used to refer to this combined inflow). The flow data for the Karamu Stream and Tutaekuri River were combined, along with an adjustment determined from the REC to account for the Ngaruroro River to estimate the total flow of these three freshwater sources into Hawke Bay. An annual average flow obtained from the REC was used for the rivers for which time-varying flow data was not available.

Outflow into Hawke Bay from two wastewater treatment plants (WWTP), the Napier and Hastings WWTPs, were included as additional freshwater sources. Time-varying flow for these WWTP discharges were provided by HBRC (Figure 2-3: Freshwater flow rate time series for the two wastewater outfalls in Hawke Bay.). Only six months (July – December) of data were provided for the Hastings WWTP. To simulate a ‘typical’ year, the same discharge data were used for the first half of the year. Even though data from the Napier WWTP suggest that this is a reasonable estimate, it is probably a slight overestimate as there are two high flow events in the later part of the year (Figure 2-3b).

Table 2-1: Model freshwater point sources. These are listed in order from north to south. See Figure 3-1 for location of the point sources. Combined NTC incorporates the Ngaruroro, Tutaekuri and Clive Rivers, which combine before discharging to the coast.

Source	Input location	Tracer
Rivers		
Nuhaka	177.7596°E, 39.0825°S	dye_01
Maraetotara	177.0047°E, 39.6458°S	dye_02
Tahaenui*	177.6770°E, 39.0731°S	
Whakaki*	177.6116°E, 39.0758°S	
Tukituki	176.9530°E, 39.6094°S	dye_03
Combined NTC	176.9516°E, 39.5839°S	dye_04
Ahuriri*	176.9128°E, 39.4834°S	
Esk	176.8928°E, 39.4204°S	dye_05
Mohaka	177.2063°E, 39.1549°S	dye_06
Wairoa	177.4152°E, 39.0834°S	dye_07
Waihua	177.2859°E, 39.1138°S	dye_08
Aropaoanui	177.0013°E, 39.3022°S	dye_09
Waikari	177.0939°E, 39.1971°S	dye_10
Wastewater Treatment Plants		
Napier WWTP	176.9673°E, 39.5707°S	dye_11
Hastings WWTP	176.9329°E, 39.5464°S	dye_12

* Rivers for which time-varying flow was not available

Ten of the rivers as well as the two WWTP outfalls were labelled separately with a dye tracer, giving a total of 12 tracers. Carrying this many tracers in the model simulation increases the computing resources required but allows the individual freshwater sources to be distinguished. The value of each dye tracer was set to 1 in the water entering (continuously) from its respective source and was initialized as zero everywhere else in the model domain. Thus, the dye concentration in the model represents the volume fraction of river and outfall-derived freshwater.

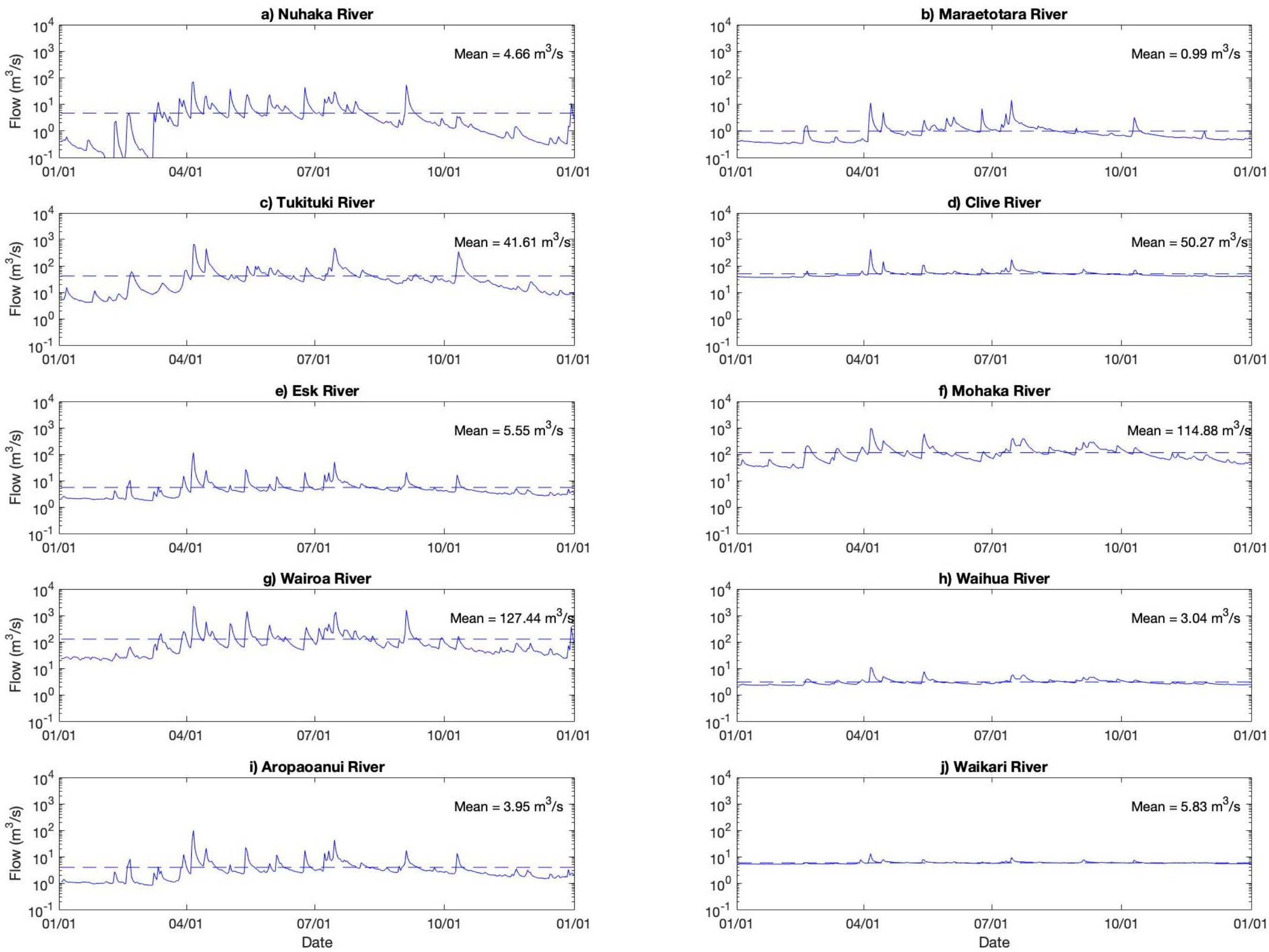


Figure 2-2: Freshwater flow rate timeseries for 10 of the rivers terminating in Hawke Bay. The flow rate is presented on a logarithmic scale. The dashed horizontal line represents the annual mean flow. The Clive River also includes the Ngaruroro and Tutaekuri Rivers.

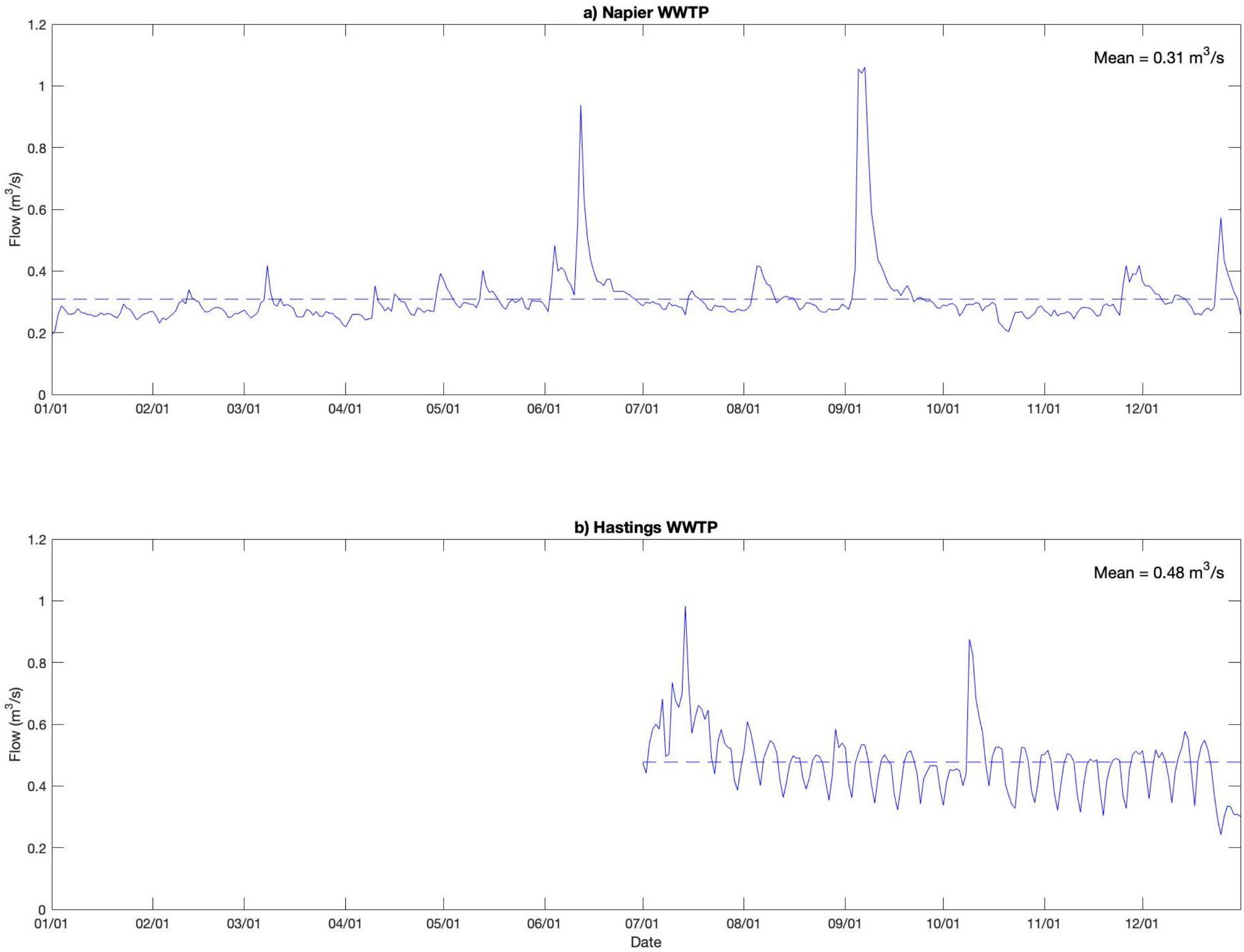


Figure 2-3: Freshwater flow rate time series for the two wastewater outfalls in Hawke Bay. The dashed horizontal line represents the annual mean flow.

3 Results

3.1 Freshwater advection

In general, freshwater from the rivers and wastewater outfalls are transported northward and southward along the coast. Freshwater concentrations tend to remain high inshore of the 50 m isobath, and decrease as it is advected within and out of the bay (Figure 3-1). Distinct plumes of high freshwater concentrations are associated with the three main rivers (the Wairoa, Mohaka, and combined NTC Rivers), a reflection of the high flow rates of these rivers (Table 3-1).

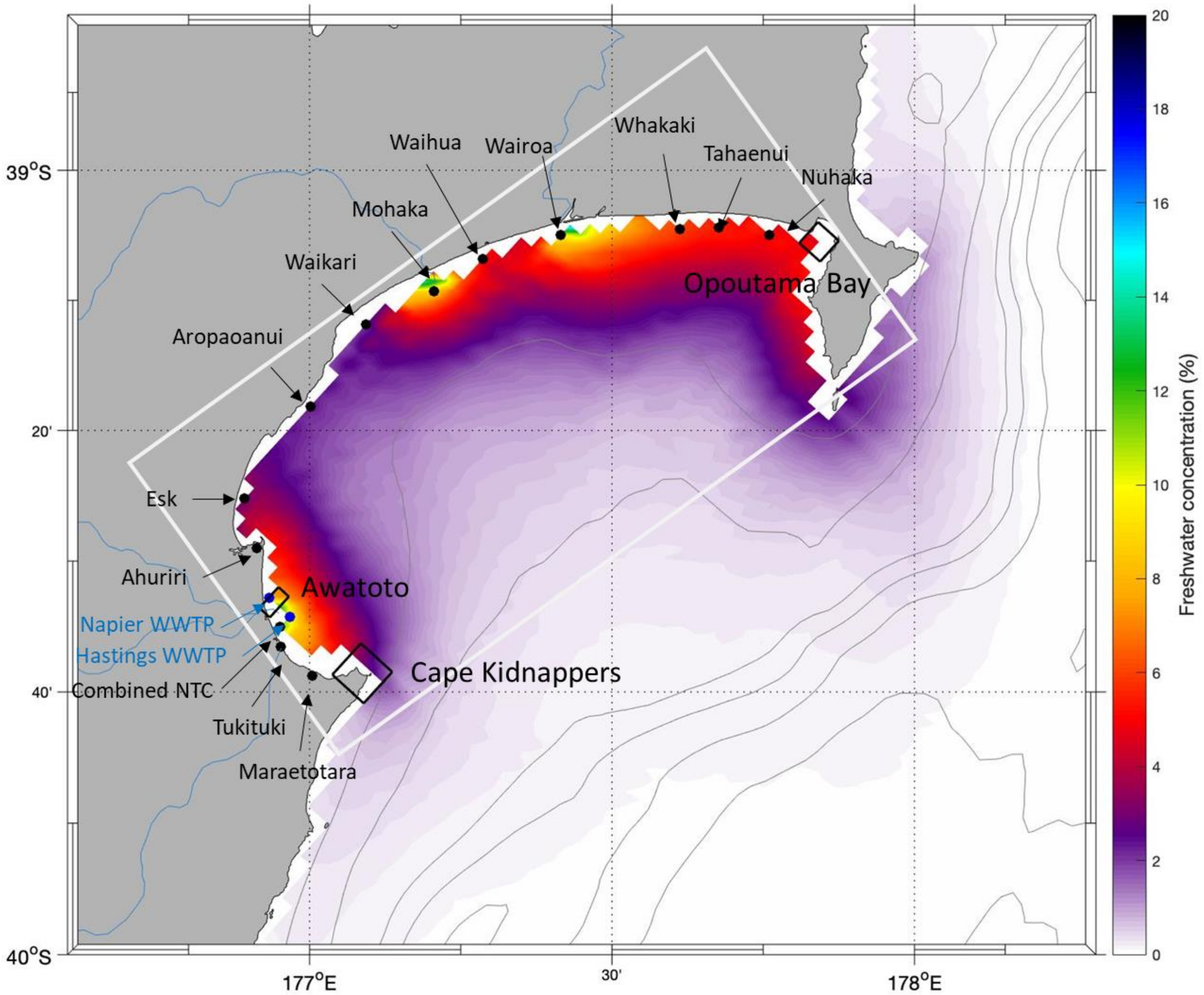


Figure 3-1: Time-averaged surface freshwater concentration for the simulation period January 2017-December 2017. The white box delineates the area considered as Hawke Bay. The black boxes indicate specific areas of interest in Hawke Bay: (from north to south) Opoutama Bay, Awatoto, Cape Kidnappers.

An animation (provided in electronic form alongside this report) of total freshwater concentration for 2017 show that the river plumes move back and forth, and the width of the coastal freshwater band fluctuates, on time scales of several days. Freshwater from the various rivers and wastewater outfalls are transported north and south along the coast by alongshore currents. This is consistent with historical studies of the circulation in Hawke Bay (Ridgeway 1960; Ridgeway and Stanton 1969). Periodically high concentrations of freshwater are advected out of Hawke Bay past Mahia Peninsula in the north as well as past Cape Kidnappers in the south. While most of the freshwater advected past Mahia Peninsula is entrained in the ECC and subsequently transported southward, a small portion is transported northward along the coast inshore of the 100 m isobath. In general, the freshwater advected past Cape Kidnappers is recirculated back into the bay or entrained in the ECC. On occasion, however, freshwater is transported past Cape Kidnappers and southward along the coast inshore of the 100 m isobath.

Two rivers of particular interest are the Mohaka and Wairoa Rivers. These two rivers, terminating roughly along the mid-line of Hawke Bay, have mean flow rates exceeding 100 m^3/s, the highest flow of all the rivers terminating in Hawke Bay (Table 3-1). Passive tracers released at the Mohaka River are advected throughout Hawke Bay (Figure 3-2). Tracer concentrations tend to remain high close to the mouth of the river decreasing with increasing distance from the source region.

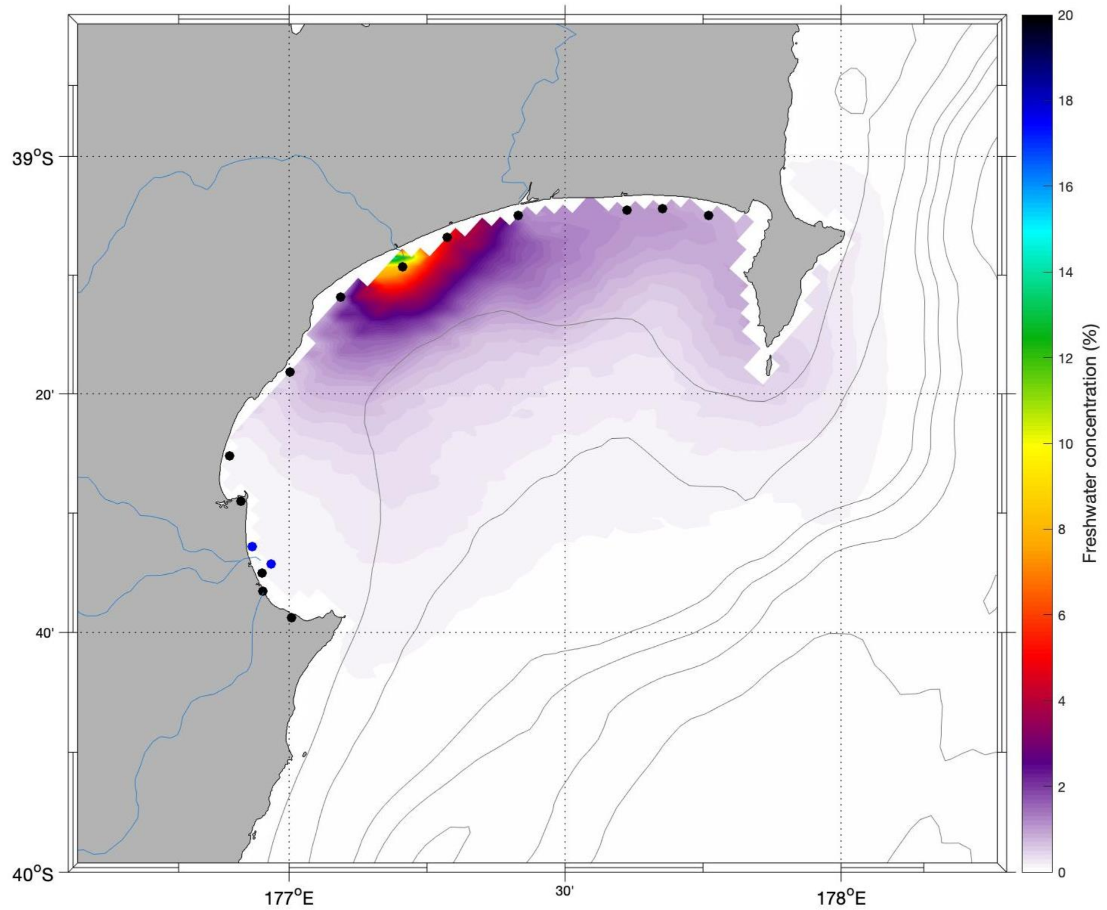


Figure 3-2: Time-averaged surface concentration for tracers released at the Mohaka River for the simulation period January 2017-December 2017. The surface concentration is expressed as a percentage of the total freshwater entering Hawke Bay.

The animation of freshwater concentration for the Mohaka River for the period January 2017 to December 2017 show that freshwater plumes from this river sometimes extend offshore past the 50 m isobath. In general, freshwater plumes from the Mohaka River are confined inshore of the 50 m isobath and advected northward along the coast into Opoutama Bay and past the Mahia Peninsula with periodic entrainment into the ECC. On occasion, high concentrations of freshwater are advected southward as far as Cape Kidnappers.

Passive tracers released at the Wairoa River are mainly confined to the northern half of Hawke Bay with very low concentrations advected south of the Mohaka River (Figure 3-3). Maximum tracer concentrations occur close to the mouth of the Wairoa River with high concentrations extending along the coast into Opoutama Bay and along the Mahia Peninsula

Advection of freshwater plumes from the Wairoa River are predominantly northward along the coast into Opoutama Bay and along the Mahia Peninsula. On occasion, high concentrations of freshwater from the Wairoa River are transported out of Hawke Bay past Mahia Peninsula. Part of this gets entrained into the ECC while the rest is advected northward along the Gisborne coast and as far north as East Cape. On very rare occasions, advection is to the south along the coast.

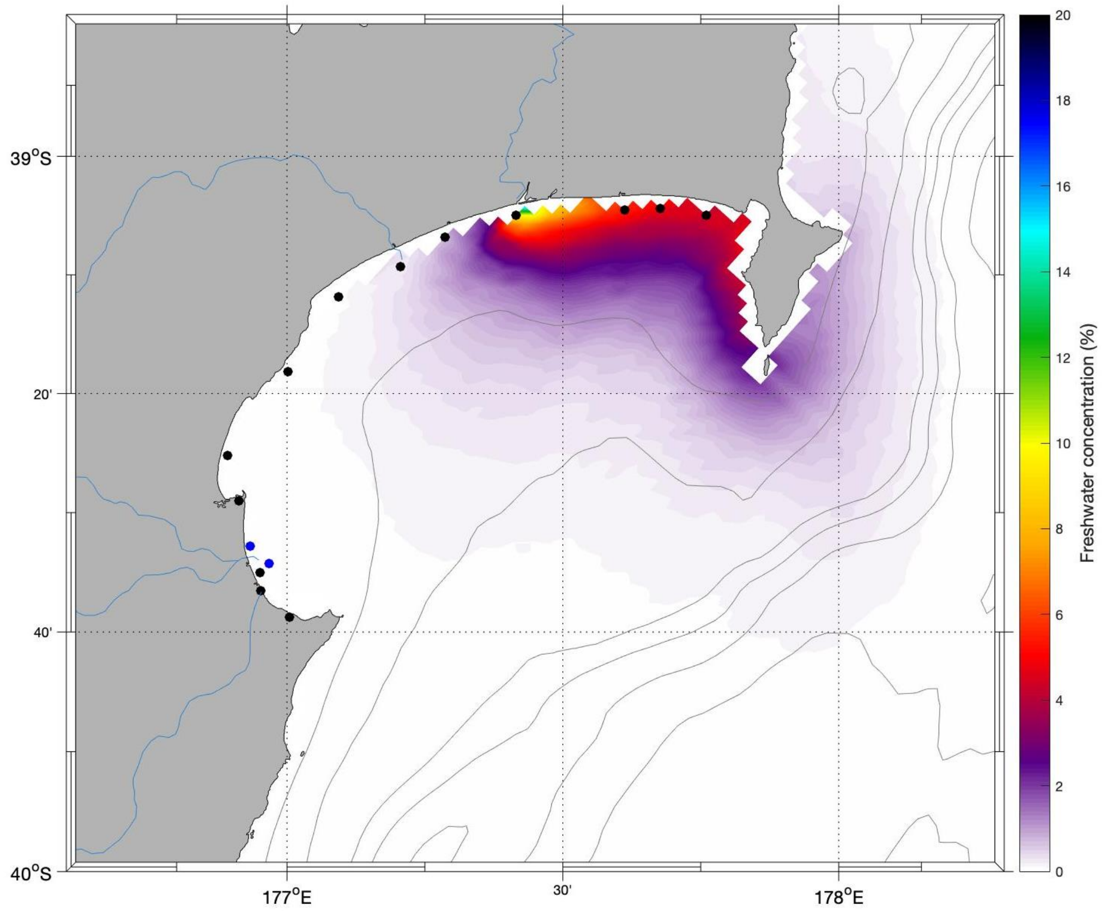


Figure 3-3: Time-averaged surface concentration for tracers released at the Wairoa River for the simulation period January 2017-December 2017. The surface concentration is expressed as a percentage of the total freshwater entering Hawke Bay.

3.2 Freshwater contribution from different water sources

The modelled tracer concentrations show the effect of the different rivers on the composition of water within Hawke Bay. Figure 3-4 shows that while the total volume averaged freshwater content in Hawke Bay derived from the main rivers and two wastewater treatment plants averages 1%, it can exceed 3%. The main sources of freshwater into Hawke Bay are the Mohaka River (32.58% of freshwater), the Wairoa River (28.41%), combined NTC River (17.95%) and the Tukituki River (11.22%). The Napier and Hastings wastewater outfalls contribute <1% of the freshwater content to Hawke Bay (0.14% and 0.2% of freshwater respectively).

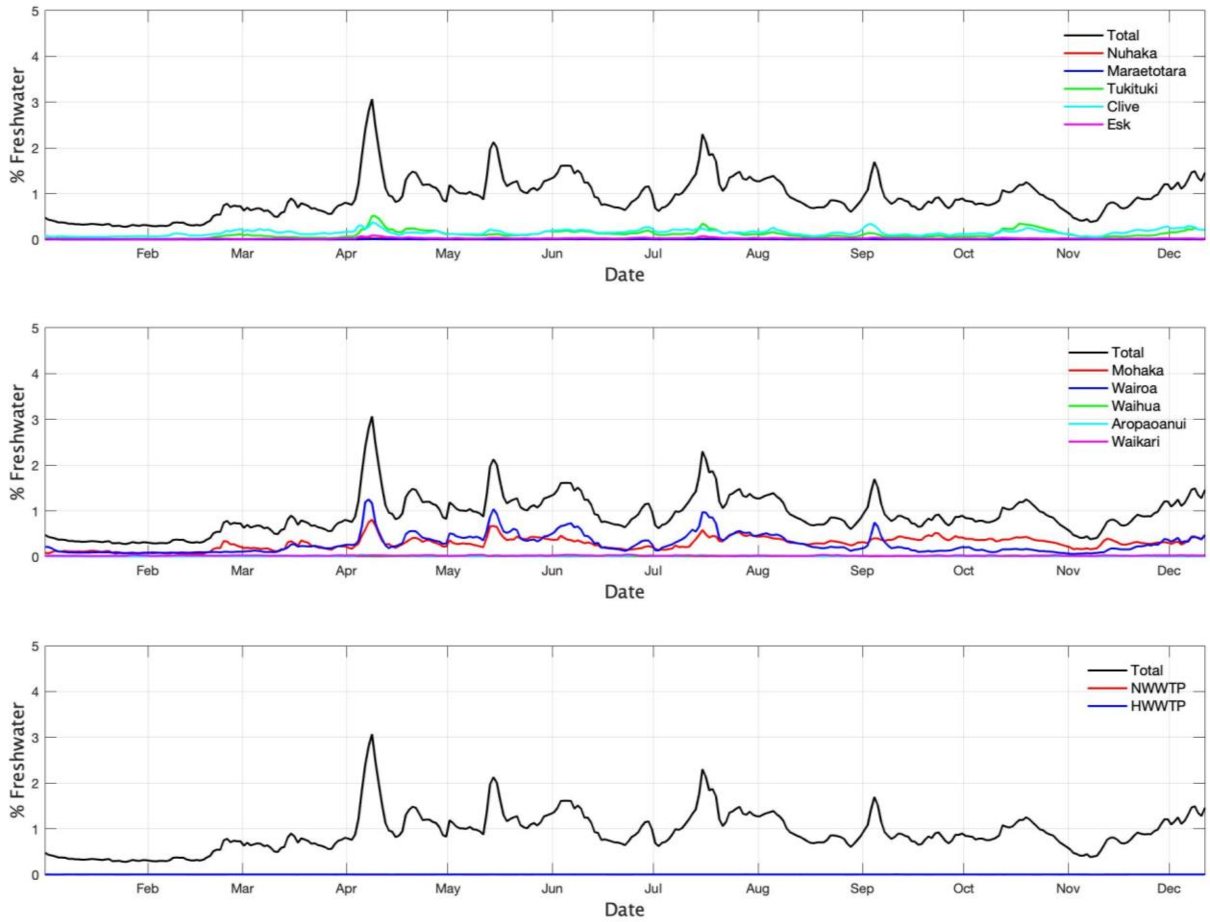


Figure 3-4: The percentage of freshwater from the different rivers (top and middle) and two wastewater outfalls (bottom) discharging into Hawke Bay . The time-series are the volume-averaged tracer concentration averaged over the white box in Figure 3-1. Clive includes the Ngaruroro and Tutaekuri Rivers. Note the Total is included on all 3 panels for comparison.

Along the coast off Awatoto, north of the Ngaruroro, Tutaekuri and Karamu confluence, the total freshwater content derived from the main rivers and two wastewater outfalls averages ~3% but can exceed 9% (Figure 3-5). Almost all of the freshwater in this region is derived from two sources: the combined NTC River which contributes more than 80% of the freshwater, and the Tukituki River contributing another 11%. The combined contribution from the other rivers amount to ~7%. The Napier WWTP outfall is located offshore of Awatoto, while the outfall for the Hastings WWTP is located slightly further south. As such the outfall from the WWTPs plants contribute more to the freshwater content off the coast of Awatoto than they do bay-wide and to other areas in Hawke Bay. The outfall from the Napier WWTP contributes 0.69% of the freshwater content while the Hastings WWTP contributes 0.99%.

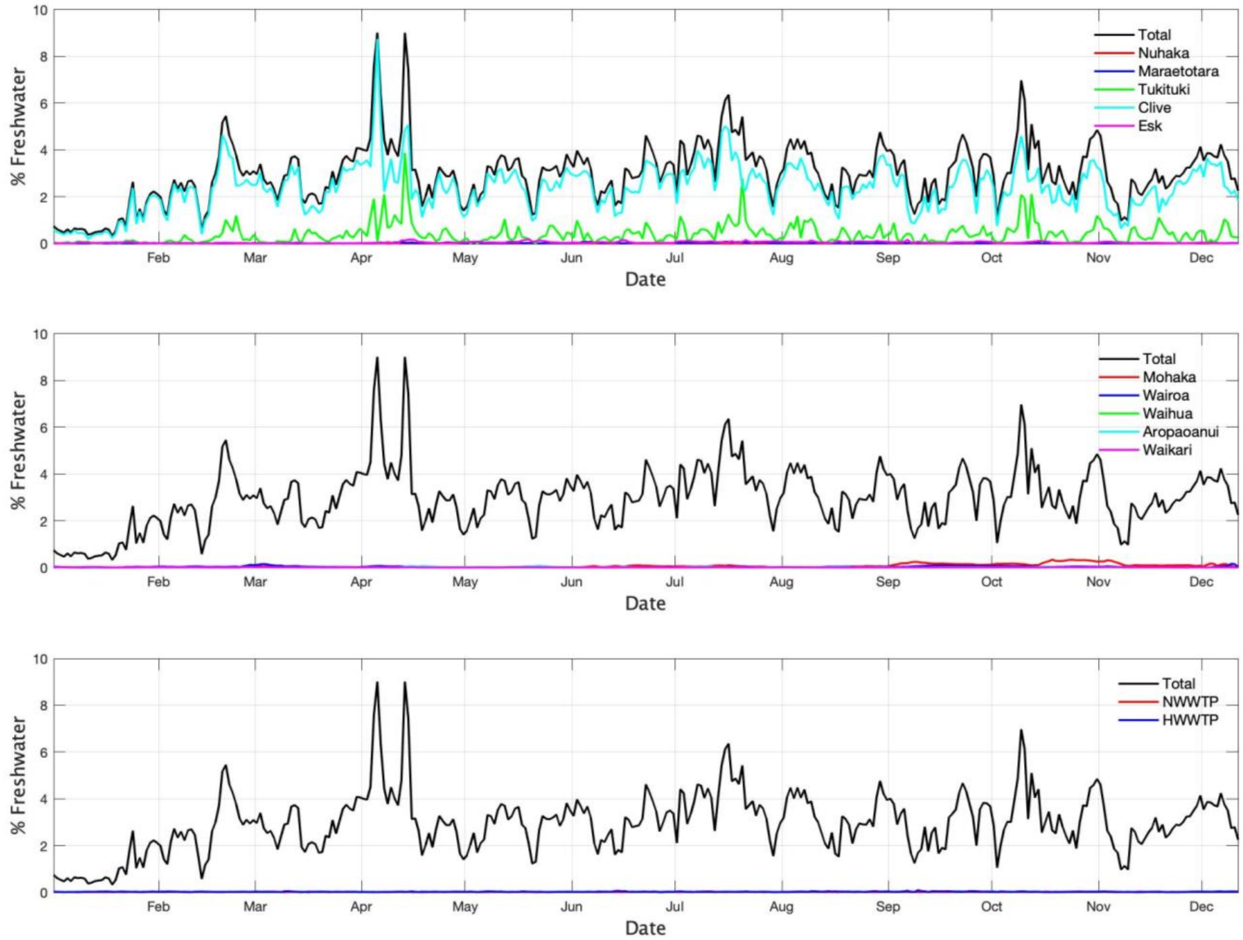


Figure 3-5: The percentage of freshwater from different rivers (top and middle) and two wastewater outfalls (bottom) contributing to the freshwater off Awatoto. The time-series are the volume-averaged tracer concentration averaged over the black box representing Awatoto in Figure 3-1. Clive includes the Ngaruroro and Tutaekuri Rivers.

The total freshwater content in Opoutama Bay derived from the main rivers and two wastewater outfalls also averages ~3% but on occasion it can exceed 20% (Figure 3-6). The main sources of freshwater into Opoutama Bay are the Wairoa (56.03% of freshwater) and the Mohaka Rivers (26.04%). Other rivers that contribute non-negligible amounts of freshwater to Opoutama Bay are the combined NTC (5.78%), the Nuhaka (5.65%) and Tukituki Rivers (3.96%). The contribution of freshwater from the two wastewater outfalls at the opposite side of Hawke Bay to Opoutama Bay is negligible (combined contribution of <0.05%).

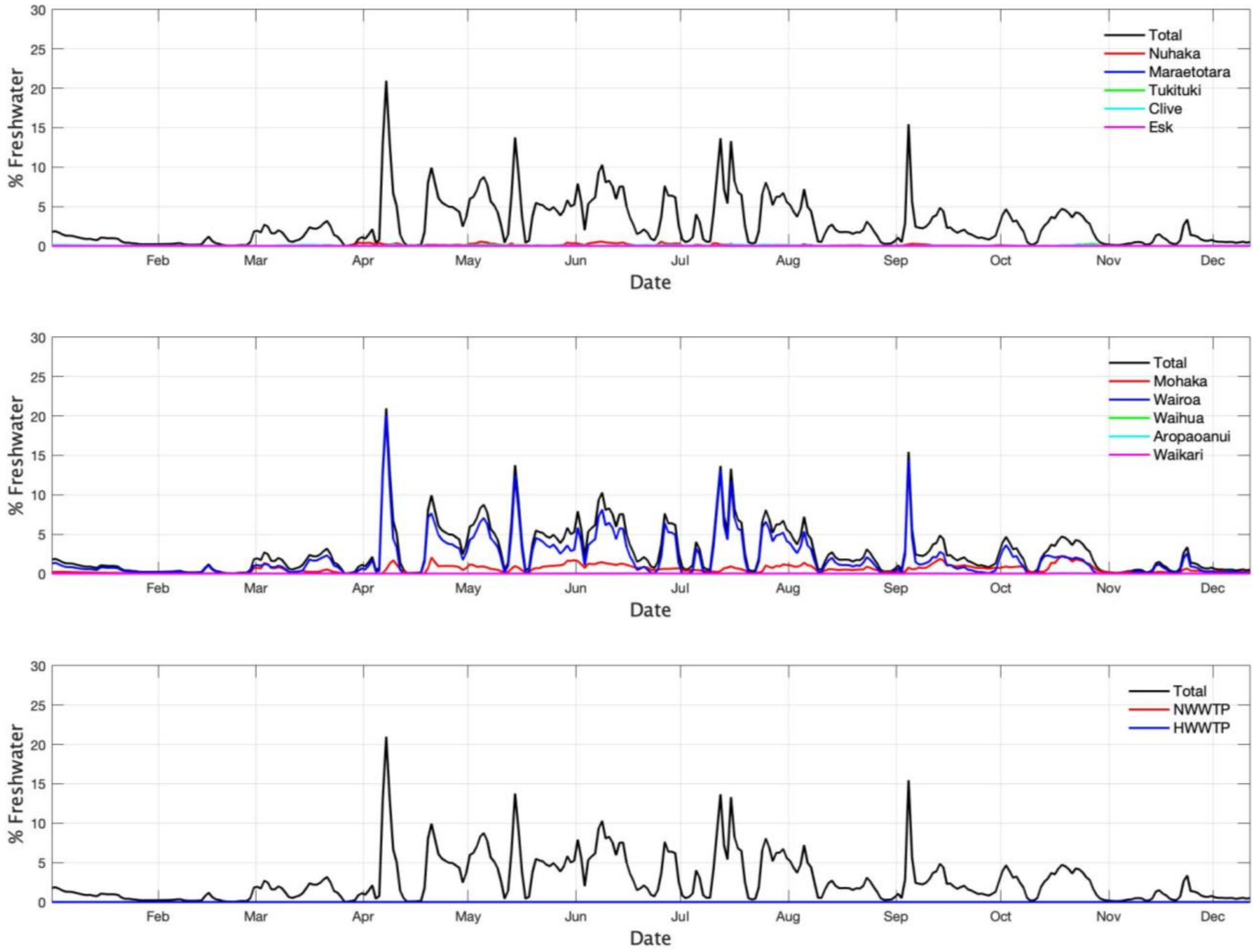


Figure 3-6: The percentage of freshwater from different rivers (top and middle) and two wastewater outfalls (bottom) contributing to the freshwater in Opoutama Bay. The time-series are the volume-averaged tracer concentration averaged over the black box for Opoutama Bay in Figure 3-1. Clive includes the Ngaruroro and Tutaekuri Rivers.

3.3 Nutrient loading

Each of the water sources – ocean, rivers and wastewater treatment plant effluent – supply nutrients to Hawke Bay. An estimate of the potential[4] nutrient (nitrogen and phosphorous) concentrations in Hawke Bay can be made by assuming nutrients can be treated as passive tracers and using mean nutrient concentrations from each of the rivers. HBRC provided observed nutrient data from monitoring sites on each of the rivers for the 2017 year. Because several of the monitoring sites were located some distance inland, we scaled nutrient concentrations to account for inputs of water and nutrients between the monitoring sites and the coast. This scaling was derived by comparing the ratio of modelled annual mean nutrient concentrations from each of the rivers (Unwin and Larned 2013) at the monitoring sites and the coast obtained from

[4] Potential nutrient concentrations are the concentrations that would occur in the absence of non-conservative processes such as uptake by algae, denitrification, or other biogeochemical processes (Plew et al. 2018, Plew et al. 2020). Observed nutrient concentrations (such as measured in water quality sampling) may often be lower than potential concentrations due to these processes, especially during periods of high seasonal growth and nutrient depletion (Bricker et al. 2003). Potential concentration is directly linked to the nutrient load, and has found to be a better predictor of phytoplankton biodiversity and biomass (Ferreira et al. 2005, National Research Council 2000) than observed concentrations, particularly during nutrient limited phases of the annual cycle (Bricker et al. 2003).

NZRiverMaps[5] (Booker and Whitehead 2017). This ratio was then applied to the observed nutrient data assuming that changes in nutrient concentrations between monitoring sites and the coast would be similar to those in the model. The observed data included nitrate + nitrite nitrogen (NNN), but not ammoniacal nitrogen. The ratio of modelled ammoniacal nitrogen to modelled dissolved inorganic nitrogen (DIN) was used to further scale the observed NNN concentrations to obtain DIN (Table 3-1).

HBRC also provided monitoring data for the wastewater treatment plants (averages for 2017). The ocean concentration of nutrients was obtained from the CSIRO Atlas of Regional Seas (CARS) 2009 climatology. The CARS climatology comprises gridded fields of mean ocean properties (temperature, salinity, oxygen, phosphate, nitrate) derived from quality-controlled historical subsurface measurements.

A summary of mean flows, concentrations and annual dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) loads from each source is given in Table 3-1. The Tukituki and Mohaka Rivers are the largest terrestrial nitrogen sources, providing 25% and 22% of the annual DIN load respectively. The Wairoa River (19%), combined NTC rivers (12%), Hastings WWTP (10%) and Napier WWTP (9%) contribute most of the remaining annual DIN load to Hawke Bay. The two WWTP provide a third of the annual DRP load (Hastings 21%, Napier 14%), with the Mohaka River (18%), Wairoa River (16%) and the Tukituki River (14%) the other major sources of terrestrial DRP.

[5] https://shiny.niwa.co.nz/nzrivermaps/

Table 3-1: Mean flows, annual mean concentrations and loads of dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) for the different sources to Hawke Bay . Mean flows for the rivers and wastewater treatment plants were calculated from daily flow rates supplied by HBRC. Nutrient concentrations for the rivers were obtained from NZRiverMaps. Ocean concentrations were obtained from the CARS climatology. WWTP discharge concentrations are averages from data supplied by HBRC. Annual loads are estimated by multiplying the mean flow and concentration.

Source	Mean Flow (m^3/s)	Observed Nitrate +Nitrite (mg/m^3)	Scaled DIN (mg/m^3)	Total DIN load (kg/y)	DRP (mg/m^3)	Scaled DRP (mg/m^3)	Total DRP load (kg/y)
Rivers							
Nuhaka	4.66	116	184	27,016	1.83	2.07	304
Maraetotara	0.99	371	380	11,855	26.8	26.8	836
Tukituki	41.61	823	838	1,100,196	24.0	25.0	32,803
Combined NTC	50.27	278	332	526,146	20.6	16.2	25,690
Esk	5.55	321	342	59,778	24.0	17.6	3,076
Mohaka	114.88	262	264	954,907	12.3	11.6	41,884
Wairoa	127.44	133	211	847,774	8.5	9.2	37,073
Waihua	3.04	245	208	19,975	39.6	36.5	3,501
Aropaoanui	3.95	276	289	36,047	25.3	17.8	2,222
Waikari	5.83	224	237	43,576	23.9	28.0	5,150
Wastewater Treatment Plants							
Napier WWTP	0.31	38,785.9		379,180	3,972.4		33,830
Hastings WWTP	0.48	28,114.2		425,600	3,263.6		49,400
Ocean (CARS)		33.07			8.61		

The ocean is also a significant source of nutrients, and the locations and behaviours of the river and wastewater plumes means that their effects on water column nutrient concentrations are not necessarily in direct proportion to their loads. The proportion of nutrients in Hawkes Bay originating from each of the different sources (rivers, wastewater treatment plants and ocean) is estimated by multiplying the nutrient concentration by the respective volume fractions. Firstly, we consider the contributions of nutrients from the different sources at the bay-scale. This is followed by examining the contributions from the different sources to particular locations in Hawke Bay.

Maps of the time-averaged surface concentrations of DIN show that the largest increases in nutrients (relative to the background oceanic concentrations) occur along the coastline near Haumona (south-west side of Hawke Bay, Figure 3-7). DIN concentrations reach close to three times those of oceanic values, while smaller increase occur near mouths of major rivers such as the Mohaka and Wairoa Rivers. Increases in DRP are small, relative to background ocean concentrations, but also occur near the mouths of major rivers (Figure 3-8).

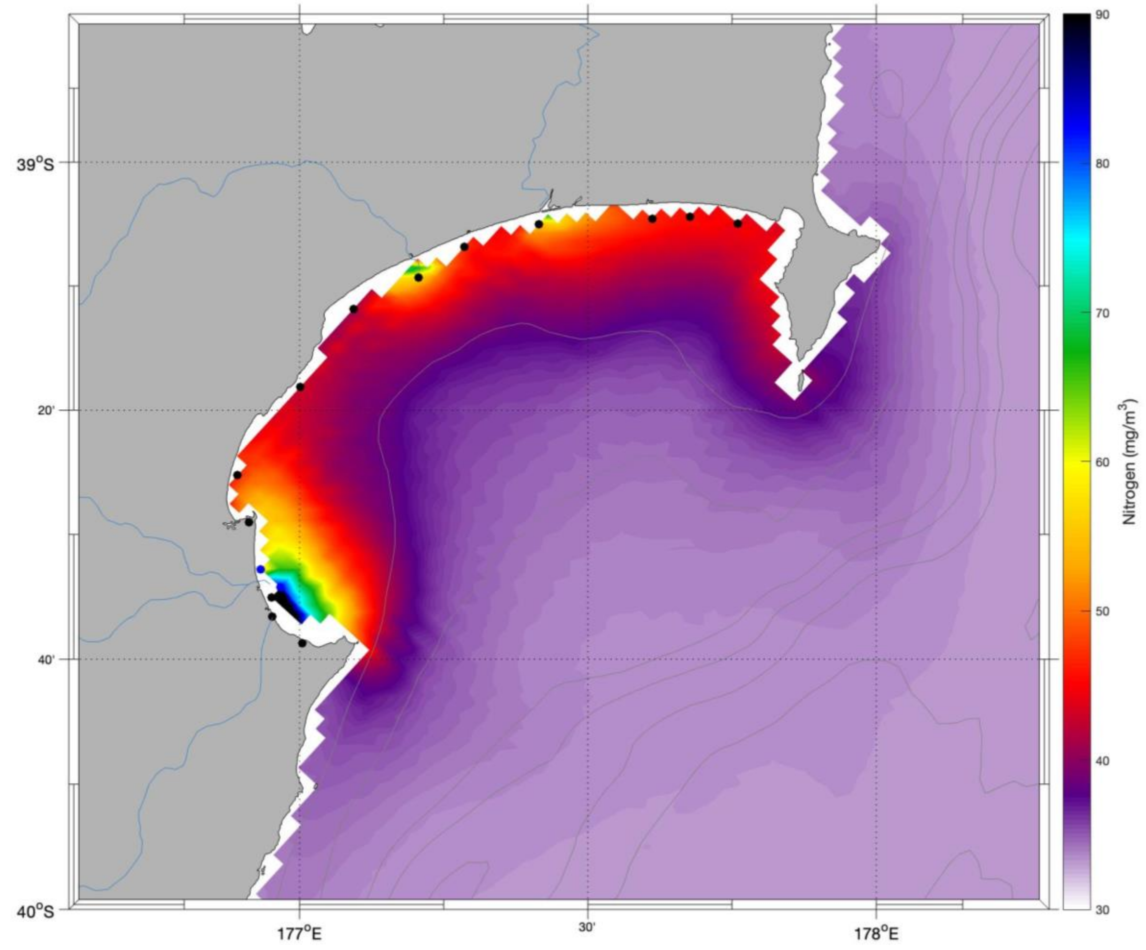


Figure 3-7: Time-averaged surface concentrations of dissolved inorganic nitrogen in Hawke Bay. The nitrogen concentration was calculated as the sum of the background oceanic DIN and the DIN concentrations originating from each source. The latter was estimated by multiplying the water volume fraction in the bay originating from each source by the mean DIN concentration in that source. A background oceanic DIN of 33.1 mg/m^3 is assumed, based on the CARS2009 climatology.

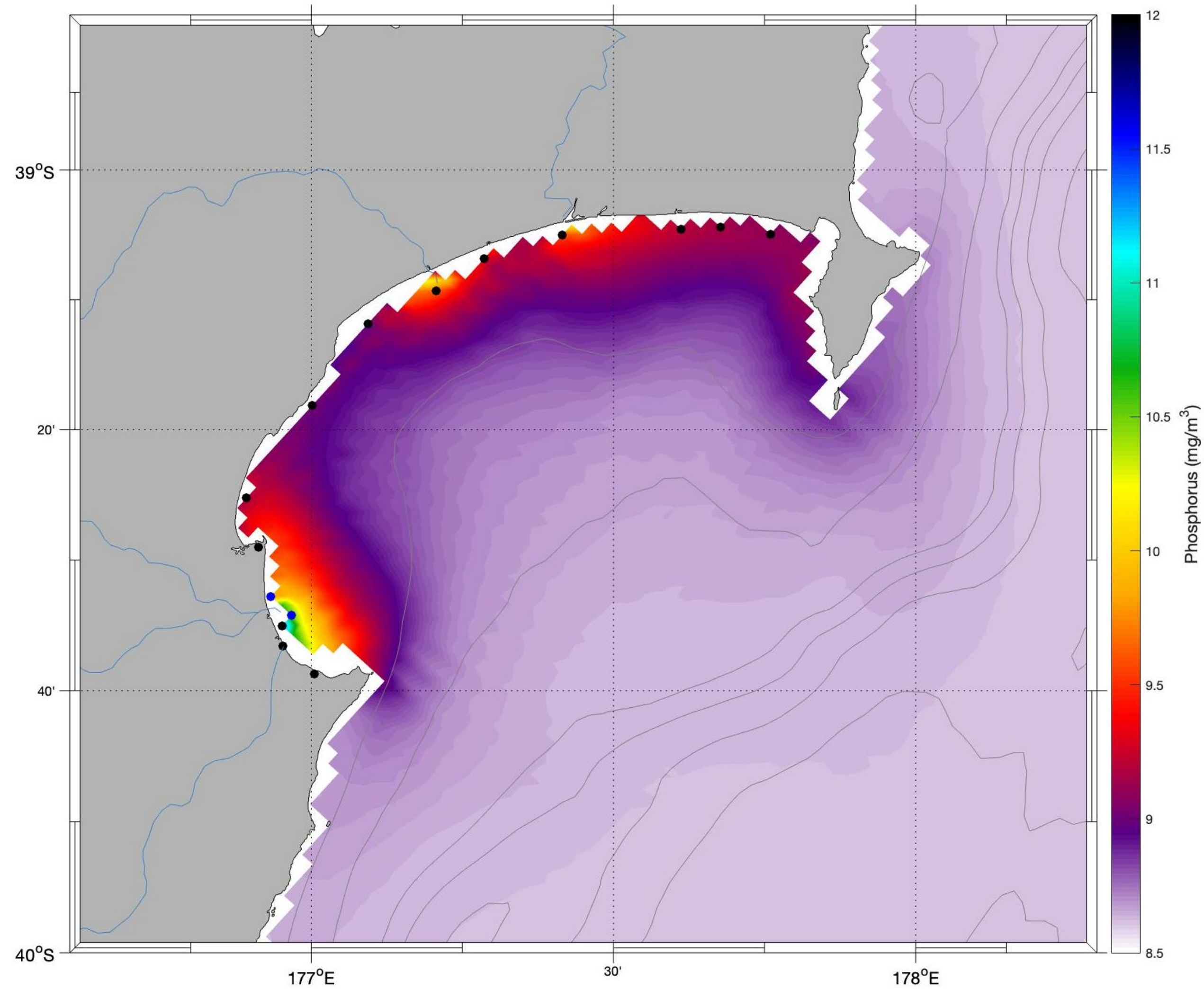


Figure 3-8: Time averaged surface concentrations of dissolved reactive phosphorus in Hawke Bay. The phosphorus concentration was calculated as the sum of the background oceanic DRP and the DRP concentrations originating from each source. The latter was estimated by multiplying the water volume fraction in the bay originating from each source by the mean DRP concentration in that source. A background oceanic DRP concentration of 8.6 mg/m^3 is assumed, based on the CARS2009 climatology.

Averaged over the year and spatially over Hawke Bay, the ocean is the dominant source of nitrogen and phosphorus to Hawke Bay (Figure 3-9). Approximately 49% of nitrogen comes from the ocean, with ~6% coming from the wastewater treatment plants, and the remaining 45% from the rivers. Nearly half of the riverine N-load is from the Tukituki River (20% of the total), while the Mohaka and Wairoa Rivers provide most of the remaining DIN. Around 84% of DRP comes from the offshore ocean, the two WWTP collectively provide close to 5%, and the rivers provide the remaining 11% (Table 3-2; Figure 3-9).

Table 3-2: Contribution of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus in Hawke Bay from different sources. The potential concentrations resulting from each source are estimated by multiplying the water volume fraction in the bay originating from each source by the mean nutrient concentration in that source. Values represent annual average concentrations. The percentages are expressed as a function of the total DIN entering Hawke Bay from the various sources.

Source	Water Fraction (%)	DIN contribution (mg/m^3)	%DIN	DRP contribution (mg/m^3)	%DRP
Rivers					
Nuhaka	0.092	0.1691	0.27	0.0019	0.02
Maraetotara	0.008	0.0304	0.05	0.0021	0.02
Tukituki	1.55	12.9956	20.40	0.3875	4.02
Combined NTC	0.662	2.1971	3.45	0.1073	1.11
Esk	0.04	0.1366	0.21	0.0070	0.07
Mohaka	2.431	6.4076	10.06	0.2810	2.92
Wairoa	2.992	6.3115	9.91	0.2760	2.86
Waihua	0.06	0.1250	0.20	0.0219	0.23
Aropaoanui	0.036	0.1042	0.16	0.0064	0.07
Waikari	0.041	0.0972	0.15	0.0115	0.12
Wastewater Treatment Plants					
Napier WWTP	0.006	2.2662	3.56	0.2321	2.41
Hastings WWTP	0.006	1.7601	2.76	0.2043	2.12
Ocean (CARS)	94.04	31.10	48.82	8.10	84.03
Total		**63.70**		**9.64**	

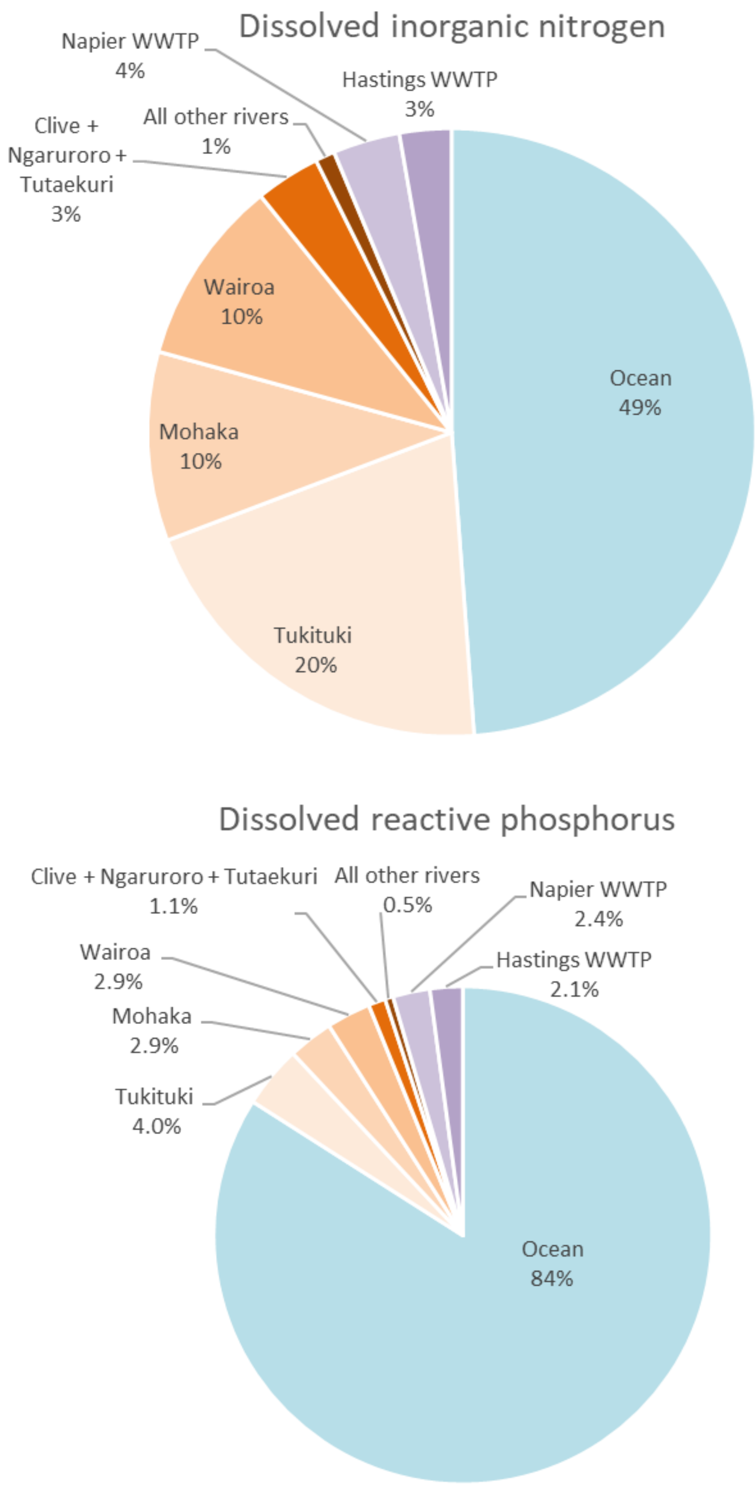


Figure 3-9: Relative contributions of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus in Hawke Bay from different sources.

Figure 3-10 shows that the amount of nitrogen and phosphorus introduced into Hawke Bay from the major sources varies greatly throughout the year. Considering that annual mean nutrient concentrations was used to estimate the nutrient contribution from the different land-based sources, the variability of the nutrient contributions can solely be attributed to the highly variable flow rates associated with each of the land-based sources (Figure 2-2). Peaks in nitrogen and phosphorus contributions from the terrestrial sources coincide with high flow events. In particular, the contribution of nitrogen from the Tukituki and Wairoa Rivers can exceed 25% and 10%, respectively, following high flow events. During high flow events, phosphorus contributions from the Wairoa River can exceed 4% while that from the Mohaka and Tukituki Rivers can exceed 1.5%.

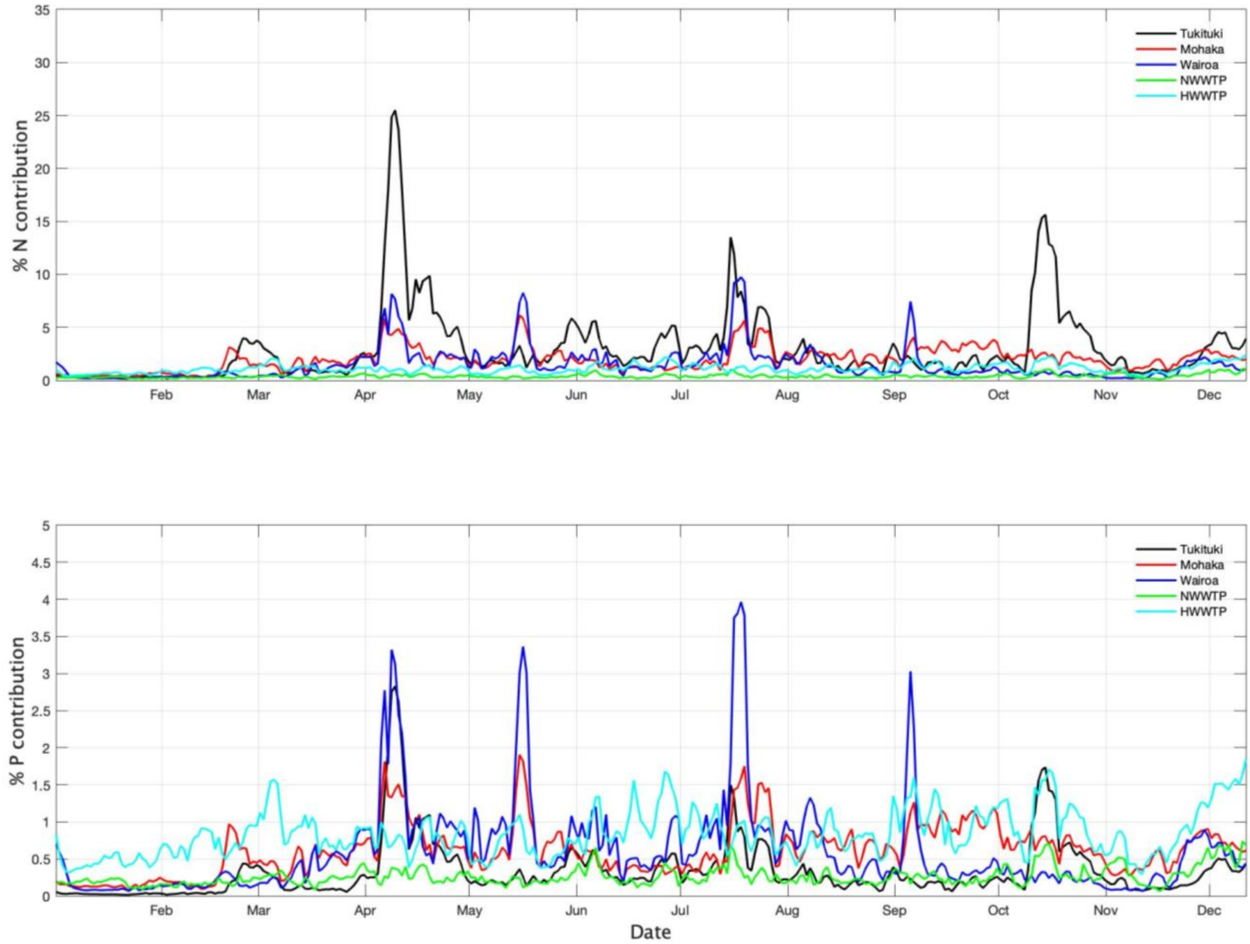


Figure 3-10: Timeseries of nitrogen (top) and phosphorus (bottom) contribution to Hawke Bay from the 5 main terrestrial sources.

The dominant source of both nitrogen and phosphorus to Opoutama Bay is the off-shore ocean (73% of nitrogen, 94% of phosphorus) (Table 3-3; Figure 3-11). The Wairoa River is the second largest contributor, supplying 20% of nitrogen and 4.2% of phosphorous. The WWTP discharges, located on the opposite side of Hawke Bay, contribute less than 0.3% of nitrogen and 0.3% of phosphorus to Opoutama Bay (Table 3-3; Figure 3-11).

Table 3-3: Contribution of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus in Opoutama Bay from different sources. The potential concentrations resulting from each source are estimated by multiplying the water volume fraction in the bay originating from each source by the mean nutrient concentration in that source. Values represent annual average concentrations. The percentages are expressed as a function of the total DIN entering Hawke Bay from the various sources

Source	Water Fraction (%)	DIN contribution (mg/m^3)	%DIN	DRP contribution (mg/m^3)	%DRP
Rivers					
Nuhaka	0.126	0.2316	0.54	0.0026	0.03
Maraetotara	0.001	0.0038	0.01	0.0003	0.00
Tukituki	0.051	0.4276	1.00	0.0127	0.15
Combined NTC	0.068	0.2257	0.53	0.0110	0.13
Esk	0.006	0.0205	0.05	0.0011	0.01
Mohaka	0.768	2.0243	4.72	0.0888	1.02
Wairoa	3.953	8.3386	19.44	0.3646	4.19
Waihua	0.019	0.0396	0.09	0.0069	0.08
Aropaoanui	0.006	0.0174	0.04	0.0011	0.01
Waikari	0.013	0.0308	0.07	0.0036	0.04
Wastewater Treatment Plants					
Napier WWTP	0.00004	0.017	0.04	0.017	0.02
Hastings WWTP	0.0004	0.0999	0.23	0.0116	0.13
Ocean (CARS)	94.99	31.41	73.24	8.18	94.01
Total		**42.89**		**8.70**	

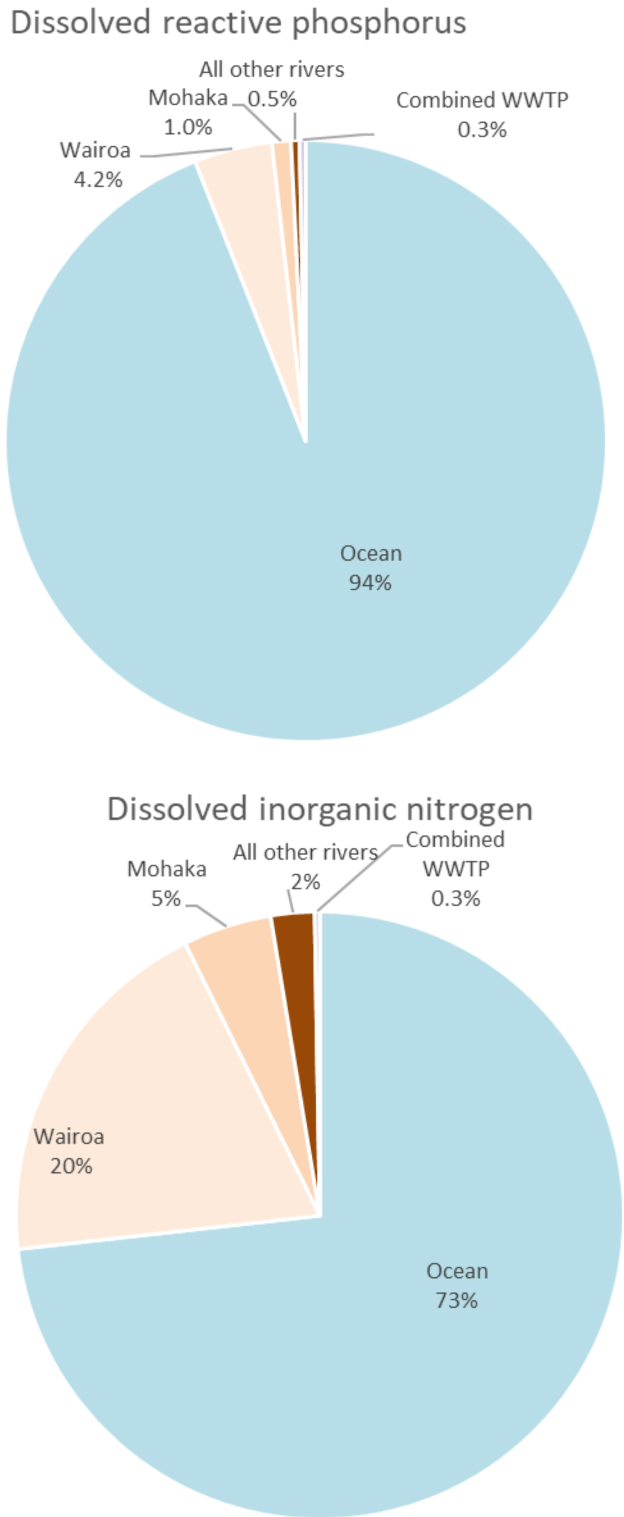


Figure 3-11: Relative contributions of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus in Opoutoma Bay from different sources.

While the ocean is the largest (35%) contributor of nitrogen to the coastal zone off Awatoto, significant portions come from the combined NTC Rivers (31%) and the Tukituki River (16%) (Table 3-4; Figure 3-12).

The two WWTPs collectively provide another 17% of nitrogen; the bulk of that coming from the Hastings WWTP. Close to three-quarters (70%) of phosphorus is oceanic, with 9.4% and 4.6% coming from the Hastings and Napier WWTPs, respectively, and the combined NTC River contributes a further 11.7% (Table 3-4; Figure 3-12).

Table 3-4: Contribution of potential total nitrogen and potential total phosphorus to the coastal zone off Awatoto from different sources. The potential concentrations resulting from each source are estimated by multiplying the water volume fraction in the coastal zone off Awatoto originating from each source by the mean nutrient concentration in that source. Values represent annual average concentrations. The percentages are expressed as a function of the total DIN entering Hawke Bay from the various sources

Source	Water Fraction (%)	DIN contribution (mg/m^3)	%DIN	DRP contribution (mg/m^3)	%DRP
Rivers					
Nuhaka	0.001	0.0018	0.00	0.0000	0.00
Maraetotara	0.058	0.2202	0.25	0.0155	0.13
Tukituki	1.685	14.1275	15.88	0.4212	3.62
Combined NTC	8.438	28.0047	31.49	1.3674	11.75
Esk	0.055	0.1878	0.21	0.0097	0.08
Mohaka	0.077	0.2030	0.23	0.0089	0.08
Wairoa	0.037	0.0780	0.09	0.0034	0.03
Waihua	0.003	0.0063	0.01	0.0011	0.01
Aropaoanui	0.014	0.0405	0.05	0.0025	0.02
Waikari	0.008	0.0190	0.02	0.0022	0.02
Wastewater Treatment Plants					
Napier WWTP	0.014	5.2467	5.90	0.5374	4.62
Hastings WWTP	0.033	9.4002	10.57	1.0911	9.37
Ocean (CARS)	94.99	31.41	35.31	8.18	70.27
Total		**88.95**		**11.64**	

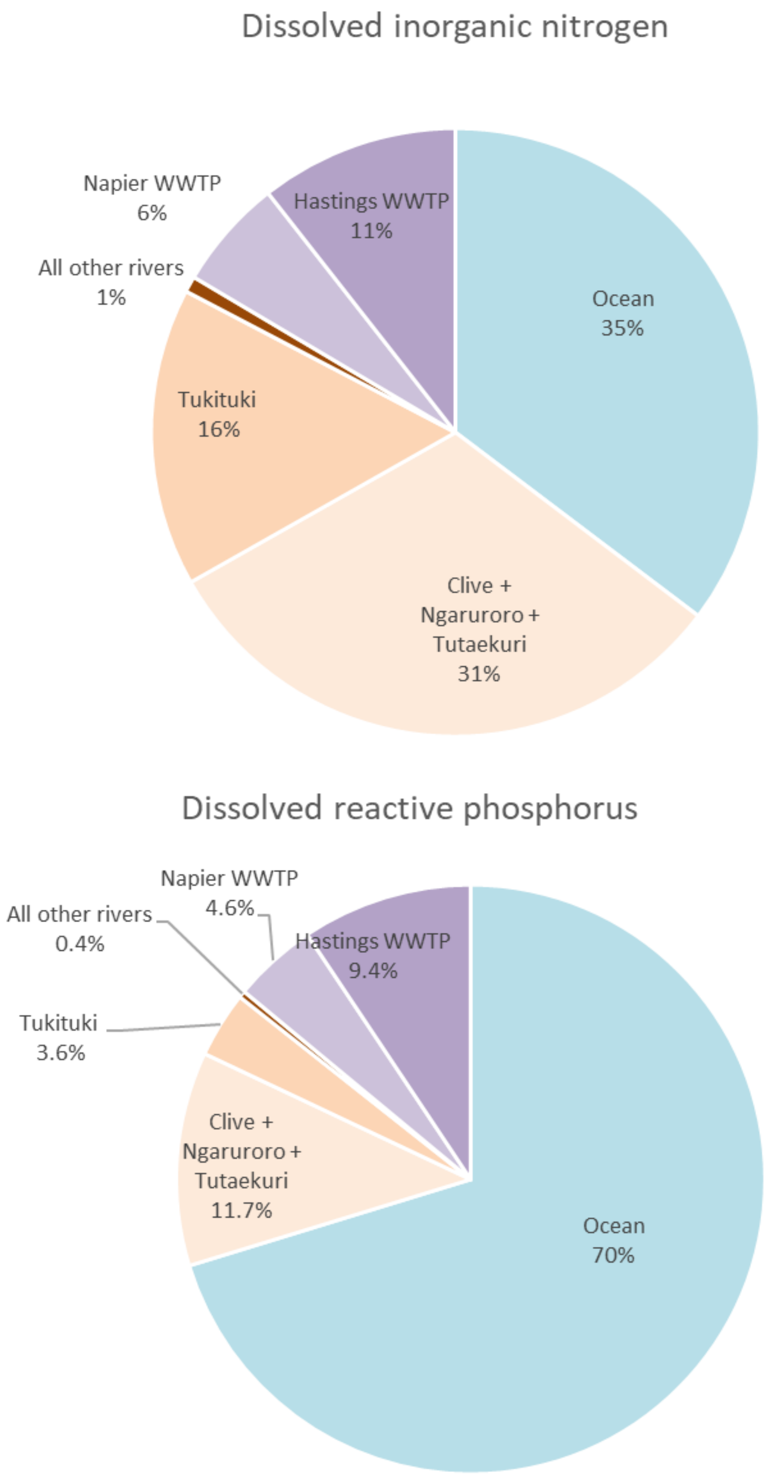
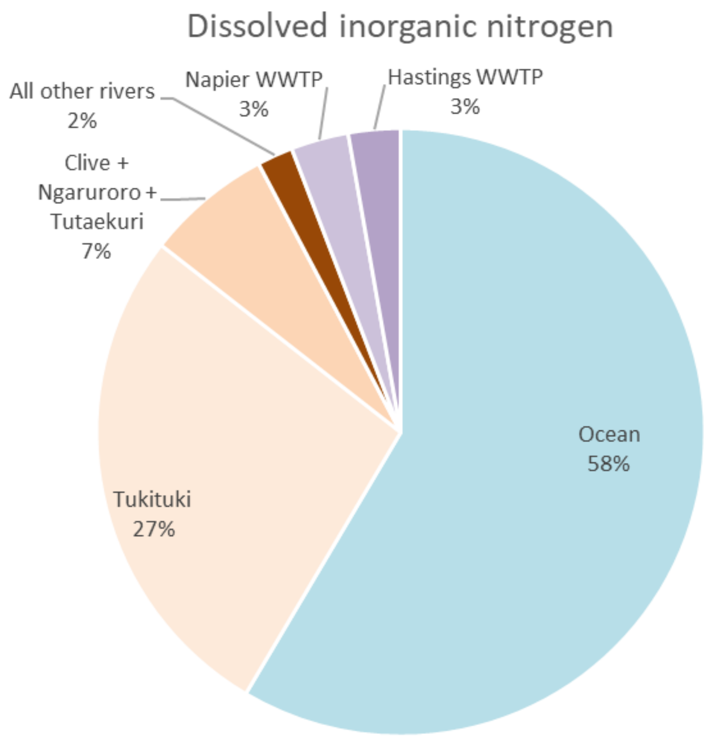


Figure 3-12: Relative contributions of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus off Awatoto from different sources.

The dominant source of nitrogen and phosphorus to the coastal zone around Cape Kidnappers is the off-shore ocean, contributing ~58% of nitrogen and ~89% of phosphorus (Table 3-5; Figure 3-13). Over half of the remaining N comes from the Tukituki (27%), while the Napier and Hastings WWTP contribute 3% of nitrogen each, having a collective influence similar to the combined NTC rivers (7%). The Tukituki River contributes 4.7% of phosphorus, with the two WWTPs and combined NTC rivers each contributing similar amounts of phosphorus (1.8-1.9% each) to the coastal zone around Cape Kidnappers (Table 3-5; Figure 3-12).

Table 3-5: Contribution of potential total nitrogen and potential total phosphorus to the coastal zone off Cape Kidnappers from different sources. The potential concentrations resulting from each source are estimated by multiplying the water volume fraction in the coastal zone off Cape Kidnappers originating from each source by the mean nutrient concentration in that source. Values represent annual average concentrations. The percentages are expressed as a function of the total DIN entering Hawke Bay from the various sources

Source	Water Fraction (%)	DIN (mg/m^3)	%DIN	DRP (mg/m^3)	%DRP
Rivers					
Nuhaka	0.006	0.0110	0.02	0.0001	0.00
Maraetotara	0.033	0.1253	0.23	0.0088	0.09
Tukituki	1.763	14.7815	27.04	0.4407	4.71
Combined NTC	1.103	3.6607	6.70	0.1787	1.91
Esk	0.027	0.0922	0.17	0.0047	0.05
Mohaka	0.167	0.4402	0.81	0.0193	0.21
Wairoa	0.149	0.3143	0.58	0.0137	0.15
Waihua	0.005	0.0104	0.02	0.0018	0.02
Aropaoanui	0.01	0.0289	0.05	0.0018	0.02
Waikari	0.008	0.0190	0.03	0.0022	0.02
Wastewater Treatment Plants					
Napier WWTP	0.004	1.6753	3.07	0.1716	1.84
Hastings WWTP	0.005	1.5163	2.77	0.176	1.88
Ocean (CARS)	96.72	31.98	58.51	8.33	89.09
Total		**54.66**		**9.35**	



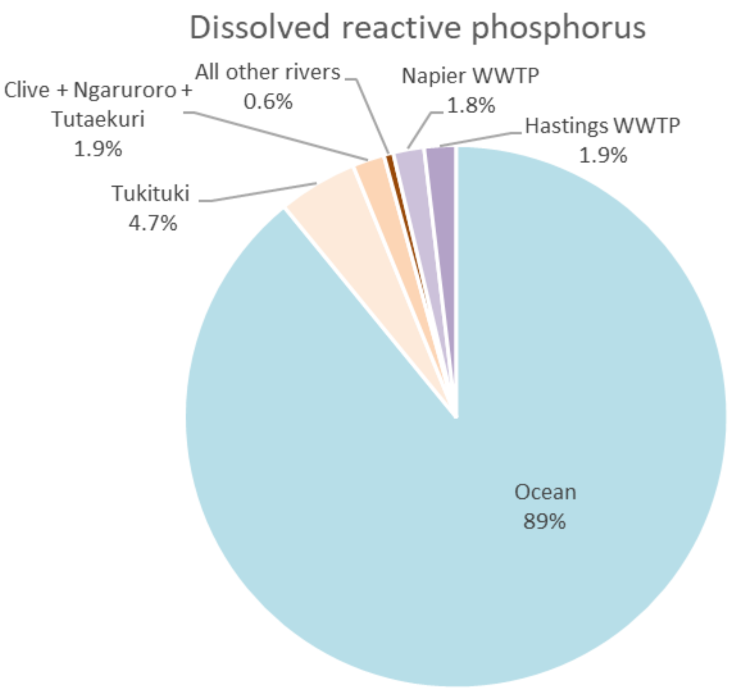


Figure 3-13: Relative contributions of potential dissolved inorganic nitrogen and potential dissolved reactive phosphorus off Cape Kidnappers from different sources.

4 Discussion and Summary

The model has produced freshwater plumes with behaviour that is physically plausible and consistent with historical studies of the circulation in Hawke Bay (Ridgeway 1960; Ridgeway and Stanton 1969). Elevated surface freshwater concentrations are generally confined close to the coast with progressive dilution away from the coast due to vertical mixing and horizontal dispersion (Figure 3-1).

The coastal freshwater band, and the river plumes within it, is transported north- and southward along the coast by alongshore surface currents. Advection of freshwater out of Hawke Bay occurs at either end of the bay. Most of the freshwater advected out of Hawke Bay past Mahia Peninsula in the north, is entrained in the ECC and subsequently transported southward. The freshwaters advected past Cape Kidnappers are generally recirculated back into the bay or also entrained in the ECC.

The model indicates higher freshwater concentrations between Mahia Peninsula and the Mohaka River and between Cape Kidnappers and the Esk River. The high freshwater concentrations between Mahia Peninsula and the Mohaka River can, for the most part, be attributed to the northward advection of freshwater plumes from the Mohaka and Wairoa Rivers, the two largest rivers that terminate into Hawke Bay. The high freshwater concentrations between the Esk River and Cape Kidnappers mainly derive from the combined NTC River that flow into Hawke Bay south of Napier.

Freshwater from the Mohaka and Wairoa Rivers show markedly different advection patterns. Freshwater from the Mohaka River is advected throughout Hawke Bay with the highest concentration being advected north- and southward along the coast. Freshwater from the Wairoa River on the other hand is confined to the northern half of Hawke Bay and is advected mainly northward into Opoutama Bay and past the Mahia Peninsula.

The biggest contributors of freshwater to Hawke Bay are, in order of contribution, the Mohaka, Wairoa, combined NTC and Tukituki Rivers (Figure 3-4). The substantial freshwater contribution (a combined contribution of >90%) of these rivers to Hawke Bay can be attributed to their high mean flow rates which exceed 100 m^3/s for the Mohaka and Wairoa Rivers and 40 m^3/s for the combined NTC and Tukituki Rivers. The Mohaka and Wairoa Rivers are also the biggest contributors of freshwater in Opoutama Bay located downstream of these rivers (Figure 3-6).

Freshwater off the coast of Awatoto comes mainly from the combined NTC River (80% of freshwater) (Figure 3-5). Even though the outfalls for the Napier and Hastings WWTPs are nearby, their collective contribution to the freshwater off the Awatoto coast is <1%.

The proportion of nutrients in Hawke Bay from each freshwater point source shows that on average at the bay scale, the Tukituki River, Mohaka River, Wairoa River and the two WWTPs are the major contributors of terrestrial nitrogen to Hawke Bay. However, nearly half (49%) nitrogen comes from the offshore ocean (Table 3-2). While the Tukituki River has a moderately high mean flow rate, the large contribution of nitrogen from this river can mainly be attributed to its extremely high nitrogen concentrations (838 mg/m^3 DIN) (Table 3-1). The nitrogen concentration of the Tukituki River is 25 times the nitrogen concentration of the ocean. It is also two to three times higher than the nitrogen concentrations of most of the other rivers that terminate into Hawke Bay. The main source of phosphorus (84%) in Hawke Bay is the offshore ocean.

The annual nitrogen and phosphorus loads, calculated from the mean flow and nutrient concentrations, indicate that the two WWTPs combined contribute around $3/4^{th}$ as much nitrogen as the Tukituki River (Table 3-1). However, averaged on an annual basis over the bay, their combined contribution to the water column nitrogen is only about 30% that of the Tukituki River (Table 3-2). This is a curious finding, particularly as the WWTP discharges and the Tukituki River are within a similar area of Hawke Bay. The likely explanation is that under most conditions, the coastal currents advect the WWTP plumes and Tukituki River plume eastward past Cape Kidnappers. However, during high flow events when much of the nitrogen load from the Tukituki River is delivered, the river plume spreads further northward into the bay, where it is captured by other circulation patterns and remains within the bay for longer time periods. This results in a greater increase in water column concentrations, with respect to annual load, in comparison to the WWTPs.

The dominant source of nitrogen and phosphorous to Opoutama Bay is the offshore ocean with significant contributions from the Wairoa River (Table 3-3). On average, nitrogen contribution from the Wairoa River is about 20%, but on occasion this can exceed 40%.

Nitrogen in the coastal zone off Awatoto comes mainly from the combined NTC rivers, the Tukituki River and the Napier and Hastings WWTPs (Table 3-4). These sources contribute 64% of the water column DIN. The Tukituki River has a similar influence to the Hastings WWTP at this location.

Even though the offshore ocean is the main contributor of nitrogen to the coastal zone around Cape Kidnappers, the Tukituki River also contributes a significant portion (27%) (Table 3-5). Most phosphorus at this location is oceanic, with a further 4.7% from the Tukituki River, and 1-2% from each of the WWTPs and combined NTC rivers.

Spatially, the largest increases in DIN were seen along the southwest coast of Hawke Bay, where the Tukituki River, combined NTC River, and the two WWTP discharges are located. Time-averaged concentrations reached values nearly three times that of background oceanic DIN concentrations, with even higher peaks during high flow events. Increases in DRP were smaller throughout Hawke Bay, in comparison to DIN. The nitrogen inputs are more significant than phosphorus inputs because waters in Hawke Bay are likely nitrogen limited. Strong nitrogen limitation occurs at N:P ratios of < 20:1, while P limitation occurs when N:P > 50 (Guildford and Hecky 2000; Smith 2006). N:P molar ratios of the ocean waters are ~8.5:1 (using the values extracted from CARS2009), indicating nitrogen limitation. In Awatoto Bay, this ratio reaches 16.9:1 (annual average). Any changes in primary productivity resulting from the river and WWTP inputs will likely result from their addition of nitrogen rather than phosphorus.

Combined with the right environmental conditions, high levels of nitrogen can cause excessive phytoplankton growth, which in turn, can lead to periodic or permanent oxygen depletion. A crude estimate of the peak phytoplankton biomass can be estimated from nitrogen concentrations, assuming a conversion of N to chlorophyll-*a* of 8.8 g N/ g chl-*a* (Cloern et al. 1995; Plew et al. 2020). This scaling suggests local values of up to 10 µg/l chl-*a* could occur along the south-eastern coastline. The background chl-*a* peak concentration from this scaling would be 3-4 µg/l chl-*a*, which is consistent with observations by Zeldis (2004) of seasonal chl-*a* peaks of 3-4 µg/l further north, across the North-East Shelf north of the Hauraki Gulf. Thus, there is sufficient additional nitrogen to potentially double productivity in the south-east part of Hawke Bay. Elsewhere along the Hawke Bay coast, nitrogen inputs could increase productivity by ~ 10-40%.

It should be noted that the nutrient contributions from the various land-based sources are estimated from annual average nutrient concentrations. In reality, these concentrations will vary both seasonally and potentially with the variable flow rates associated with the various sources. This, however, does not negate the results presented here which indicate that rivers with high flow rates and high nutrient concentrations deliver much of their nutrient load in short-lived pulses. If the resulting plumes disperse quickly, which the model suggest is often the case, the resulting algal blooms will be infrequent. However, if the plumes have a long residence time (several days / weeks), it could result in sustained algal blooms which will be detrimental to the water quality in Hawke Bay.

5 Acknowledgements

Thank you to Hawke’s Bay Regional Council for providing the river flow and discharge data used in this study and Mark Hadfield (NIWA) for the initial set up of the ROMS simulation.

6 Glossary of abbreviations and terms

CARS	CSIRO Atlas of Regional Seas
ECC	East Cape Current
GEBCO	General Bathymetric Chart of the Oceans
HBRC	Hawke's Bay Regional Council
HYCOM	HYbrid Coordinate Ocean Model
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NZLAM	New Zealand Limited Area Model
ROMS	Regional Ocean Modelling System
SST	Sea Surface Temperature
WCC	Wairarapa Coastal Current
WWTP	Wastewater Treatment Plant

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Appendix A Animations

Several animations of model output were produced to accompany this report. The following animations were produced from the model simulation:

- Total_tracer_concentration_2017.gif – this animation shows the dispersal and transport of all the tracers released in the model simulation for the period January 2017-December 2017.
- Mohaka_River_tracer_concentration_2017.gif – this animation shows the dispersal and transport of tracers released at the mouth of the Mohaka River.
- Tukituki_River_tracer_concentration_2017.gif – this animation shows the dispersal and transport of tracers released at the mouth of the Tukituki River.
- Wairoa_River_tracer_concentrations_2017.gif – this animation shows the dispersal and transport of tracers released at the mouth of the Wairoa River.
- DIN_concentration_freshwater_sources_ocean.gif – this animation shows the dissolved inorganic nitrogen concentration in Hawke Bay. The nitrogen concentration was calculated as the sum of the background oceanic DIN (33.1 mg/m^3 based on the CARS2009 climatology) and the DIN concentrations originating from each source.
- Mohaka_River_DIN_concentration_ocean.gif – this animation shows the dissolved inorganic nitrogen concentration originating from the Mohaka River.
- Tukituki_River_DIN_concentration_ocean.gif – this animation shows the dissolved inorganic nitrogen concentration originating from the Tukituki River.
- Wairoa_River_DIN_concentration_ocean.gif – this animation shows the dissolved inorganic nitrogen concentration originating from the Wairoa River.