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Interpreting Northland's Coastal Water Quality Monitoring Results Under Different Tide Conditions

RESEARCH BASED SOLUTIONS

Interpreting Northland's Coastal Water Quality Monitoring Results Under Different Tide Conditions

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EXECUTIVE SUMMARY

As part of State of the Environment (SoE) Monitoring, New Zealand regional councils undertake water quality monitoring of coastal waters primarily to assess the health of coastal water quality and identify environmental issues. Coastal waters (including estuaries) are physically dynamic and are heavily influenced by freshwater inflows via terrestrial runoff and rivers and also oceanic processes such as tides and waves. These factors, among others, lead to high variability in routinely measured water quality parameters, such as water column nutrients, turbidity (suspended sediments), and faecal indicator bacteria (FIB)

Tide stage has been identified as an important factor to consider when collecting samples for water quality monitoring; however, there is little known about the role of tides in reducing the ability to assess changes in water quality over time. This report, funded through the Ministry for Science and Innovation Envirolink Scheme, aims to provide (1) advice to Northland Regional Council (NRC) on the interpretation of coastal water quality data in relation to tide stage, (2) recommendations if and how data could be analysed to reduce variability associated with tides, and (3) guidance on future water quality sampling and monitoring.

In order to meet the above objectives, we carried out a short review of the International literature and conducted an analysis of water quality monitoring data supplied by NRC. Included is an analysis of results from a field study involving high frequency sampling over a tidal cycle and during dry weather conditions that was carried out by NRC staff in three different estuaries in order to isolate the potential effects of tides on water quality parameters. Historical water quality from select NRC coastal water quality monitoring sites were also analysed to assess the contribution of tides to variability observed in water quality parameters.

In summary, tides can have a strong influence on some water quality parameters such as salinity, dissolved nutrients and turbidity, and the extent of tidal influence varies depending on the sampling location within an estuary. Variability due to tides is likely driven by differences between the concentrations of contaminants (*e.g.* nutrients, suspended solids) in freshwater entering estuaries and incoming oceanic water. Increased current velocity and sediment resuspension during ebbing and flooding tides also contributes to patterns observed in water clarity and turbidity. While tides may influence some parameters such as nutrients and turbidity, others such as water temperature and dissolved oxygen (DO) were influenced to a greater degree by solar radiation inputs and therefore appear to vary as a function of the time of day rather than tides.

Based on a statistical analysis of historic datasets of water quality parameters in the Kaipara and Whangarei Estuaries, we found relatively weak correlations for only ~10% of the cases examined across all sites and parameters. This indicates that there are likely a range of factors other than just tides influencing water quality data, including differences in antecedent rainfall, cloudiness, time of day, and wind conditions. It is also likely that the datasets are of insufficient size and sampling frequency to fully tease apart the effects of tides.

For the purpose of SoE monitoring, we would not recommend altering the current sampling programme to minimise variability due to tides. However, it is recommended that sampling occurs at

a consistent time of day (preferably in the morning hours) to minimise variability in parameters such as dissolved oxygen and FIB that are strongly influenced by solar radiation inputs.

Ideally water samples would also be collected at a comparable tide height; however, this is logistically difficult and would likely not markedly improve the ability to assess changes in water quality conditions over time. Nonetheless, knowledge of the effects of tides on water quality parameters is required when interpreting results over time within the context of guideline compliance. For example, in some cases water quality parameters such as turbidity fluctuated above and below maximum guideline standards as a function of tide stage. Hence in those cases where guideline values are exceeded, knowledge of the potential influence and stage of the tide at a sampling site, perhaps through more detailed sampling, will assist in interpreting results.

In order to better understand temporal variability within a given estuary, the deployment of logging sensor(s) (either on a periodic or preferably permanent basis) at designated SoE monitoring locations (*e.g.* mid estuary) is recommended. Sensors for obtaining time-series measurements of basic water quality parameters such as salinity, temperature, turbidity and chlorophyll *a* (chl *a*) are becoming more reliable and affordable and would facilitate interpretation of data collected as part of water quality sampling programmes. In the absence of deployed sensors, higher frequency sampling events (such as the sampling conducted in this study) are required to quantify and more fully understand the role of tides and other factors such as rainfall in driving variability in the data. In addition to field sampling, a cost-effective ‘desktop’ approach to understanding spatial and temporal variability in water quality conditions as a function of drivers such as tides and rainfall events is the analysis of satellite imagery. Such analysis allows the examination of patterns in near-surface turbidity, water temperature and levels of chl *a* under varying physical conditions.

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1. INTRODUCTION

As part of State of the Environment (SoE) Monitoring, New Zealand regional councils undertake water quality monitoring of coastal waters in order to assess:

- the health of coastal water quality and identify environmental issues
- compliance of activities with resource consent conditions, rules and plans, and
- water quality for safe swimming and recreational use.

There are currently no standardised protocols for coastal water quality monitoring in New Zealand. Coastal waters (including estuaries) are physically dynamic and are heavily influenced by freshwater inflows via terrestrial runoff and rivers and also oceanic processes such as tides and waves. These factors, among others, lead to high variability in routinely measured water quality parameters, such as water column nutrients, turbidity (suspended sediments), and faecal indicator bacteria (FIB).

Tide stage has been identified as an important factor to consider when collecting samples for SoE Monitoring (*e.g.* Boehm 2002; Bordalo 2003 Mallin *et al.* 1999). However, in New Zealand councils have different sampling protocols in place with regard to tides and little is known about the role of tides in reducing the ability to assess changes in water quality over time.

This Envirolink project aims to assist Northland Regional Council (NRC) with interpretation of their water quality data in relation to tide stage, provide recommendations regarding if and how data could be analysed to reduce variability associated with tides, and provide guidance on future water quality sampling and monitoring. In order to meet these objectives, we carried out a short review of the International literature and conducted an analysis of water quality monitoring data supplied by NRC. Included is an analysis of results from a field study involving high frequency sampling over a tidal cycle during dry weather conditions that was carried out by NRC staff in three different estuaries in order to isolate the potential effects of tides on water quality parameters. Historical water quality from select NRC coastal water quality monitoring sites were also analysed to assess the contribution of tides to variability observed in water quality parameters.

2. REVIEW OF THE POTENTIAL EFFECTS OF TIDES ON WATER QUALITY MONITORING

Estuaries and coastal waters are physically dynamic and respond over time as a function of riverine and oceanic processes. Parameters traditionally measured for assessing water quality, such as concentrations of dissolved nutrients and FIB, can vary considerably in the coastal environment in response to changes in physical factors such as solar radiation, tides, wave climate, water temperature, and rainfall. In addition to physical factors, biological processes can also influence water quality parameters. Examples include the effects of phytoplankton biomass on water clarity and nutrient concentrations. These physical and biological factors lead to significant spatial and temporal variability in water column constituents that can impede the ability to identify trends over time in response to changes in anthropogenic pressures. For example, enterococci concentrations in coastal waters have been shown to vary by 60% on average and by as much as 700% between samples that are collected only minutes apart (Boehm 2007).

All other factors aside, tides have a strong potential to influence parameters in estuaries due to mixing of freshwater and marine waters, each of which varies in terms of physical, chemical and biological characteristics. For instance, rivers draining developed catchments that include agriculture typically carry waters that have higher concentrations of contaminants (sediments, nutrients, faecal microorganisms) than the receiving waters in an estuary or near a river mouth. Indicators of the contaminants therefore have the potential to vary depending on the stage of the tide and sampling location in addition to variations in river loading due to rainfall and associated runoff.

Tides become more important when concentration gradients are large (Dilorenzo *et al.* 2004) and the effects of tides often depend on location and proximity to the mouth of estuaries (Santaro & Boehm 2007). Concentrations of land-derived contaminants would therefore be highest when sampling inner regions of estuaries at low tide where freshwater flows are less diluted by marine waters. Conversely, as you move to outer regions of an estuary and/or during high tides, land-derived contaminants will become more diluted. An example is the change in concentration of ammonium over a tide cycle in shallow waters of Florida Bay, where waters from agricultural lands drain and flow over the bay on outgoing tides and are diluted by oceanic waters during incoming tides (Cornelisen & Thomas 2007; Figure 1). Another example, based on monitoring data collected in New Zealand, demonstrates that elevated concentrations of faecal bacteria, nutrients and suspended sediments tend to coincide with periods of low tide (Figure 2). However, high levels of variability remain beyond that explained by tides alone; hence other factors such as those indicated above must also influence water quality data.

A summary of the potential influence of tides on commonly measured parameters used for water quality monitoring, *i.e.* dissolved oxygen (DO), turbidity/water clarity, dissolved nutrients and FIB, is provided in Table 1. Included in the table are three other physical factors (rain, wind, solar radiation) known to influence (sometimes cumulatively) these same water quality parameters. In addition to the parameters described in the table and further below, pH is also typically measured and can be directly influenced by tides since pH will vary as a function of salinity and the carbonate-bicarbonate buffer system.

Water quality in the coastal environment is ultimately a function of multiple factors that lead to the conditions at any one point in time and/or space; hence the extent to which tides have an influence on water quality can also vary as a function of these other factors. The following information also highlights the importance of collecting ancillary data and information for describing environmental conditions during routine water quality sampling; *e.g.* tide stage, wind/wave conditions, rainfall, salinity, turbidity, chlorophyll a (chl *a*).

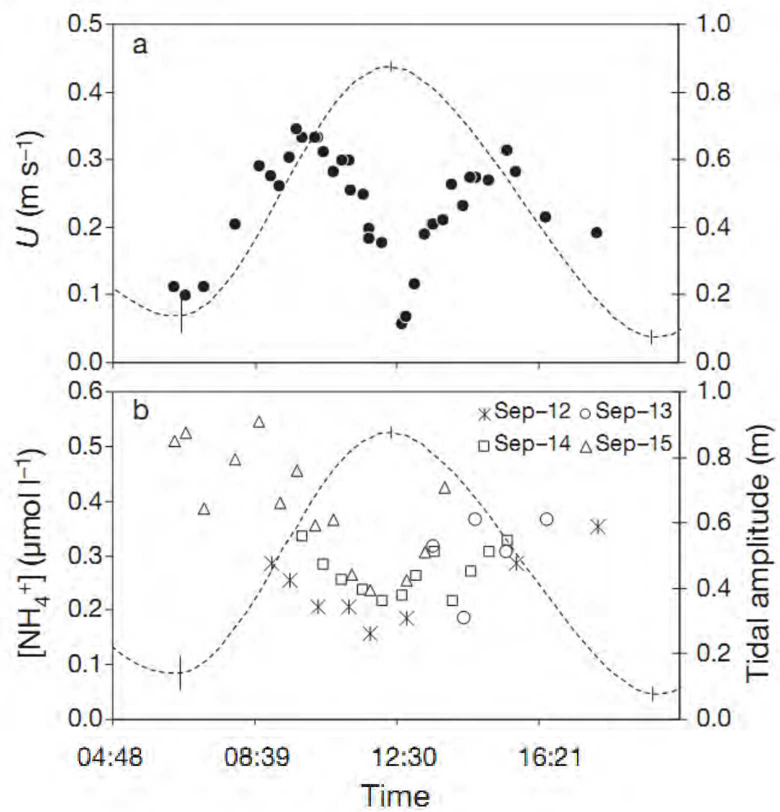

Figure 1. Mid-water current velocity (top panel) and water column ammonium concentrations (bottom panel) as a function of tides in Florida Bay, U.S. Data during the four day period of field sampling are overlaid with the average predicted tidal amplitude with bars representing tide variation among days. Figure from Cornelisen & Thomas (2009).

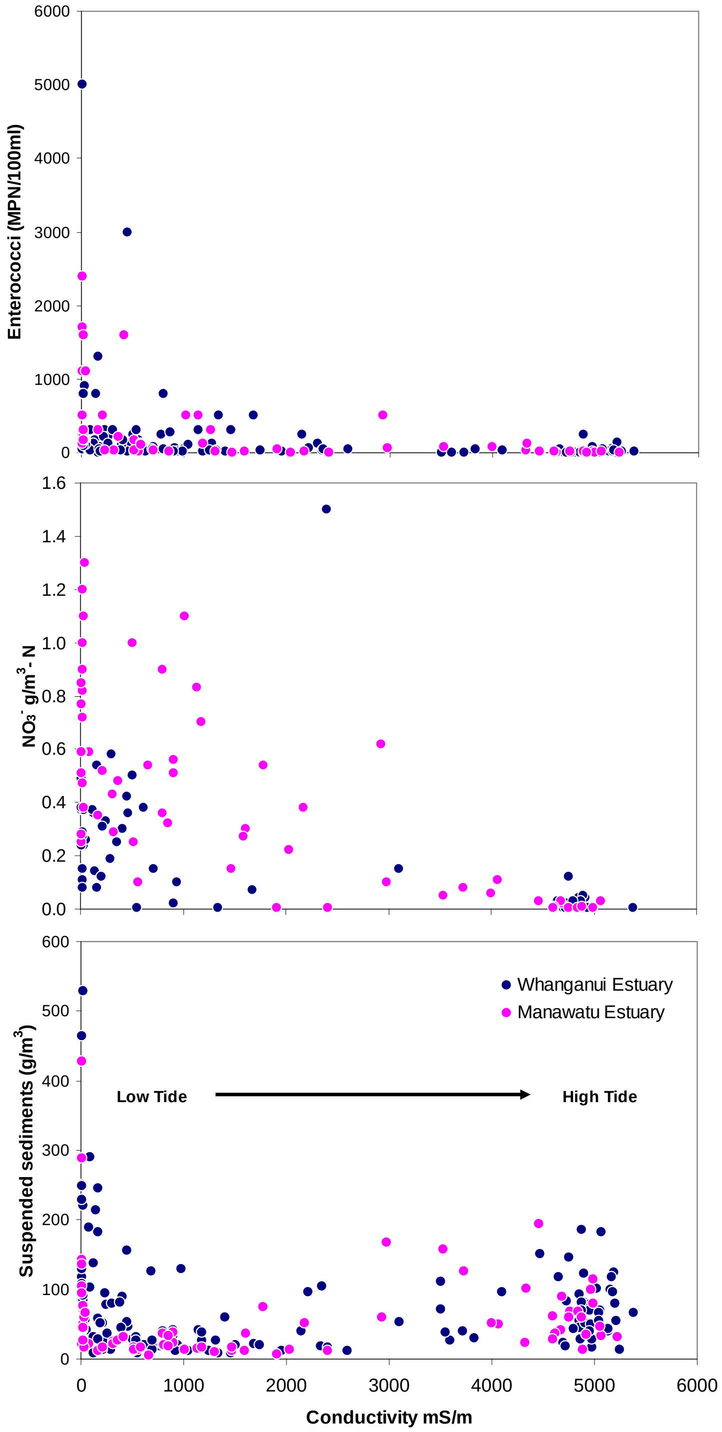

Figure 2. Enterococci concentration (top), Nitrate concentration (middle) and suspended sediments (bottom) for water samples collected between 1992 and 2005 in the Whanganui Estuary, and between 1991 and 1998 in the Manawatu Estuary. Data are presented according to the conductivity of the water, with low and high conductivity readings suggesting low and high tides during sampling, respectively. Figure reproduced from Cornelisen (2009).

2.1. Dissolved inorganic nutrients

Concentrations of commonly measured nutrients (ammonium, nitrate+nitrite nitrogen (NNN), dissolved reactive phosphorus (DRP)), for estuary and coastal water samples have the potential to vary considerably depending on the stage of the tide. Nutrient concentrations at a given location will depend on the extent to which water masses of different origins (*e.g.* terrestrial versus marine) have mixed; each can differ in nutrient concentrations and their contributions to a water sample will vary depending on the stage of the tide (*e.g.* low tide = potential for greater influence from freshwater; high tide – potential for greater dilution from marine waters; see Figures 1 and 2; Magni *et al.* 2002). Depending on environmental conditions leading up to sampling, the differences between terrestrial and oceanic nutrient concentrations will also vary.

Following rain, nutrient concentrations in runoff entering estuaries and coastal waters can be elevated (Gillespie *et al.* 2011, MacKenzie 2004). The gradient in concentration between low and high tides may subsequently be greatest during wet periods. Nutrient concentration in the coastal receiving environments may also vary over time depending on the level of primary production which affects assimilation rates and/or upwelling/onwelling of oceanic nutrients along the coast (MacKenzie & Adamson 2004; Zeldis 2008). For instance, nutrient concentrations may be highest during winter months when light levels are low and as a result phytoplankton production (and therefore nutrient assimilation) is in turn low (MacKenzie 2004).

Nutrients can be elevated close to shore due to the flux of porewater nutrients within nearshore and beach sediments into the water column as a function of tide and wave driven currents. Current velocities are greatest during ebbing and flooding tides and lowest during slack tides (Figure 2). The magnitude of current velocities will also vary over longer time-scales as a function of spring and neap tide conditions. Increased current velocities near the sediment-water interface can result in increased porewater advection and flux of nutrients from permeable sediments into the overlying water column (*e.g.* Precht & Huettel 2003). In addition to tidal driven flows, oscillatory flows from wind-driven wave action in shallow waters promotes resuspension of sediments and increased nutrient flux (*e.g.* Cowan *et al.* 1996; Morin & Morse 1999; Tengberg *et al.* 2003). There are also potentially interactive effects between tides and waves, with waves having a larger effect in shallow waters during low tide. Lastly, tides may also influence the flux of groundwater (and nutrients) through sediments and beach sands into coastal waters (*e.g.* Burnett *et al.* 2003).

2.2. Suspended sediments, turbidity and water clarity

The mechanisms affecting suspended sediments, turbidity and water clarity within estuaries and coastal waters are similar to those described for dissolved inorganic nutrients. It is important to note, however, that these three water quality parameters are not always directly correlated (Davies-Colley & Smith 2001). For example, there are factors other than suspended sediments that influences water clarity, such as chlorophyll levels or coloured dissolved organic matter (CDOM). Similarly, the relationship between turbidity and water clarity can vary as a function of salinity and changes in the characteristics of particles, which affect light penetration and therefore perceived water clarity (Davies-Colley & Smith 2001). In this particular case, tides can therefore not only influence these parameters but also the extent to which they are correlated to one another.

Oceanic waters are typically clearer than freshwater runoff from coastal catchments. As a result, water samples collected in estuaries and/or near river plumes following rainfall can be elevated in suspended sediments and turbidity (with decreased water clarity). Tides are most likely to have a measureable influence when strong gradients in suspended sediments between incoming freshwaters and marine waters exist. As described above, elevated current velocities near the seabed during ebbing and flooding tides can result in increased sediment resuspension and elevated levels of sediments in the water column (*e.g.* Gibbs 2001). In shallower waters, winds can confound the effects of tides on resuspension (Mitchell *et al.* 2008)

2.3. Faecal indicator bacteria (FIB)

FIB concentrations are often highly correlated to rainfall and increased inputs of diffuse sources of faecal contamination (from pastoral farming) during and following rain events (*e.g.* Wilkinson *et al.* 2011; Cornelisen *et al.* 2011). Regardless of tide stage, river flooding and antecedent rainfall patterns will therefore play a large role in driving FIB concentrations. Commonly measured indicator bacteria such as *E. coli* and enterococci are known to persist in the environment once released by the host (Ishi & Sadowsky 2008). These bacteria can be stored for periods of days to weeks in river bed sediments, which can then be released in large pulses of contamination to coastal environments during flood events (Wilkinson *et al.* 2011).

With the exception of birds, the dominant sources of faecal contamination contributing to coastal waters will primarily be associated with diffuse non-point source pollution and potentially point source pollution (sewage outfalls). Spatial gradients in FIB concentrations are likely to exist within coastal environments between higher concentrations in proximity to incoming sources and lower concentrations with distance and dilution with marine waters. Tides influence the extent of dilution in nearshore waters; FIB concentrations can be higher during outgoing tides than during incoming and high tides when dilution of land-derived sources in freshwater inflows can occur (see Figure 2; Bordalo 2003; Santaro & Boehm 2007). Tides can also interact with groundwater flows through soils and beach sands (*e.g.* Burnett *et al.* 2003) that may be contaminated (in some cases by septic systems) and released into the coastal environment (Boehm *et al.* 2002). In addition to river bed sediments, estuary sediments and beach sands can also act as reservoirs for FIB that can be released into the water column just following high tides (*e.g.* G. Lewis presentation at WaterMicro2011 on Bethells Beach; Boehm & Weisburg 2005; Yamahara *et al.* 2007). Wave action enhances resuspension of sediments and beach sands, and thereby has the potential to release persistent populations of FIB to the marine environment (Yamahara *et al.* 2007). Such events may explain why episodic high faecal counts in both water samples and shellfish, such as cockles, can occur in the absence of recent rainfall (pers comm. with shellfish industry).

The primary driver of faecal bacteria mortality is exposure to UV radiation. FIB concentrations in waters exposed to sunlight typically decline over the course of the day and can be highest during the night (Rosenfield *et al.* 2006). As a result, time of day, combined with antecedent rainfall patterns and proximity to incoming freshwater sources, will likely have larger influences on variability in FIB concentrations than tides.

2.4. Dissolved oxygen (DO)

Dissolved oxygen is a good indicator of ecosystem health since it is directly linked to rates of primary production (and respiration) in aquatic environments, which in turn can be impacted by stressors such as nutrient loading. Primary production (and respiration) is the primary driver of DO levels in coastal waters; however, factors such as water temperature and vertical mixing of the water column and air-sea exchange at the water surface also affect DO levels at a given location and time.

Increased nutrient loading associated with runoff can lead to high primary productivity and extremes in DO (high and low), particularly within areas in close proximity to river plumes. Winds (particularly in shallow estuary environments) influence the extent of water column mixing and therefore the degree of stratification. This, in turn, affects the distribution of DO throughout the water column.

Solar radiation affects DO concentrations due to changes in water temperature and rates of photosynthesis; hence DO in water changes over the course of a day and according to season (Hubertz & Cahoon 1999). Increased primary production due to increased nutrient loading can lead to eutrophication and greater extremes in DO (Prasad *et al.* 2011).

The above factors are likely to have the largest influence on DO concentrations in estuaries and coastal waters. However, tides can also influence DO due to their effect on mixing of different water masses that can differ in DO concentrations (*e.g.* incoming freshwaters mixing with downstream coastal waters that vary in DO). Patterns in DO that coincide with tides may depend on the season *e.g.* low levels of DO may correspond with low tide during summer months (Edwards *et al.* 2004).

Table 1. Potential response of water quality parameters to different physical factors. See main text for references.

Factor	Dissolved Oxygen	Turbidity/water clarity	Dissolved nutrients	Faecal indicator bacteria
	Water quality parameters			
Tides	DO measured at a given location can vary according to tidal stage due to differences in the DO concentrations between fresh/marine waters that are mixing over the course of a tide. Patterns in DO that coincide with tides may depend on the season *e.g.* low levels of DO may correspond with low tide during summer months.	Tides can impact levels of turbidity, water clarity and suspended solids in the water column due to (1) the effect of increased currents on near-bed resuspension during ebbing and flooding tides, and (2) differences in the turbidity between typically clearer oceanic water vs more turbid freshwaters entering and mixing within an estuary.	Relative proportion of land-based vs oceanic sources of nutrients (and therefore concentrations) vary as a function of tides. Increased tidal currents can also increase flow near the seabed and nutrient flux from sediments.	Faecal indicator bacteria (FIB) concentrations will often be greatest during low and outgoing tides, versus incoming and high tides when dilution of land-derived sources in freshwater inflows can occur. Tides can also influence the flux of contaminants entering through sub-surface groundwater flows.
Rainfall	DO can vary as a function of the level of freshwater flows for the same reason as described for tides (i.e. the amount of DO in the incoming freshwater could vary from that in marine waters). Increased nutrient loading associated with runoff can lead to high primary productivity and extremes in DO (high and low), particularly within areas in close proximity to river plumes.	Rainfall and runoff via rivers results in increased sedimentation into the coastal environment; hence turbidity and water clarity in estuaries and coastal waters can be highly correlated to rain events and the extent of sedimentation during flooding.	Runoff of fertilizers and other land-based nutrient sources can lead to high concentrations during and following rainfall events.	FIB concentrations are often highly correlated to rainfall and increased inputs of diffuse sources of faecal contamination (from pastoral farming) during and following rain events.
Winds	Winds (particularly in shallow estuary environments) influence the extent of water column mixing and therefore the degree of stratification and DO concentrations throughout the water column (e.g. high winds - greater mixing - less likely to have low DO near the bottom). Wind disturbance of the seabed can also result in increased benthic O2 consumption through mixing with 02 depleted interstitial water.	Winds (particularly in shallow estuary environments and along the coast) promotes resuspension of bottom and shoreline sediments and as a result can heavily influence levels of turbidity/water clarity. Winds can confound effects of tides on resuspension.	Increased winds and wave action can result in resuspension of sediments and subsequent release of sediment porewater nutrients into the water column.	High winds and associated wave action can result in resuspension of sediments and beach sands that can harbour persistent populations of FIB.
Solar radiation (time of day and season)	Solar radiation affects DO concentrations due to changes in rates of photosynthesis. As a result, DO can vary over the course of a day and according to season. Increased solar radiation coupled with increased runoff (nutrients) can lead to greater extremes in DO (high and low).	evels of solar radiation influence rates of primary production and can indirectly influence water clarity as a function of changes in phytoplankton biomass.	Solar radiation inputs indirectly affect nutrient concentrations through changes in rates of primary production and nutrient assimilation.	The primary driver of faecal bacteria mortality is exposure to UV radiation. FIB concentrations in waters exposed to sunlight typically decline over the course of the day and can be highest during night-time.

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3. FIELD STUDY

3.1. Methods

A field study for investigating the effects of tides on water quality was carried out by staff at Northland Regional Council at three locations in both the Whangarei Harbour and Kerikeri Inlet, and at two locations in the Otamatea River, Kaipara Harbour). Details on site characteristics, including maps showing their locations, are provided in Appendix 1. Field sampling was conducted during a dry period to minimise the influence of rainfall/runoff. In order to obtain high-resolution data on water quality conditions over several tide cycles, YSI Sondes were deployed for collecting time-series data on temperature, salinity, DO, pH and turbidity. Not all Sondes were equipped with an optical turbidity sensor; hence a second optical sensor (Scufa – Turner Designs) was deployed in some cases (Table 2). The sensors were moored in place in waters 1-4 m deep (depending on tide stage) and within about 0.5 m of the surface.

Table 2. Sites and dates sampled using deployed YSI Sondes for collection of temperature (T), salinity (S), dissolved oxygen (DO), pH and turbidity (T). [1] Deployment of Turner Designs Scufa sensors for recording turbidity.

Estuary	Site	Dates sampled	Time series data
Whangarei Harbour	Site 100211 Town Basin	8 – 10 Dec 2010	T, S, DO, pH, T
	Site 100200 Kaiwaka Point	8 – 10 Dec 2010	T, S, DO, pH
	Site 100190 Mair Bank	9 – 10 Dec 2010	T, S, DO, pH
Kerikeri Inlet	Site 101526 Waipara River	9 – 10 Mar 2011	T, S, DO, pH, T
	Site 105707 Windsor Landing	9 – 10 Mar 2011	T, S, DO, pH
	Site 101544 Wainui Island	9 – 10 Mar 2011	T, S, DO, pH, T[1]
Otamatea Channel	Site 109665 Wahiwaka Creek	7 – 8 Mar 2011	T, S, DO, pH, T
	Site 109666 Te Hoanga Point	7 – 8 Mar 2011	T, S, DO, pH, T[1]

Within each 3-day deployment of the moored instrumentation, a water-quality survey involving water sampling over a ~ 10 hour period (between 0515 and 1600 hours) was conducted (Table 3). At each of eight sampling intervals (spaced at 1-2 hours), discrete water samples (n=1 at each interval for a total of eight samples at each site) were collected and later analysed in the laboratory within 24 hr for suspended sediments and turbidity, dissolved nutrients (ammonium, nitrate+nitrite nitrogen (NNN), DRP), and enterococci. At each sampling interval, a measure of water clarity was recorded using a Secchi disk, and a hand-held YSI was used to record the same parameters measured by the deployed YSI Sondes (see Table 1). Data using the hand-held instrument were collected at the water's surface (0 to 0.3 m), rather than 0.5 to 1.0 m deep where YSI Sondes were deployed. Guideline (ANZECC) values/ranges for water quality parameters are provided in the Table 4.

Tide data for each of the estuaries was provided by NRC. Tide data were extracted using WXTide32 (http://www.wxtide32.com/) in cases where tide data did not overlap completely with field surveys. Tide height at the point of time where water quality samples were collected was extracted through linear interpolation.

Table 3. Sites and dates of where and when water sampling was conducted for the field study. Sampling occurred between 0515 and 1600.

Estuary	Site	Date sampled
Whangarei Harbour	Site 100211 Town Basin Site 100200 Kaiwaka Point Site 100190 Mair Bank	9 Dec 2010 9 Dec 2010 9 Dec 2010
Kerikeri Inlet	Site 101526 Waipara River Site 105707 Windsor Landing Site 101544 Wainui Island	10 Mar 2011 10 Mar 2011 10 Mar 2011
Otamatea Channel	Site 109665 Wahiwaka Creek Site 109666 Te Hoanga Point	8 Mar 2011 8 Mar 2011

For qualitative analysis, data for each parameter were plotted with tide height as a function of time. Correlations between tide height and water quality variables were evaluated using Pearson's correlation. The hypothesis of no correlation between tide and water quality variable was evaluated using student t-test and a significance level of 0.05 was applied (Zar 1996). All analyses were conducted using the free software R version 2.13.0 (R Development Core Team 2011).

Table 4. Water quality parameters and guideline value/range. Compliance is typically based on the percentage of time that values fall below these standards (or above for DO).

Parameter	Units	Guideline value/range
Dissolved Oxygen (DO)	% saturation	80
Turbidity	NTU	5-10
Enterococci	MPN/100ml	140
Ammonia	g/m^3	0.015
Total phosphorus (TP)	g/m^3	0.03
Total nitrogen (TN)	g/m^3	0.3

3.2. Results

3.2.1. Whangarei Harbour

Time series

The Sonde deployed at Mair Bank failed to collect sufficient data for analyses. Visual review of time series data over a 2-day period at the other two sites in Whangerei Harbour reveal that some parameters, such as salinity and turbidity, followed patterns consistent with changes in tide height (Figures 3 and 4). Turbidity at Town Basin increased during flooding and to a lesser extent during ebbing tides. Turbidity levels at this site also exceeded the guideline range of 5-10 NTU depending on tide conditions. The pH also followed tides at the Kaiwaka Point site, which is further removed from freshwater influences than the Town Basin site, where the effect of tides on pH was less apparent. However, as might be expected, the overall effect of tides on data appears dependent on proximity to the inner region of the estuary, with less tidal influence with distance away from river inflows. For example, the effect of tides on salinity was much greater at the Town Basin site (range spanning 6 psu) than at the Kaiwaka Point site (range < 1 psu).

Some parameters, including DO and water temperature changed as a response of time of day (solar inputs) and did not appear to be affected by tides. Correlation analyses between each of the time series parameters and tide height were statistically significant, which is in large part due to the large sample size. The greatest correlation for time series data was found for salinity and pH at both sites and turbidity at the Town Basin site (Table 5).

Discrete measurements for some of the parameters using the hand-held YSI are also shown in Figures 3 and 4. In some cases, such as water temperature, the patterns in these measurements follow those of the YSI Sonde. However, for others, the eight discrete measurements follow a similar pattern but are considerably different in absolute value from the time series data. This was likely a function of sampling depth as discrete measurements were collected close to the surface of the water and therefore reveal data consistent with more buoyant low salinity water near the surface that also had a higher concentration of DO. Turbidity near the surface at the Town Basin site was also lower than that recorded by the Sonde located closer to the sediment, where resuspension (and elevated turbidity) appears to be occurring just prior to low and high tide.

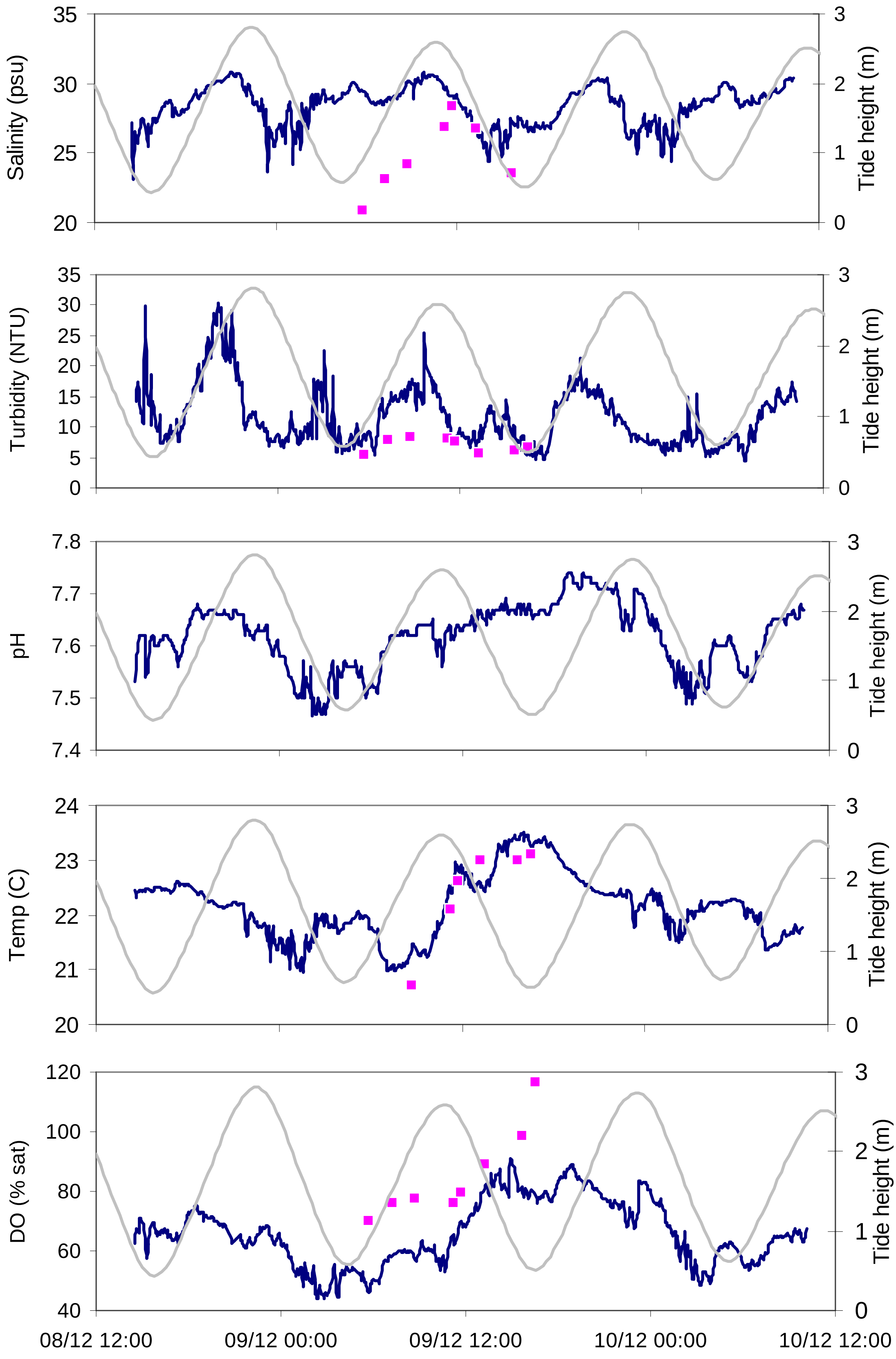

Figure 3. Time series of water quality parameters measured at the Town Basin site and tide height. Also shown are results from the eight discrete measurements (pink squares) collected near the water surface using a hand-held YSI instrument.

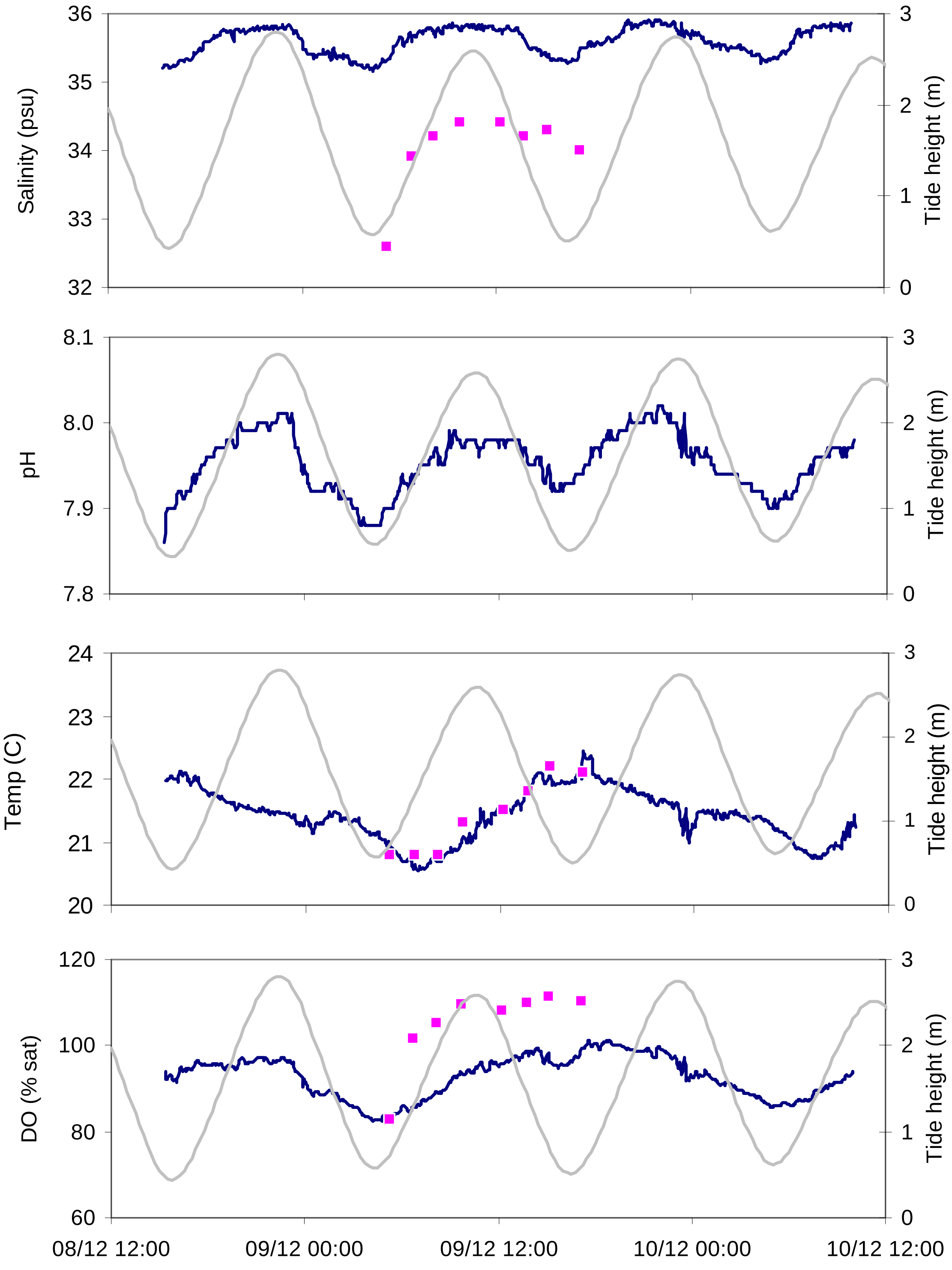

Figure 4. Time series of water quality parameters measured at the Kaiwaka Point site and tide height. Also shown are results from the eight discrete measurements (pink squares) collected during the water quality sampling.

Table 5. Correlation coefficients (r) for water quality parameters versus tide height based on time series data for sites sampled in Whangarei Harbour. Also shown are t statistics and p values.

Site	Parameter	r	t	p
Town Basin	Salinity	0.40	9.82	<0.001
	Turbidity	0.41	10.35	<0.001
	Temperature	-0.35	-8.62	<0.001
	DO (% sat)	0.13	3.03	<0.001
	pH	0.40	10.08	<0.001
Kaiwaka Point	Salinity	0.88	41.49	<0.001
	Temperature	-0.23	-5.27	<0.001
	DO (% sat)	0.37	8.86	<0.001
	pH	0.82	32.68	<0.001

Field sampling

Field sampling showed patterns primarily associated with site location (proximity to inner versus outer regions of the estuary) rather than patterns consistent with tide effects. The exception was dissolved nutrients and turbidity at the Town Basin site, which were significantly correlated to tide height (Figure 5; Table 6). Both nutrients and turbidity were elevated at high tide and may relate to advection of suspended sediments and nutrients up into the estuary on the incoming tide. This may explain why nutrient concentrations and turbidity were higher during the incoming tide but lower at high tide at the Kaiwaka Point site (Figure 5). Furthermore, suspended sediments likely settle out when tide currents attenuate. Nutrient levels exceeded guideline values (see Table 4) at the Town Basin site and tide conditions can strongly influence whether or not guideline values are exceeded.

There were only two significant correlations between water quality parameters and tide height beyond the Town Basin site. Levels of water quality parameters were significantly higher at the Town Basin site than at sites with greater proximity to ocean influences. This is likely a result of dilution of river inputs.

The only ‘elevated’ concentration of enterococci observed during the study was at the Town Basin site in the first sample collected (111 MPN/100 ml at 0545); hence, there were no patterns in enterococci concentrations consistent with tidal stage and they were not included in the analysis. At these sites the effect of tides, if any, is likely to be observed only during and following rainfall when concentrations are elevated.

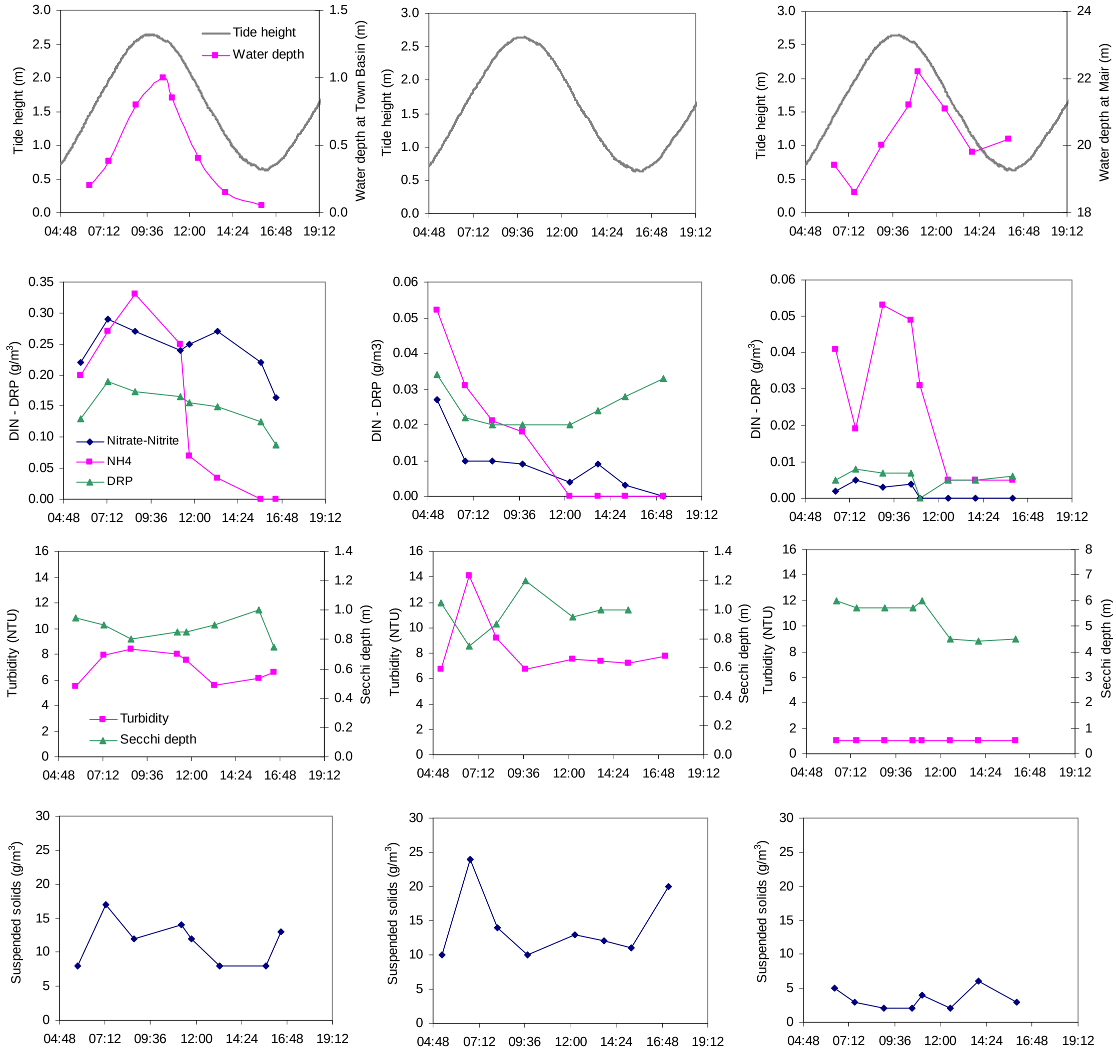

Figure 5. Predicted tide height and measured water depth (top row), dissolved inorganic nitrogen and phosphorus (second row), turbidity and secchi depth (third row), and suspended sediments (bottom row). Columns are arranged according to sites (left-Town Basin, middle-Kaiwaka Point, right-Mair Bank). Note that the Y-axis is different between sites for dissolved nutrients.

Table 6. Correlation coefficients (r) for water quality parameters measured at eight points in time versus tide height (see Figure 4) for sites sampled in Whangarei Harbour. Shaded cells indicate those where estimates of r were significant ($p<0.05$).

Site	Variable	r	t	p
Town Basin	NNN	0.69	2.33	0.06
	NH_4	0.70	2.39	0.05
	DRP	0.83	3.62	0.01
	Turbidity	0.74	2.71	0.04
	Secchi depth	-0.30	-0.76	0.48
	Suspended solids	0.44	1.21	0.27
Kaiwaka Point	NNN	0.00	0.00	1.00
	NH_4	0.03	0.08	0.94
	DRP	-0.85	-3.93	0.01
	Turbidity	0.10	0.26	0.81
	Secchi depth	0.18	0.40	0.71
	Suspended solids	-0.14	-0.35	0.74
Mair Bank	NNN	0.46	1.28	0.25
	NH_4	0.70	2.42	0.05
	DRP	-0.01	-0.03	0.98
	Turbidity	NA	NA	NA
	Secchi depth	-0.36	-0.95	0.38
	Suspended solids	0.28	0.71	0.50

3.2.2. Kerikeri Inlet

Time series

Correlation analyses between all of the time series parameters and tide height were statistically significant, which is primarily due to the large sample size and likely co-variation between tide height and time of day (Figures 6 through 8; Table 7). Review of time series data over a 1-day period at the three sites in Kerikeri Inlet reveal that some parameters, such as salinity at Wainui Island and Windsor Landing, and pH at Wainui Island were influenced by tides (Figures 7 and 8). An effect of tides on turbidity was not apparent at the Waipapa River site (Figure 6); however, slight increases in turbidity occurred during incoming tides at the Wainui Island site located further from the River (Figure 7).

Despite some co-variation in tides and time of day (*e.g.* see Figure 7 when low tide occurred during the night and DO and water temperature was lowest), patterns in DO and water temperature appear to have been driven by time of day (solar radiation inputs).

As was the case for Whangarei Harbour, discrete surface water measurements for some of the parameters using a hand-held YSI did not always agree with data collected by the Sondes, which were moored 0.5 to 1.0 m beneath the surface. Measurements at the surface of the water reveal data consistent with more buoyant low-salinity water near the surface. Similarity in salinity between the discrete measurements using the hand-held instrument and time series at Wainui Island (Figure 7) suggests that the large deviation in turbidity measurements at this site may be associated with instrument error.

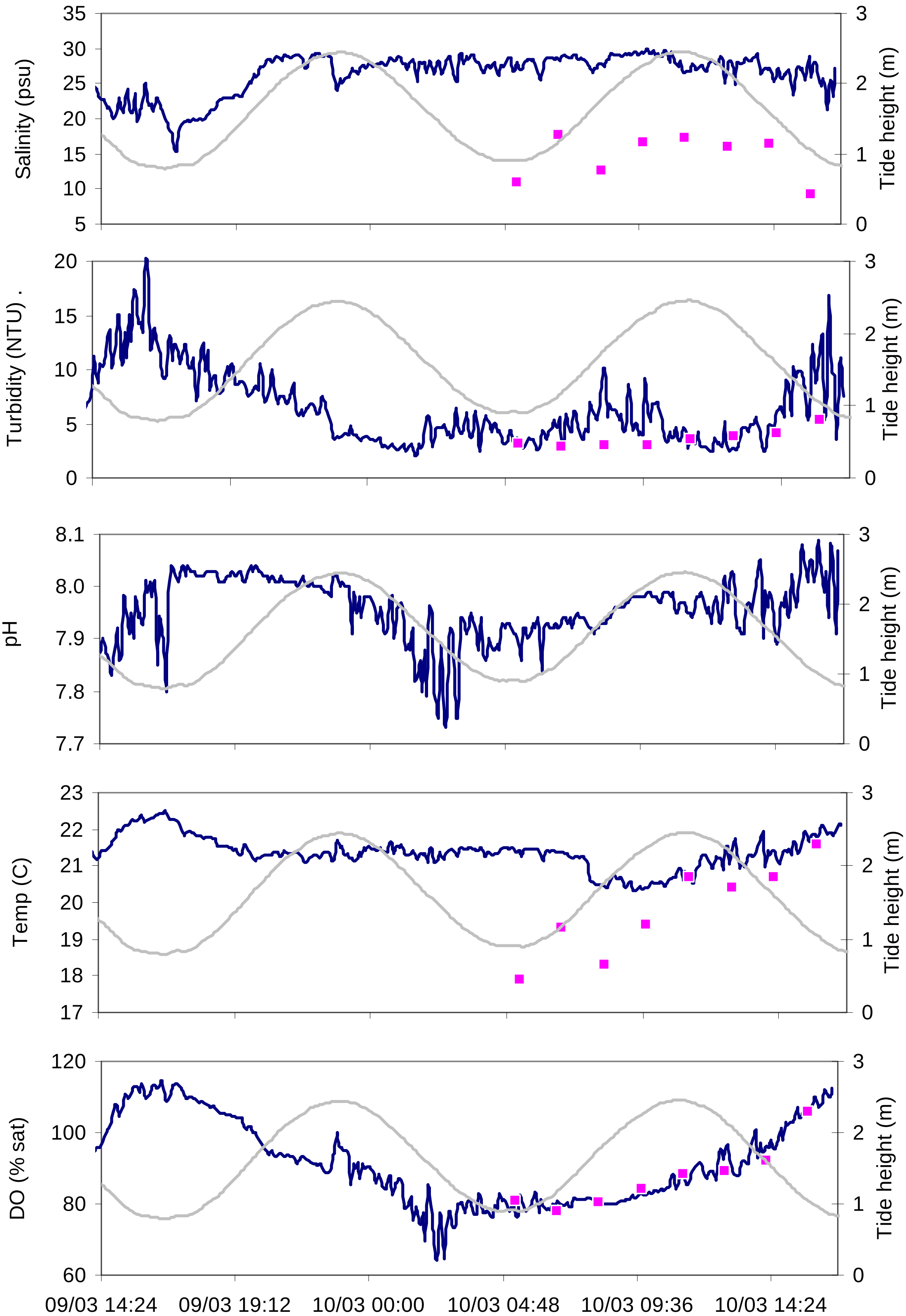

Figure 6. Time series of water quality parameters measured at the Waipapa River site and tide height in Kerikeri Inlet. Also shown are results from the eight discrete measurements (pink squares) collected during the water quality sampling.

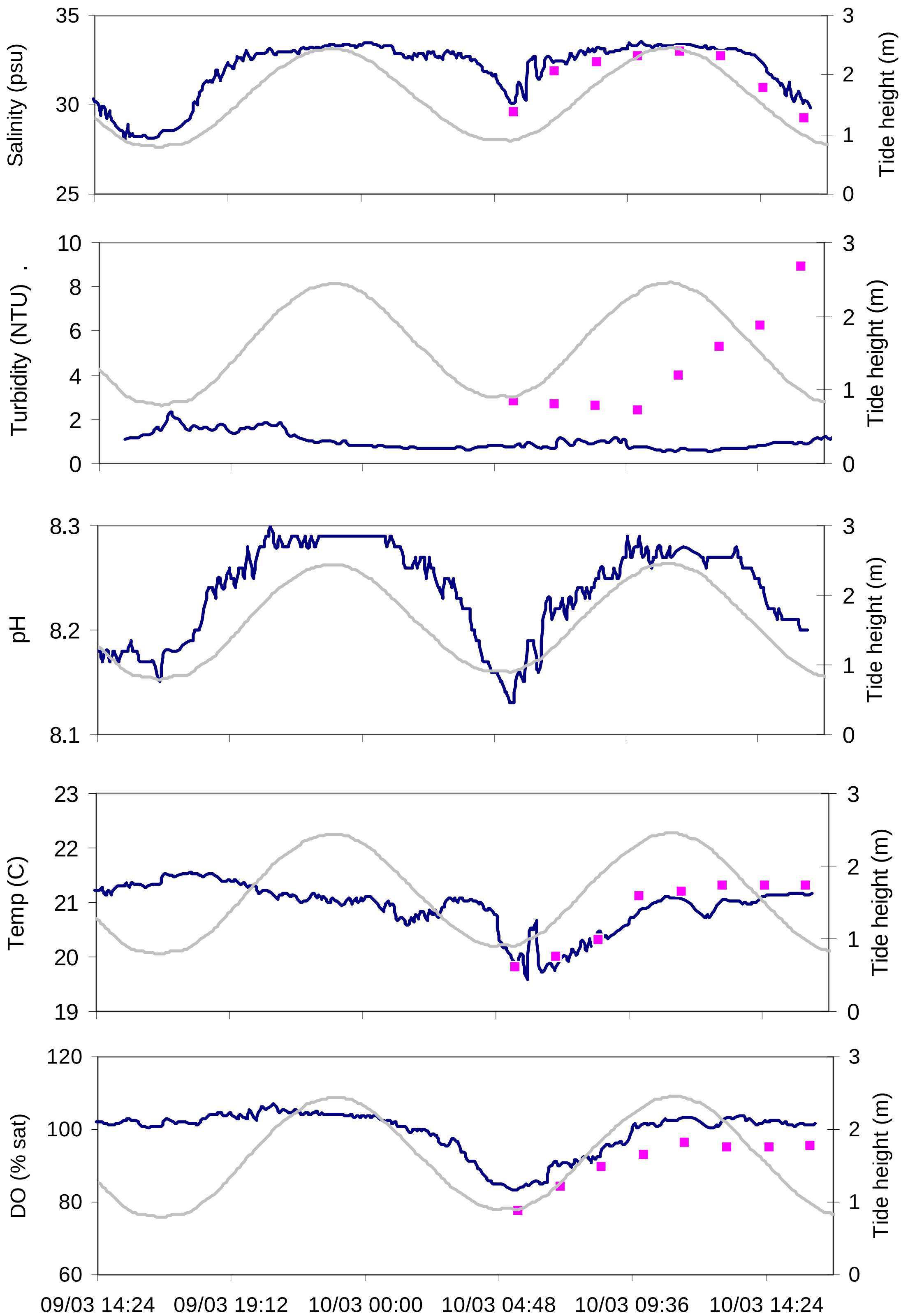

Figure 7. Time series of water quality parameters measured at the Wainui Island site and tide height. Also shown are results from the eight discrete measurements (pink squares) collected during the water quality sampling.

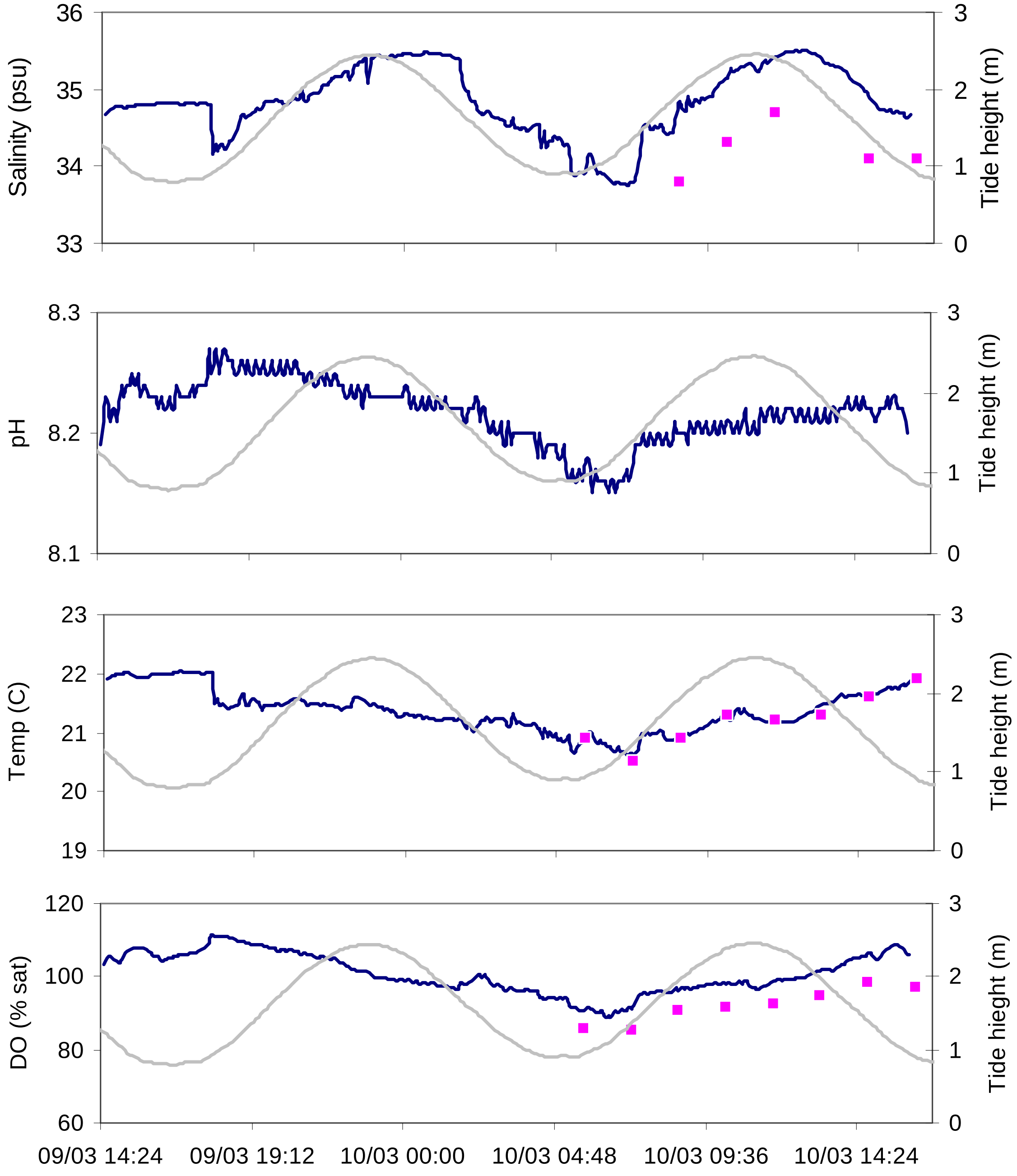

Figure 8. Time series of water quality parameters measured at the Windsor Landing site and tide height. Also shown are results from the eight discrete measurements (pink squares) collected during the water quality sampling.

Table 7. Correlation coefficients (r) for water quality parameters versus tide height based on time series data for sites sampled in Kerikeri Inlet. Also shown are t statistics and p values.

Site	Parameter	r	t	p
Waipapa River	Salinity	0.56	11.88	<0.001
	Turbidity	-0.50	-10.19	<0.001
	pH	0.19	3.34	<0.001
	Temperature	-0.64	-14.60	<0.001
	DO (% sat)	-0.33	-6.10	<0.001
Wainui Island	Salinity	0.76	19.30	<0.001
	Turbidity	-0.18	-3.14	<0.001
	pH	0.88	30.27	<0.001
	Temperature	0.03	0.55	<0.001
	DO (% sat)	0.50	9.57	<0.001
Windsor Landing	Salinity	0.73	18.36	<0.001
	pH	0.16	2.77	<0.001
	Temperature	-0.20	-3.57	<0.001
	DO (% sat)	-0.13	-2.24	<0.001

Field sampling

Significant correlations between parameters and tide height were observed for suspended sediments at the Waipapa River site, and dissolved nutrients and water clarity (secchi depth) at the Wainui Island site (Table 8; Figure 9). Although not statistically significant, patterns in suspended sediments and water clarity also appear to follow the tide at the Windsor Landing site. Suspended sediments and water clarity tended to be lower and higher, respectively, at high tide than during periods of low tide (Figure 9).

Nutrient concentrations were generally low for all sites, with the exception of elevated nitrate+nitrite nitrogen (NNN) at the Waipapa River site, which likely reflects the proximity of the site to river discharges draining a catchment that is largely agricultural. Enterococci concentrations at the Waipapa River site were highest in the morning and during low tide and were lower (near detection limits) during the period of high tide. There was an increase in enterococci at the Windsor Landing site during mid-morning and coinciding with high tide. This site is located near the entrance of the estuary and a designated mooring area (see Appendix); hence it is possible that localised sources (*i.e.* moored vessels) may be contributing to periodic contamination events at the Windsor Landing site.

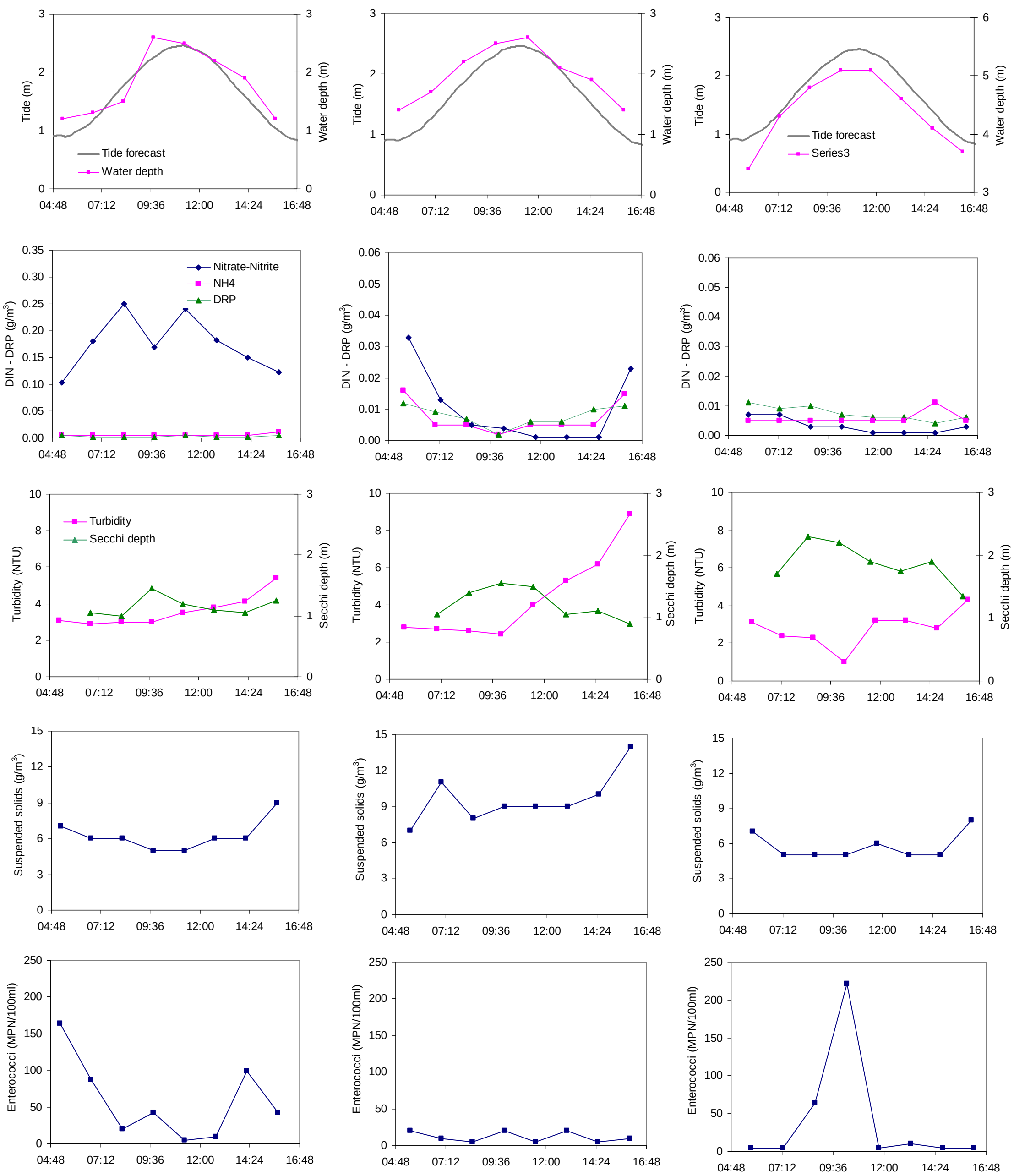

Figure 9. Predicted tide height and measured water depth (top row) (top row), dissolved nutrients (second row), turbidity and secchi depth (third row), suspended sediments (fourth row) and enterococci concentrations (bottom row). Columns are arranged according to sites (left-Waipapa River, middle, Wainui Island, right-Windsor Landing). Note that the Y-axis is different between sites for dissolved nutrients.

Table 8. Correlation coefficients (r) for water quality parameters measured at eight points in time versus tide height (see Fig. 7) for sites sampled in Kerikeri Inlet; r values indicated in bold were significant ($p<0.05$).

Site	Parameter	r	t	p
Waipara River	NNN	0.69	2.33	0.06
	NH_4	-0.43	-1.16	0.29
	DRP	-0.28	-0.72	0.50
	Turbidity	-0.24	-0.60	0.57
	Secchi depth	0.32	0.76	0.48
	Suspended solids	-0.76	-2.85	0.03
Wainui Island	NNN	-0.84	-3.72	0.01
	NH_4	-0.80	-3.22	0.02
	DRP	-0.91	-5.22	0.00
	Turbidity	-0.32	-0.84	0.43
	Secchi depth	0.83	3.39	0.02
	Suspended solids	-0.35	-0.91	0.40
Windsor Landing	NNN	-0.55	-1.61	0.16
	NH_4	-0.18	-0.45	0.67
	DRP	-0.22	-0.54	0.61
	Turbidity	-0.57	-1.68	0.14
	Secchi depth	0.72	2.35	0.07
	Suspended solids	-0.61	-1.91	0.11

3.2.3. Kaipara Harbour - Otamatea River

Time series

Of the three estuaries studied, water quality parameters measured at the Otamatea Channel sites were the most clearly influenced by tides. Review of time series data over a 1-day period reveal that some parameters such as salinity, turbidity and pH were strongly influenced by tides at the two sites (Figures 10 and 11), while others such as DO and water temperature were more closely linked to time of day (solar radiation inputs).

With the exception of turbidity and DO at the Wahiwaka Creek site and water temperature at the Te Hoanga Point site, correlation analyses between all of the time series parameters and tide height were statistically significant (Table 9). Although not significant based on a simple correlation of tide height versus turbidity, there was clearly an effect of tides on turbidity at the Wahiwaka Creek site (Figure 10). Increases in turbidity coincided with ebbing and flooding tides, which is consistent with resuspension occurring with increased current velocities. This same pattern was observed at the Te Hoanga site (Figure 11), although the levels of turbidity at this site were considerably lower than the Wahiwaka Site. As was the case at the Town Basin site in Whangarei Harbour, turbidity levels at the Wahiwaka site fluctuated above and below the guideline range of 5-10 NTU depending on tide conditions.

Discrete measurements at the surface using the hand-held YSI instrument generally agreed with the time-series data collected with the YSI Sondes. There was some variation between the two datasets which is likely associated with depth of sampling as was observed at the other study sites and possibly instrument error in the case of turbidity measurements (see Figure 11).

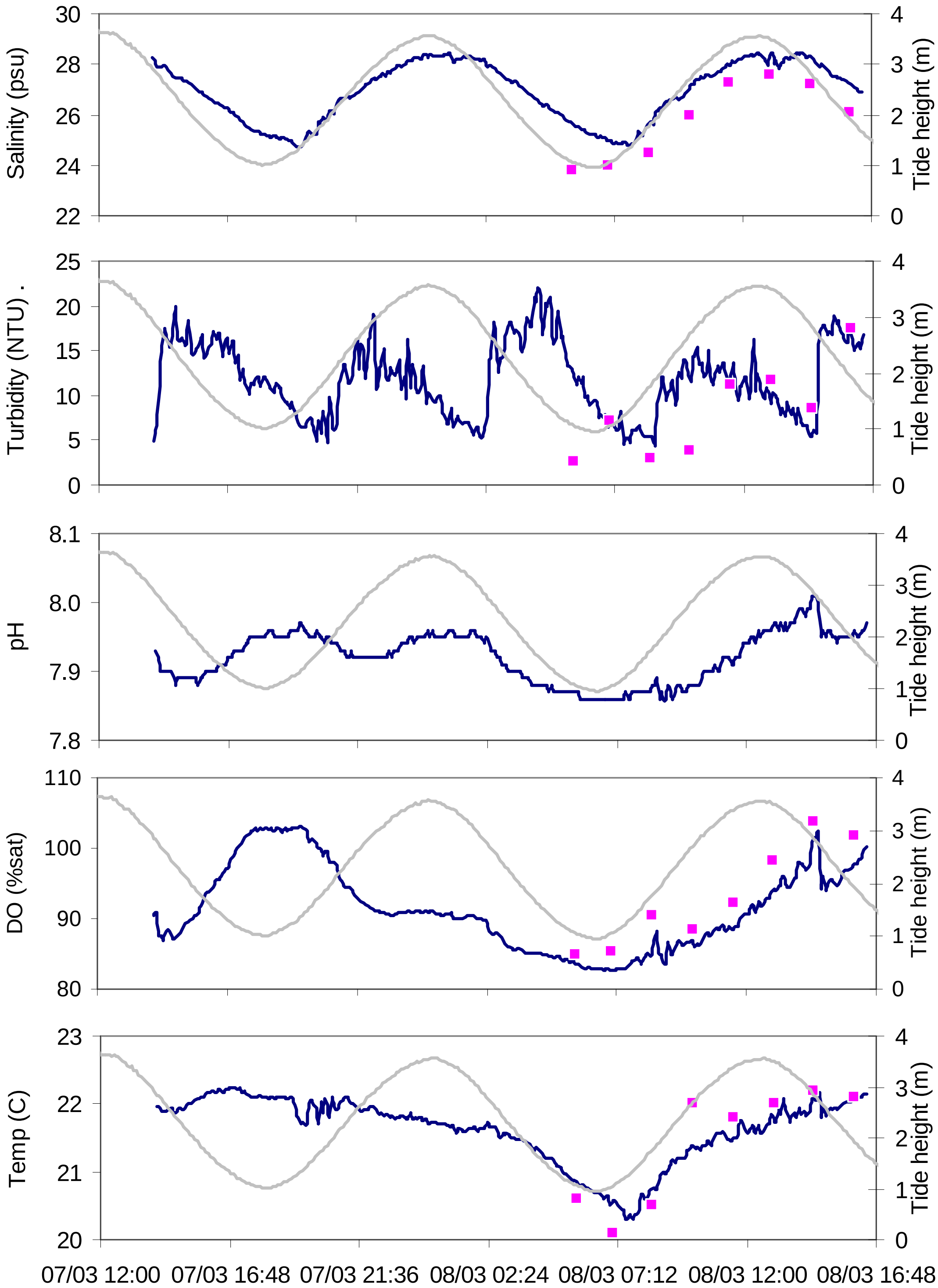

Figure 10. Time series of water quality parameters measured at the Wahiwaka Creek site and tide height. Also shown are results from discrete measurements (pink squares) collected during the water quality sampling.

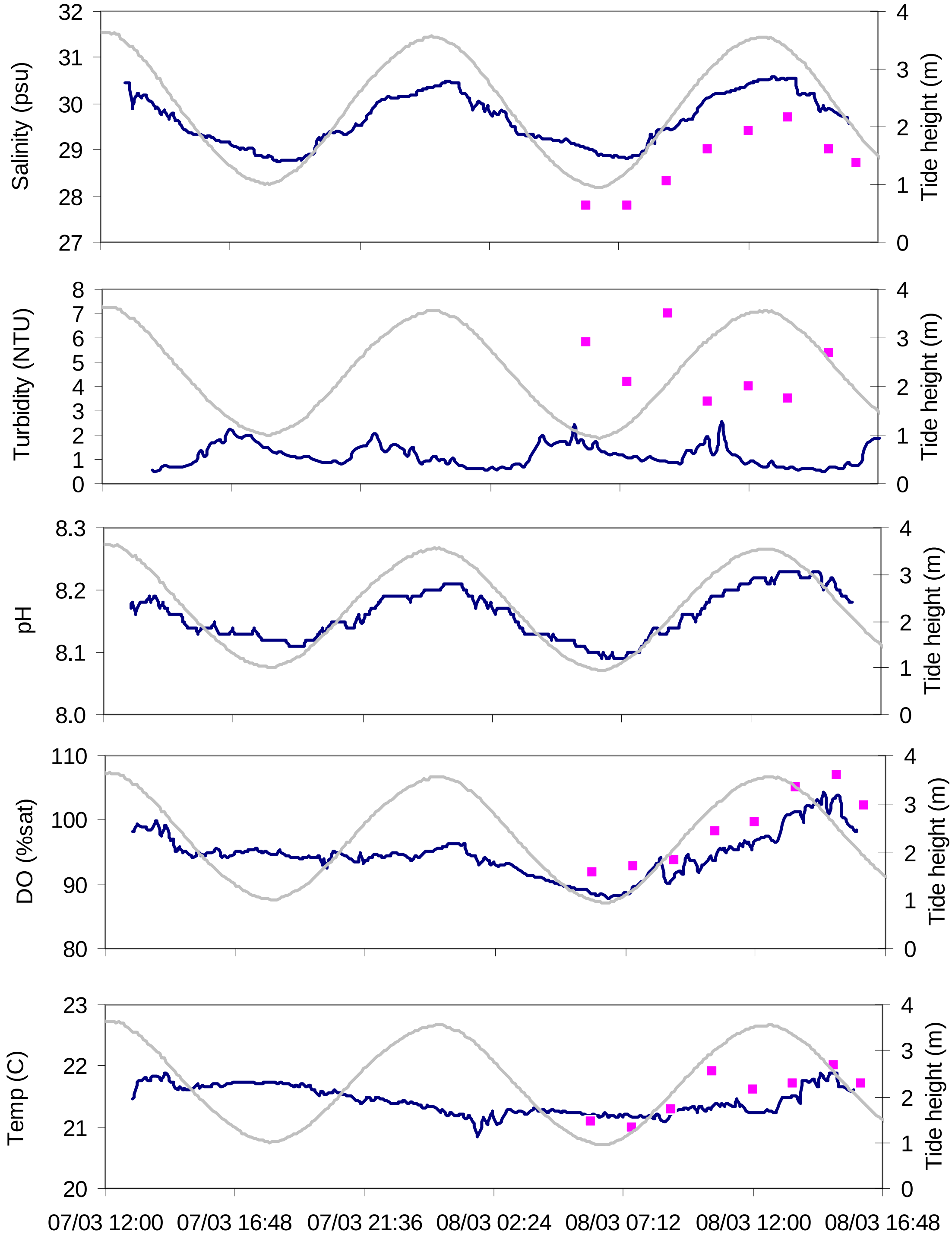

Figure 11. Time series of water quality parameters measured at the Te Hoanga Point site and tide height. Also shown are results from the eight discrete measurements (pink squares) collected during the water quality sampling. Note that the last measurement for turbidity (14.5 NTU) is not shown in order to maintain a scale for visualising time series data, which were considerably lower in absolute NTU values.

Table 9. Correlation coefficients (r) for water quality parameters versus tide height based on time series data for sites sampled in Otamatea River, Kaipara Harbour. Also shown are t statistics and p values.

Site	**Variable**	**r**	**t**	**p**
Wahiwaka River	Salinity	0.91	39.19	<0.001
	Turbidity	-0.07	-1.19	0.23
	pH	0.45	9.01	<0.001
	Temperature	0.26	4.69	<0.001
	DO (% sat)	-0.05	-0.87	0.39
Te Hoanga Point	Salinity	0.97	71.32	<0.001
	Turbidity	-0.39	-7.50	<0.001
	pH	0.92	41.38	<0.001
	Temperature	-0.09	-1.70	0.09
	DO (% sat)	0.59	12.99	<0.001

Field sampling

With the exception of DRP at both sites and Secchi depth at the Te Hoanga site, there were no significant correlations between water quality parameters and tide height (Figure 12; Table 10). Although not statistically significant, there appears to have been similar effects on turbidity and suspended sediments consistent with observations made from time-series data for turbidity (peaks during flood or ebb tide). Enterococci concentrations at the two sampling sites were too low (≤ 10 MPN/100 ml) to assess effects of tides on FIB levels and therefore they were omitted from the figures and analysis.

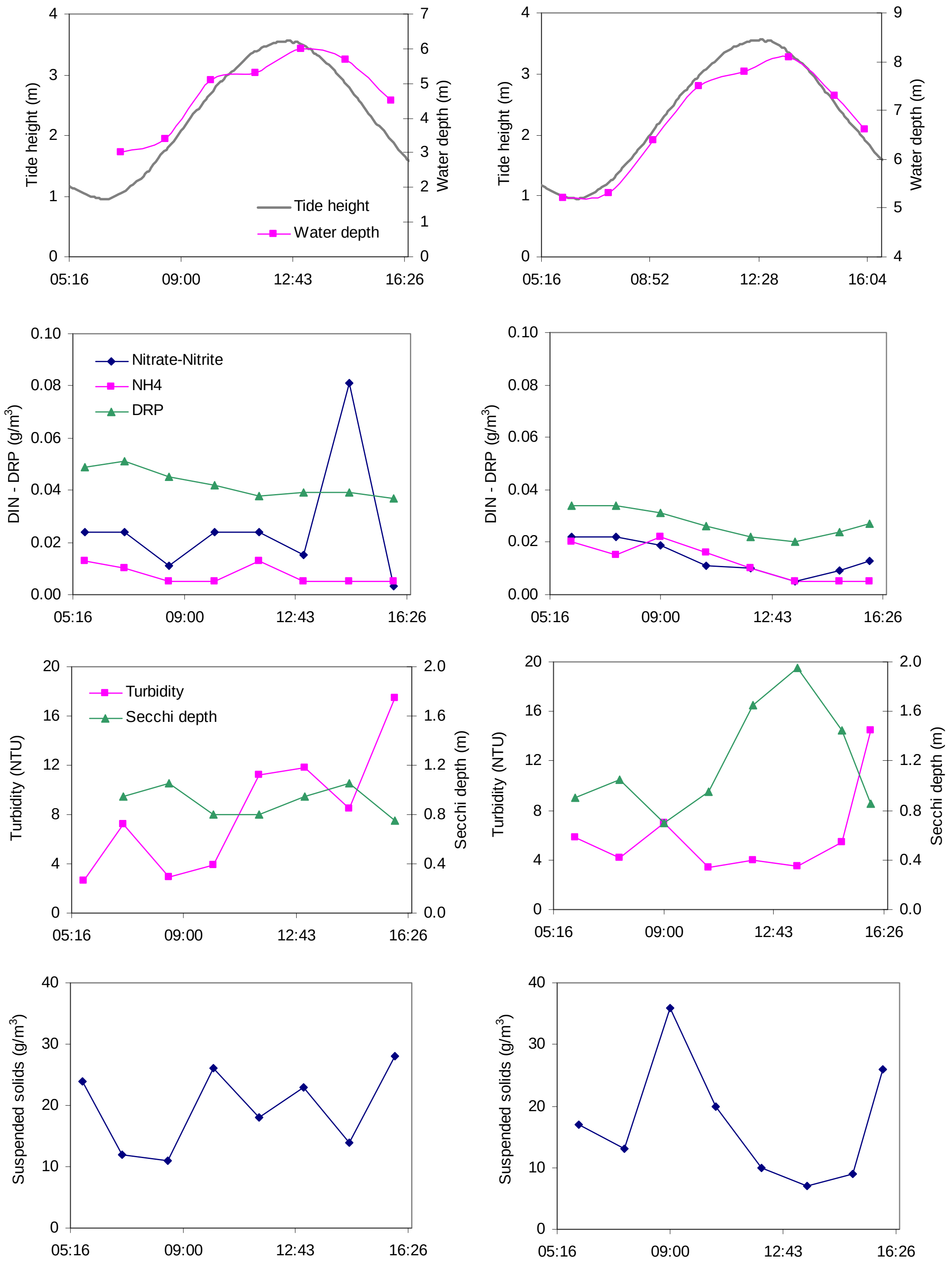

Figure 12. Predicted tide height and measured water depth (top row), dissolved nutrients (second row), turbidity and secchi depth (third row), and suspended sediments (bottom row). Columns are arranged by site (left-Wahiwaka Creek, right-Te Hoanga Point).

Table 10. Correlation coefficients (r) for water quality parameters measured at eight points in time versus tide height (see Figure 7) for sites sampled in Otamatea Channel, Kaipara Harbour. Values of r indicated in bold were significant ($p<0.05$).

Site	Parameter	r	t	p
Wahiwaka Creek	NNN	0.22	0.55	0.60
	NH4	-0.27	-0.70	0.51
	DRP	-0.81	-3.36	0.02
	Turbidity	0.38	1.01	0.35
	Secchi depth	-0.15	-0.34	0.75
	Suspended solids	0.16	0.40	0.70
Te Hoanga Point	NNN	-0.89	-4.83	0.00
	NH4	-0.48	-1.35	0.23
	DRP	-0.93	-6.27	0.00
	Turbidity	-0.34	-0.89	0.41
	Secchi depth	0.70	2.39	0.05
	Suspended solids	-0.35	-0.91	0.40

4. ANALYSIS OF HISTORICAL WATER QUALITY DATA

Historical (2000-2011) water quality data for 16 sites in Whangarei Harbour and 10 sites in Kaipara Harbour were provided by NRC. Tide data were extracted from the Land Information New Zealand (LINZ) Tide Predictions tool (http://www.linz.govt.nz/hydro/tidal-info/tide-tables) and then interpolated to acquire tide heights that matched each time interval when parameters were measured.

All data for each parameter across all sites were first pooled and analysed using correlation analysis. Due to the variability in data between sites, there were no significant correlations between tide height and water quality variables in either the Whangarei or Kaipara Harbour datasets. This result indicates that location within the estuary will have a larger effect on the overall results for an estuary than tides.

When data was separated according to site, there were few cases where parameters were significantly correlated with tide height at sites within either of the two estuaries (Tables 10 and 11). No one parameter (*e.g.* nutrients, DO, turbidity) was consistently correlated to tide height across all sites. However, some sites such as Limeburners in Whangarei Harbour and Five Fathoms in Kaipara Harbour appear to be affected by tides with regard to water-column nutrients.

The overall low number of correlations is likely due in part to the difficulty in teasing out effects of tides using a relatively small and temporally coarse dataset. We were able to acquire a greater number of significant correlations when we incorporated lags (up to six hours) into the analysis, which essentially involved 'shifting' the time component in order to acquire a better fit between the variables. While this improved results, the lags varied considerably for each variable and between variables (between one and six hours); hence while fitting the data using time lags improved the results, it is unlikely the results accurately represent a functional relationship between tides and water quality parameters.

The results from this analysis combined with those from the field study indicate that the response of water quality parameters to tides varies considerably across sites and the parameters measured, and that the tide related processes that influence water quality may not be directly linked to tide height (*e.g.* the effect of ebbing and flooding tides on turbidity). Although tides can influence many of these parameters as demonstrated in the field study, the extent of effects will depend on a number of additional factors such as rainfall and time of day. These results also suggest that normalising an entire monitoring programme to tides is unlikely to markedly improve the ability to monitor changes over time.

Table 11. Correlation coefficients (r) for tide height and selected water quality parameters from historical data collected in Whangarei Harbour. Significant values are shaded. Samples sizes for each parameter at each site ranged between 13 and 102.

Site	DO%	DRP	NH_4	NNN	SECCHI	TURB	ENT	FC
Blacksmith Creek	0.17	-0.38	0.21	0.39	-0.52	0.04	-0.14	0.43
H & H Slipway	-0.03	-0.51	-0.32	-0.17	0.08	0.30	0.39	0.39
Kaiwaka Point	0.06	-0.43	0.05	0.23	-0.27	0.21	0.16	-0.07
Kissing Point	0.18	-0.68	-0.46	-0.28	0.10	0.02	0.02	-0.08
Limeburners	0.38	-0.71	-0.65	-0.54	0.22	0.18	0.03	-0.11
Mair Bank	0.20	-0.38	0.09	0.45	0.14	0.16	-0.05	-0.11
Mangapai River	0.55	-0.03	0.07	0.53	0.17	0.28	0.44	0.11
Mid town basin	0.08	0.10	0.07	0.36	-0.35	0.18	0.16	0.00
NZRC Jetty	0.21	-0.31	0.25	0.45	0.11	0.16	-0.04	0.08
One tree point	0.31	-0.33	0.19	0.40	0.26	0.00	0.35	0.39
Onerahi Sea Scouts	0.16	-0.20	0.18	0.46	0.44	-0.11	0.38	0.52
Port Marker H26	-0.13	0.23	0.03	0.36	-0.15	0.39	0.28	0.15
Port Whangarei	0.09	-0.49	-0.26	-0.10	0.10	0.36	0.43	0.31
Portland	0.24	0.18	0.12	0.48	0.63	-0.46	0.37	0.47
Snake Bank	0.14	-0.35	0.26	0.25	0.11	-0.39	0.34	0.23
Tamaterau	0.05	-0.43	0.16	0.29	0.51	-0.25	-0.07	-0.08

Table 12. Correlation coefficients (r) for tide height and selected water quality parameters from historical data collected in Kaipara Harbour. Significant values are shaded. Samples sizes for each parameter at each site ranged between 14 and 31.

Site	DO%	DRP	NH_4	NNN	TURB	ENT
Oruawharo River	-0.25	0.53	0.08	-0.24	0.43	-0.07
Hargreaves Basin	-0.10	-0.05	-0.13	-0.66	0.73	0.08
Wahiwaka Creek	0.03	-0.31	0.04	0.00	0.34	0.00
Wahiwaka Creek	0.03	-0.31	0.04	0.00	0.34	0.00
TeHoanga Point	0.22	-0.43	-0.15	-0.03	0.05	-0.11
Te Kopua	-0.30	0.07	-0.29	-0.26	0.08	-0.11
Kapua Point	-0.32	0.33	-0.25	-0.34	0.10	-0.14
	0.04	-0.20	-0.28	-0.82	0.08	-0.01
FiveFathom Channel	-0.10	-0.50	-0.49	-0.73	0.00	-0.32
Otamatea Channel	0.08	0.02	-0.37	-0.46	0.43	-0.44

5. SUMMARY OF FINDINGS AND RECOMMENDATIONS

Tides can influence water quality parameters measured as part of routine water quality monitoring. Variability due to tides is likely driven by differences between the concentrations of contaminants (*e.g.* nutrients, suspended solids) in freshwater entering estuaries and incoming oceanic water. In addition, increased current velocity and sediment resuspension during ebbing and flooding tides also contributes to patterns observed in water clarity and turbidity.

While tides may influence some parameters such as nutrients and turbidity, others such as water temperature and DO are influenced to a greater degree by solar radiation inputs and therefore vary as a function of the time of day rather than tides. The field study demonstrated that small differences in the depth at which samples are collected (surface (0 – 0.3 m) vs. 0.5-1.0 m depth) within estuaries can also lead to variability in water quality data.

Based on a statistical analysis of historic datasets of water quality parameters in the Kaipara and Whangarei Estuaries, we found relatively weak correlations for only ~10% of the cases examined across all sites and parameters. This indicates that there are likely a range of factors other than just tides influencing water quality data, including differences in antecedent rainfall, cloudiness, time of day, and wind conditions. It is also likely that the datasets are of insufficient size and sampling frequency to fully tease apart the effects of tides.

For the purpose of SoE Monitoring, we would not recommend altering the current sampling programme to minimise variability due to tides. However, it is recommended (if not already done so) that sampling occurs at a consistent time of day (preferably in the morning hours) to minimise variability in parameters such as dissolved oxygen and FIB that are strongly influenced by solar radiation inputs. Ideally water samples would be collected at a comparable tide height; however this is logistically difficult and would likely not markedly improve the ability to assess changes in water quality conditions over time. Nonetheless, knowledge of the effects of tides on water quality parameters is required when interpreting results over time within the context of guideline compliance. For example, replicate field sampling over a tide cycle demonstrated that in some cases the value of turbidity and dissolved nutrients can fluctuate above and below maximum guideline standards as a function of tide stage. Hence in those cases where guideline values are exceeded, knowledge of the potential influence and stage of the tide at a sampling site, perhaps through more detailed sampling, will assist in interpreting results.

There are additional parameters that may assist in linking water quality data with land-based activities. For instance, determination of organic and inorganic fractions of suspended sediments within water samples may assist in understanding contributions of terrestrial versus marine sources of particulates. Measures of coloured dissolved organic matter (yellow substance) either in discrete water samples, or using deployed optical sensors, can also provide information on the contribution of terrestrial inputs to the coastal zone. The application of microbial source tracking markers would assist in providing information on the dominant sources of faecal contamination in areas where FIB are historically high.

In order to better understand temporal variability within a given estuary, the deployment of logging sensor(s) (either on a periodic or preferably permanent basis) at a designated SoE monitoring location (*e.g.* mid estuary) is recommended. Sensors for obtaining time-series measurements of basic water quality parameters such as salinity, temperature, turbidity and chl *a* are becoming more reliable and affordable and would facilitate interpretation of data collected as part of water quality sampling programmes. The monitoring programme for the U.S. National Estuarine Research Reserve System provides an example of the standardised integration of time series instrumentation and water sampling programmes in multiple estuaries (www.nerrs.noaa.gov).

In the absence of deployed sensors, higher frequency sampling events (such as the sampling conducted in this study) are required to quantify and more fully understand the role of tides and other factors such as rainfall in driving variability in the data. Examples of high frequency sampling events conducted as a component of routine monitoring can be found at (www.nerrs.noaa.gov). Another possible approach that has been used to inform water quality monitoring programmes is to conduct a 'snapshot' that involves high spatial and temporal sampling over the course of the same day each year or perhaps a 'first flush' day that involves sampling directly after a major rain event (*e.g.* see www.montereybay.noaa.gov).

In addition to field sampling, a cost-effective 'desktop' approach to understanding spatial and temporal variability in water quality conditions as a function of drivers such as tides and rainfall events is the analysis of satellite imagery. Such analysis allows the examination of patterns in near-surface turbidity, water temperature and levels of chl *a* under varying physical conditions (Hellweger *et al.* 2004).

6. ACKNOWLEDGEMENTS

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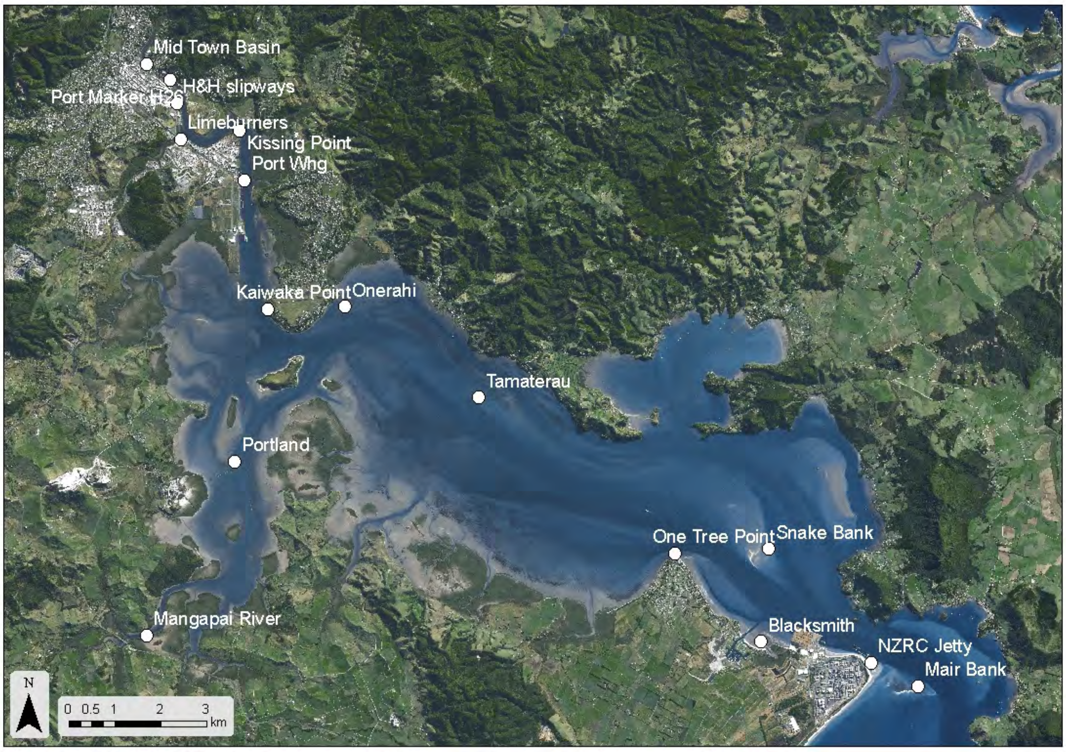
8. APPENDIX

8.1. Study site descriptions (Provided by NRC)

Whangarei Harbour



Whangarei Harbour (Latitude 35^{o}48'S, Longitude 174^{o}26' E) is a drowned river valley system located on the east coast of the Northland peninsula The harbour covers an area of approximately 10,000 ha and includes 5,400 ha of intertidal flats, 1,400 ha of mangroves and 200 ha of saltmarsh (Morrison 2003). The harbour is connected to Bream Bay, a large coastal embayment, via a relatively narrow inlet approximately 0.8 km wide, between Marsden Point and Lort Point. The main channel extends inland approximately 24 km in a westerly direction and then divides into two arms, the Hatea River in the north and the Mangapai River in the south.

The harbour drains a catchment of 29507 ha and the land use in the catchment has been heavily modified, with a considerable proportion of the catchment cleared for urban use in the north west of the catchment, and agricultural land use in the east and south. GIS catchment analysis using the land use classification from the New Zealand Land Cover Database (LCDB2) indicated that in 2001, 49% (14541 ha) of the catchment was covered by high producing exotic grassland, for cattle and dairy farming, 10% (3006 ha) with plantation forestry, 10% (2933 ha) with urban land uses, and 20% (5903 ha) with indigenous forest.

The city of Whangarei, located on the banks of the Hatea River is the regional capital of Northland and had an estimated population of 51,100 in June 2008 (Statistics New Zealand 2008).

Sample Sites
Site 100211 Town Basin

The site is located at of the northern end of the Hatea River arm of the Harbour. The site is located in the main channel, which flows through the Town Basin Marina. The Town Basin and surrounding tidal creek system has been heavily modified by drainage, channelisation and reclamation for urban, industrial and infrastructure development. The Town Basin itself is a man made feature, and was dredged to create a Marina facility. The Whangarei waste water treatment system discharges into Limburners creek, which joins the Hatea River approximately 2 km downstream of the Town Basin

Site 100200 Kaiwaka Point
The site is located in the Hatea River arm of the Harbour just before the river connects to the Harbour. The Whangarei waste water treatment system discharges into Limburners creek, which joins the Hatea River approximately 5.5 km upstream of Kaiwaka Point.

Site 100190 Mair Bank
The site is located at the entrance of the Harbour.

Kerikeri Inlet

Kerikeri Inlet (35°12'S 174°59'E) is located on the east coast of the Northland peninsula and covers an area of 1132 ha. The main axis of the Inlet, Pickmere Channel, extends inland approximately 7 km in a westerly direction. At the western end of the Inlet, the channel forks into 2 arms, the Kerikeri River and the Waipapa River, which together drain the majority of the catchment. The estuary is connected to the Bay of Islands, a semi protected coastal environment, through an opening approximately 1 km wide.

The Inlet drains a catchment of 21157 ha, and the land cover in the catchment was been heavily modified with a considerable portion of the catchment cleared for agricultural land use. Geographic information system (GIS) catchment analysis using the land use classification from the New Zealand Land Cover Database (LCDB2) indicated that in 2001 52% (10938 ha) of the catchment was covered by high producing exotic grassland, for cattle and dairy farming, and 18% (3875 ha) was used for horticulture. Plantation forestry accounted for a further 12% (2484 ha), with native forest covering just 6% (1344 ha) of the total catchment.

Sample Sites
Site 101526 Waipara River
The site is located in the Waipapa River arm of the Inlet just before the river joins the main Channel. The channel is relatively narrow.

Site 101544 Wainui Island
The site is located at the western end of Wainui Island, approximately 3 km from the Waipara River site and 8 km from the entrance of the Inlet.

Site 105707 Windsor Landing
The site is located 2.5 km from the Wainui site and 2 km from the entrance of the Inlet at the eastern, near the southern shoreline of the Inlet in a mooring area on the southern shore of the Inlet. Two live-aboard vessels were present in the mooring area at the time of the tidal experiment.

Otamatea River

The Otamatea River (36^{o}25'S 174^{o}13'E) is located on the west coast of the Northland peninsula. The River is part of the Kaipara Harbour system, a large estuarine system extending over 95000 ha. The main channel of the River extends inland approximately 12 km in a north easterly direction before splitting into two arms, the Wairau River and the Kaiwaka River.

The Otamatea River drains a catchment of 14003 ha, and the land cover in the catchment was been heavily modified with a considerable portion of the catchment cleared for agricultural land use. Geographic information system (GIS) catchment analysis using the land use classification from the New Zealand Land Cover Database (LCDB2) indicated that in 2001 78% (10890 ha) of the catchment was covered by high producing exotic grassland, for cattle and dairy farming, with native forest covering just 13% (1788 ha) of the total catchment.

Sample Sites
Site 109665 Wahiwaka Creek
Wahiwaka Creek, is located at the northern eastern end of the Otamatea River, approximately 1.5 km meters before the channel, forks into the Wairau River and the Kaiwaka River. The Maungaturoto and kaiwaka waste water treatment plants discharge into the Wairau River and the Kaiwaka River respectively. The Fonterra Maungaturoto Plant discharges into the Otamatea River, approximately 800 m upstream of the site.

Site 109666 Te Hoanga Point
Te Hoanga Point is located towards the south western end of the Otamatea River, approximately 9km downstream fo Wahiwaka Creak and 2 km before the Arapaoa River joins the Otamatea River.