New Zealand Coastal Water Quality Assessment Update

Prepared for Ministry for the Environment

May 2018

Prepared by:
Bruce Dudley
Charlotte Jones-Todd

For any information regarding this report please contact:

Bruce Dudley
Hydrologist
+64-3-3411 2842
bruce.dudley@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

NIWA CLIENT REPORT No: 2018096CH
Report date: May 2018
NIWA Project: MFE18501

Quality Assurance Statement		
	Reviewed by:	John Zeldis
	Formatting checked by:	Fenella Falconer
	Approved for release by:	Helen Rouse

Contents

Tables

Figures

Executive summary

As part of Environment Aotearoa 2019, the synthesis report in development by The Ministry for the Environment (MfE) and Statistics New Zealand, the MfE commissioned NIWA to collate and analyse trends in existing coastal water quality data gathered by the 16 regional and unitary authorities up until December 31, 2017. These trend analyses use methods as close as possible to those in the recent report for MfE 'New Zealand Coastal Water Quality Assessment' (Dudley et al. 2017).

This report includes brief methods used for data processing, trend analysis and data presentation and a concise summary of national-scale trends. Supplementary files include plots with site-specific 10- and 12-year trend data, and a spreadsheet with spatial data and results of the water quality trends analyses for every site that met our criteria for sampling duration and frequency.

Trends in water quality were examined over two-time scales: 2008-2017 (up to 156 sites considered) and 2006-2017 (up to 138 sites considered). Trends in water quality from 2006-2017 were calculated from a smaller dataset than those from 2008-2017 because fewer sites were sampled as far back as 12 years and filtering rules excluded more sites from the analyses.

Over both 2006-2017 and 2008-2017, most sites where time trends could be confidently detected showed improving trends in nutrients and faecal pollution. Exceptions to this were ammonia/ammonium (NHXN) and total nitrogen (TN), which showed concentration increases at substantially more sites than decreases over the last 10 years. Temperature showed increases in many more sites than decreases over both 10- and 12-year time periods.

We emphasise that site distribution maps included in this report should be consulted when interpreting trends at national scale. There are regional differences in the physical geography of New Zealand coastal hydrosystems and consequently regional differences in water quality. Also, there are large gaps and unevenness in site coverage nationally, and spatial coverage was further fragmented by data filtering rules applied to trend analyses. Lack of spatial representativeness in this dataset has likely created bias in derived national trends. There is also regional inconsistency in sampling methods across the dataset such as inconsistency in time of sampling with respect to tidal state, which has created some regional bias in the analyses. Because of these representativeness issues, the state and trend results in this report appear to be most appropriate as 'case study' indicators of coastal water quality (as defined by Statistics New Zealand[1]).

[1] http://www.stats.govt.nz/browse_for_stats/environment/environmental-reporting-series/environmental-indicators/Home/About.aspx#topics (accessed 31/10/16).

1 Introduction

The Ministry for the Environment (MfE) commissioned NIWA to collate and analyse coastal water quality data gathered by the 16 regional and unitary authorities to provide temporal trends across New Zealand over the last 10 and 12 years, up to December 31, 2017. The report consists of a brief outline of methods for data processing and analysis, and a concise summary of trends for sites nationally where sufficient data exist. The methods for data management and analysis used in the current study follow as closely as possible those used in recent national-scale coastal water quality reporting (Dudley et al. 2017). While concise methods are provided in this study, the reader is referred to chapters 2 and 3 of that report for detailed methodology including criteria for the selection of variables.

In this report, as in Dudley et al. (2017), our trend analysis tests the *direction* of a trend rather than the existence of a trend. If the direction of a trend cannot be confidently inferred, the result is stated as "insufficient data to reveal the trend direction", rather than "not statistically significant". This procedure prevents the common misinterpretation of a trend test result that fails to attain statistical significance when testing the "nil hypothesis"—that conditions are "stable" or "being maintained". If a trend direction can be inferred, we go on to report its magnitude. Subsequently the importance of a trend may be determined by estimating time to reach a recognised threshold toward which concentrations may be heading, such as a regulatory 'bottom line'.

The report is accompanied by several files: a file of all data compiled from councils, site-specific trend results in Microsoft Excel format, associated metadata for data files, and trend analysis plots for each site.

2 Data acquisition, organisation and processing

New Zealand regional and unitary councils carry out water quality monitoring at > 400 open coastal and estuarine sites (Figure 2-1). For the monitoring sites used in this report, monthly or quarterly monitoring has been underway for 10 to 35 years. A variety of physical, chemical and biological variables are measured at these sites to meet the regional environmental reporting requirements of each council. In addition, water quality monitoring has been carried out by Invercargill City Council (ICC) since 1976 at sites in the New River Estuary, and ICC sampling methods have remained unchanged since 1991. Recognising the high quality of the ICC data and the paucity of other coastal water quality data from Southland, Westland and Otago, we included the ICC data from 1991 to present in this study. In this section we describe the water quality variables, data sources and organisation of the coastal water quality data, and explain the data processing procedures used to derive datasets suitable for trend analyses.

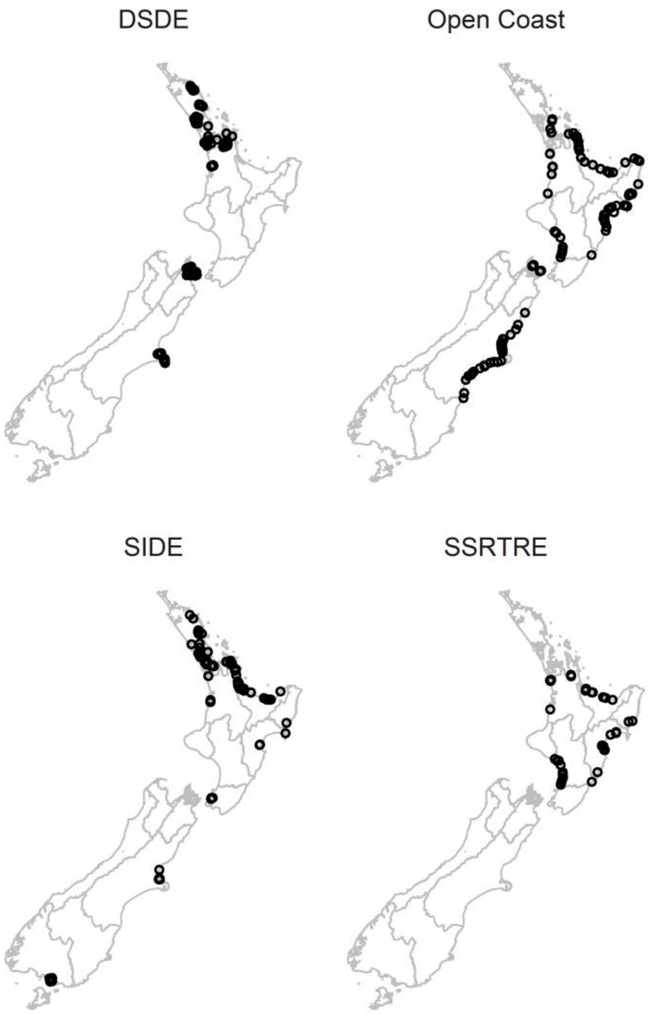

Figure 2-1: Locations of all coastal monitoring sites in water quality datasets provided by councils. The legend gives the New Zealand Estuarine Trophic Index (ETI) classification of the site. Classifications are: deep subtidal-dominated estuaries (DSDEs) shallow intertidal-dominated estuaries (SIDEs), shallow, and short residence-time tidal river estuaries (SSRTREs). See section 3.2 for classification rationale.

2.1 Variable selection for analysis of trends in coastal water quality

We described coastal and estuarine water quality using fifteen variables that correspond to physical, chemical and microbiological conditions (Table 2-1). In this report, we use "coastal water quality" as a general term to refer to some or all of the fifteen variables. Unless otherwise stated, we made no distinction between data collected at regional council sites and ICC sites. Brief rationale for the inclusion of these variables in analyses is included below, and further details are available in Dudley et al. (2017).

Table 2-1: Coastal water quality variables included in this study.

Variable type	Variable	Abbreviation	Units	Values addressed (rationale)
Physico-chemical	Dissolved oxygen	DO	mg/L	Ecosystem health
	pH	PH	pH units	Ecosystem health (local and global change)
	Salinity	SAL	parts per thousand	Ecosystem health ('master' variable measuring freshwater content)
	Temperature	TEMP	degrees Celsius	Ecosystem health (global change)
Optical	Visual clarity (Secchi)	CLAR	m	Ecosystem health; Recreation
	Turbidity	TURB	NTU	Ecosystem health (Proxy for visual clarity or suspended particle concentration; continuously measurable)
	Suspended solids	SS	mg/L	Ecosystem health; Recreation
Nutrients	Ammoniacal nitrogen	NHXN	mg/L	Ecosystem health
	Nitrate-nitrite nitrogen	NOXN	mg/L	Ecosystem health
	Total nitrogen (unfiltered)	TN	mg/L	Ecosystem health
	Dissolved reactive phosphorus	DRP	mg/L	Ecosystem health
	Total phosphorus (unfiltered)	TP	mg/L	Ecosystem health
Microbiological	Faecal coliforms	FC	n/100 mL	Recreation; Shellfish aquaculture
	Enterococci	ENT	n/100 mL	Recreation; Shellfish aquaculture
	Chlorophyll-*a*	CHLA	mg/L	Ecosystem health

Dissolved oxygen (DO) is the oxygen concentration in water, and is influenced by oxygen supply and oxygen consumption taking place in water and sediments that are in contact with shallow water. High DO values can reflect high primary production or aeration relative to respiration. Low values can be indicative of high rates of decomposition of organic material in sediments and waters, and may result in reduced species diversity and faunal biomass (GESAMP 2001). Salinity (SAL) was included because salinity data are needed to assess freshwater content of coastal waters. Water temperature (TEMP) was included because temperature controls rates of biochemical reactions plus equilibria (e.g., DO saturation) and for assessing climate change. We have included pH data because decreases in pH result from sequestration of atmospheric CO_2, and may also reflect more local scale processes caused by eutrophication (Cai et al. 2011). However, in coastal waters interactions between DO, dissolved nitrogen, and dissolved inorganic carbon and their responsiveness to temperature, acidification and eutrophication make it difficult to assign a cause to observed changes in pH (Hewitt et al. 2014). We note also that while the accuracy of the pH method used in this study is likely to be insufficient to detect recent changes in New Zealand's open ocean, e.g., an annual change of 0.0013 ±0.0003 in Southern Ocean waters (Law, Bell et al. 2018). It may however be valuable for detecting changes in trophic state driven by eutrophication, e.g., a shift from pH 8.1 in the oligotrophic outer waters of the Firth of Thames to pH 7.9 in the mesotrophic inner Firth (Law, Bell et al. 2018).

The optical variables provide information on the transmission of light through waters. Reductions in visual water clarity (CLAR) result from light attenuation due to absorption and scattering by dissolved and particulate material in water. Turbidity (TURB) measured with an optical sensor (nephelometer) is an index of side-scatter from a beam of light transmitting through the water sample. Visual clarity and turbidity are monitored because the attenuation of light in waters (and with depth in the water column) affects primary production, plant and animal distributions and ecological health, aesthetic quality and recreational values (Davies-Colley et al. 2003). Suspended solids (SS) are a major cause of both reduced visual clarity in water and reduced light penetration with depth through the water column (Gall et al. *in review*). Suspended solids include organic matter (e.g., phytoplankton, or fine particles of decomposing plant matter), and inorganic matter (e.g., inorganic sediment from terrestrial erosion). High suspended sediment concentrations are associated with estuarine and coastal sedimentation, reduced light levels in benthic environments and reduced feeding rates and health of estuarine and coastal animals (Lowe et al. 2015).

The five nutrient species (NOXN, NHXN, DRP, TN and TP) were included because they influence aquatic primary production - the growth of benthic microalgae (periphyton), photosynthetic bacteria, phytoplankton, macroalgae, and aquatic vascular plants. This is because phosphorus (P) and particularly nitrogen (N) are the nutrients that are in shortest supply relative to demand by aquatic primary producers during spring and summer in temperate coastal waters, including in New Zealand (Hanisak 1983). Hence, increases in the availability of these nutrients are associated with increased primary production. Estuaries and open coasts are mixing zones for nutrients that originate in fresh and marine water, which can increase the availability of multiple nutrients (Sharp 1983). In severe cases, nutrient loading in coastal mixing zones results in proliferations of aquatic primary producers that can, in turn, degrade estuarine and coastal habitat, cause water colour and odour problems, and may be toxic to consumers, including humans (GESAMP 2001, Karez et al. 2004). There are two or more methods in use to measure concentrations of some nutrient species, and not all methods give comparable results. Some data obtained by non-comparable analytical techniques/methods were excluded from the analyses (see Section 2.4).

Enterococci (ENT), and faecal coliform (FC) bacteria are included as their abundances indicate recent faecal pollution and the possible presence of human faecal pathogens in coastal waters. Hence, they represent the risk of infectious disease from waterborne pathogens; ENT is collected by councils as an indicator of the suitability of water for contact recreation and FC as an indicator of the suitability for gathering shellfish. Chlorophyll-*a* (CHLA) is a measure of phytoplankton biomass. In coastal waters, high CHLA concentrations may occur during periods of high nutrient loading or upwelling of nutrients from deeper ocean waters, and CHLA is a primary indicator of eutrophication.

2.2 Data acquisition and organisation

Data requests to regional councils and ICC were based on variables included for analyses in Dudley et al. (2017). We requested measurements of the variables included in that study from the beginning of systematic coastal water quality monitoring to the present day. Water quality data were supplied by 10 of the 16 regional councils and unitary authorities and by ICC. Abbreviations of council names used in the report are as follows: NRC - Northland Regional Council, AC – Auckland Council, WRC - Waikato Regional Council, BOPRC - Bay of Plenty Regional Council, GDC - Gisborne District Council, HBRC - Hawke's Bay Regional Council, HRC - Horizons Regional Council, GWRC - Greater Wellington Regional Council, MDC - Marlborough District Council, CRC – Canterbury Regional Council, ICC – Invercargill City Council. We requested data up to and including dates in December 2017.

2.3 Data processing

The raw coastal water quality data provided by councils varied widely in reporting formats, reporting conventions for variable names, site identifiers, date and time formats, units of measurement, and other data structure elements. We imported the datasets into the statistical software 'R', and applied a consistent set of reporting conventions matching those reported in Dudley et al. (2017). Analysing and formatting the database in R allowed us to attach information to individual data points. This information included flags for censored data, unit conversions (e.g., from µg/L to mg/L), and quality codes. Our final database had 420 sites, consisting of 411 regional council sites plus nine ICC sites in the New River Estuary.

In addition to water quality data, the following spatial data were associated with each monitoring site: Regional Council ID, regional council site identification code, site names (if available), NZTM grid reference, and site notes. After compiling the site data, each site was assigned a unique identifier.

Water quality data were processed in several steps to ensure that the data were accurate and the datasets used for analyses were internally consistent. These steps match those described in detail in Dudley et al. (2017) but are briefly described here:

<u>Step 1. Comparable field and laboratory methods.</u> The first data processing step was to assess methodological differences for all variables. For many variables, two or more measurement procedures were represented in the datasets. Table 2-2 lists the most common procedures used for each variable, and the procedures corresponding to data retained for analysis. This table differs from table 2 in Dudley et al. (2017) only in that both secchi disc and black disc clarity (CLAR) measurements have been included for analysis in this study, based on advice received since the publication of that report (Pers. Com. R. Davies-Colley, NIWA, April 2017).

<u>Step 2. Error correction and adjustment.</u> The second data processing step was to manually inspect the data, and correct identifiable errors. We used quantile plots to identify and remove gross outliers for each variable. Where necessary, values were adjusted to ensure consistent units of measurement across all datasets.

<u>Step 3. Censored and substituted values</u>. The final data processing step concerned censored and substituted values. For several water quality variables, some values were too low (or, occasionally, too high) for laboratories to measure with precision, and these are traditionally reported as less than a "detection limit", even though this amounts to 'censoring' (of information) because the laboratories do have an (imprecise) estimate. Cases where values of variables are below the detection limit or above the reporting limit are often indicated by the data entries "<DL" and ">RL",

where DL and RL are the laboratory detection limit and reporting limit, respectively. In some cases, the censored values had been replaced (by the monitoring agency) with substituted values to facilitate statistical analyses. Common substituted values are 0.5 × detection limit and 1.1 × reporting limit. Water quality datasets from New Zealand often include DRP and NHXN measurements that are below detection limits, and occasional ECOLI and CLAR measurements that are above reporting limits. Although commonly used, replacement of censored values with constant multiples of the detection and reporting limits can result in misleading results when statistical tests are subsequently applied to those data (Helsel 2012). Data that we received that were composed of censored and substituted values were replaced with imputed values using procedures identical to those described in Dudley et al. (2017).

Table 2-2: Measurement procedures for water quality variables. Procedures retained: data generated by the procedures in this column, and corresponding monitoring sites, were retained for analysis in this study.

Variable type	Variable	Measurement procedures	Procedures retained
Physico-chemical	DO	In situ, automatic profilers, surface water grab-samples, DO measured on boat or in helicopter from surface water	Both procedures (presumed to give comparable results)
	PH	APHA 4500-H B. Surface water pH measurement using handheld meter	APHA 4500-H B. Surface water measurement using handheld meter
	SAL	Handheld digital salinometer in surface water. Method APHA 2520 B	Handheld digital salinometer in surface water. Method APHA 2520 B
	TEMP	Glass mercury/alcohol thermometer Handheld digital water quality meter (e.g., YSI)	Both procedures (presumed to give comparable results)
Optical	CLAR	Black-disk Secchi-disk	Both procedures (presumed to give comparable results)
	TURB	Hach turbidity meter. Method APHA 2130 B	Hach turbidity meter. Method APHA 2130 B
	SS	Gravimetric determination of total suspended solids	Gravimetric determination of total suspended solids
Nutrients	NHXN	Filtered. Phenyl/hypochlorite colorimetry	Filtered. Phenyl/hypochlorite colorimetry
	NOXN	Nitrate-N, filtered, Ion chromatography Nitrate-N + nitrite-N (or "NNN"), filtered, cadmium reduction. Nitrate + Nitrite-N – Nitrite-N (filtered, Azo dye colourimetry)	All procedures (NO_3^- used when NNN unavailable; nitrite presumed to be negligible in unpolluted water)
	TN	Unfiltered, persulfate digestion Filtered, measured as dissolved inorganic+organic nitrogen	Unfiltered, persulfate digestion Sample filtered, filtrate N measured as dissolved inorganic+organic

Variable type	Variable	Measurement procedures	Procedures retained
		Sample filtered, filtrate N measured as dissolved inorganic+organic nitrogen, added to mass of N in filtered solids Unfiltered, by Kjeldahl digestion (TKN + NNN)	nitrogen, added to mass of N in filtered solids. Unfiltered, by Kjeldahl digestion (TKN + NNN)
	DRP	Filtered, molybdenum blue colourimetry	Filtered, molybdenum blue colourimetry
	TP	Unfiltered, persulfate digestion Unfiltered, nitric acid/hydrogen peroxide digestion. Filtered, measured as dissolved inorganic + organic phosphorus	Unfiltered, persulfate digestion
Microbiological	FC	Membrane filtration (APHA 9222D) Multiple tube (APHA 9221E)	Both procedures (presumed to give comparable results)
	ENT	Multiple tube (APHA 9230B) Membrane filtration (APHA 9230C) Fluorogenic Substrate Enterococcus Test 'Enterolert' (APHA 9230D)	All procedures (presumed to give comparable results)
	CHLA	Acetone pigment extraction, spectrofluorometric measurement. In situ and laboratory fluorometry	Acetone pigment extraction, spectrofluorometric measurement

3 Analysis methods

3.1 Censored values

We used a three-step process to impute replacements for censored values. For comparative purposes we also performed equivalent analyses using the traditional substitution rules (i.e., left censored values substituted with values corresponding to one half the reported laboratory detection limit and right censored values increased by 10%). Detailed description of each step is available in Dudley et al. (2017).

<u>Step 1. Left-censored data</u>. We manipulated "less than" data using ROS (Regression on Order Statistics) to impute replacement values (Helsel 2012).

<u>Step 2. Right-censored data</u>. The right-censored data in our datasets were limited to field CLAR (Secchi depth) measurements limited by shallow water, and ENT and FC measurements that exceeded the value which laboratories could measure on their chosen dilutions (they should have retained sufficient sample for re-testing at a higher dilution.) All right-censored data were replaced with values estimated using a procedure based on "survival analysis" (Helsel 2012).

<u>Step 3. Striping</u>. In some cases, laboratory results for low nutrient concentrations were reported on a semi-discrete scale (e.g., 1-2 decimal places), resulting in horizontal lines on plots of water quality variable versus time, or "striping". These stripes correspond to tied data, which can pose problems for trend analyses, such as producing trends with slopes of exactly zero. Replacement of these tied values by imputation of randomised ROS values is inappropriate, because the striped concentrations are not the result of censoring. Instead, we "jittered" these results about their reported values to minimise the occurrence of ties. The jittering procedure is not applied to any previously imputed values and only considers duplicated values, i.e., where more than one instance of the same number is reported for each variable at each site. For these duplicated numbers a small (<2% of value), randomly selected number is either added to or subtracted from the reported value.

3.2 Grouping sites

Open coastal, fjord, and estuarine monitoring sites were grouped into classes to aid the explanatory power of trend analyses. Classifications were made according to the typology used in the New Zealand Estuary Trophic Index (ETI) (Zeldis et al. 2017). These classifications are designed to reflect the susceptibility of hydrosystems to eutrophication resulting from nutrient loading, and may account for some variation in water quality associated with environmental heterogeneity. The ETI rationale for hydrosystem classification is based on dilution, retention and loss of inflowing nutrients. For a given rate of nutrient loading, eutrophication is more likely to occur when dilution is low, and retention and uptake of nutrients within the hydrosystem are high.

The definitions of the classes match those given in Dudley et al. 2017, and Robertson et al. 2016 with the exception that the classification system for the ICOLL class in the more recent versions of the ETI has changed (Zeldis et al. 2017). Intermittent opening and closing of an estuary is not a classification metric according to Zeldis et al. (2017). This resulted in two sites in estuaries previously termed ICOLLs in Dudley et al. (2017) being subsumed into the SSRTRE estuary class in this report. In all other cases where sites had previously been assigned an ETI classification by Dudley et al. (2017), we used the classification assigned in that study. Where data received from councils came from a site not recorded in Dudley et al. (2017) we used the classification methods of that study, as detailed below.

The ETI typology is informed by depth, water residence time, inflow/estuary volume and intertidal area, we used hydrological and geographical information from the Coastal Explorer database (Hume et al. 2007) to inform our decisions when classifying sites. For classification of borderline/transitional sites we compared hydrological and geographical data and Estuarine Environment Classification (EEC) class (Hume et al. 2007) to the draft "New Zealand Hydrosystems Classification" (NZCH) class descriptions (Hume 2016). We then compared NZCH class descriptions to the corresponding ETI class according to Hume (2016). As the ETI typology is focussed on estuarine systems it does not cover open coastal locations included in council monitoring programmes. In this report we have grouped sites that did not conform to an ETI class (those sites with mean salinity > 30, indicating that freshwater content was low, and on exposed coastlines with an angle between head of estuary and two outer headlands > 150°, indicating little or no shelter from oceanic swell) in a further class designated as 'Open Coast'.

Both the ETI and NZCH projects recognise that many coastal hydrosystems, particularly the large ones, contain areas that are more suitably described as subtypes of the larger system (Hume 2016). An example of this are the shallow inner arms of the Waitemata Harbour; while the Waitemata harbour system meets the ETI classification of a Deep Subtidal Dominated Estuary (DSDE) based on mean depth and intertidal area, the northern inner arms contain extensive tidal flats more suitably classified as Shallow Intertidal Dominated Estuaries (SIDEs). Based on recommendations in the ETI, we grouped sites within large hydrosystems that fitted different ETI class descriptions according the classification appropriate at the finer scale.

3.3 Trend analyses

3.3.1 Sampling dates and time periods for trend analyses

Trend analysis is only meaningful for a specified time period over which the dataset being analysed has few missing values. The datasets provided by the regional councils had variable starting and ending dates, variable sampling frequencies (monthly or quarterly), and variable numbers of missing values. We used time periods of 10 and 12 years as selected by MfE but note that these time periods result in trade-offs between the number of qualifying sites (i.e., sites that met our filtering rules concerning missing and censored values) and the duration of the time period. Variations in site numbers with duration for each variable are presented graphically in Section 4. We assessed trends using monthly data preferentially, and quarterly data when monthly data were not available, provided the filtering rules were met.[2] We applied two filtering rules to identify the sites to be included in trend analyses for each water quality variable: 1) 80% of the sampling dates in each of 80% of the years in a trend period had to have observations. For all variables, the rule about 80% of sampling dates applied to monthly or quarterly samples. 2) The number of censored values in a trend period had to be < 15% of the total number of observations, following the recommendation of Helsel (1990). We note that sites with many non-detects (i.e. regularly low concentrations of analytes) will be disproportionately excluded from trend analyses unless detection limits at these sites are lower. These filtering rules match those used in Dudley et al. (2017).

[2] Note that as in Larned et al. (2015), quarterly sampling will more commonly give rise to the finding of "insufficient data to detect trend direction".

3.3.2 Statistical trend analyses

Our statistical methods for trend analysis exactly follow those in Dudley et al. (2017). We used the approach of Larned et al. (2015) to draw inferences about trend direction; if a symmetric confidence interval around the trend (estimated using the Seasonal Sen Slope Estimator, SSSE) did not contain zero, then the trend direction was established with confidence. If it did contain zero, we concluded that there were insufficient data to determine the trend direction. For significant trends, in Larned et al. (2015), the "equivalence testing" procedure advanced by McBride et al. (2014) was extended to trend analyses to define trend importance using threshold-values of different water quality variables and critical time spans. This method used published guidelines, including attribute bands in the NPS-FM, as threshold-values for different water quality variables. In the absence of widely recognised thresholds or baseline conditions for New Zealand coastal water quality, when a trend direction was established with confidence our approach necessarily stopped short of assessing trend importance. In this study we present counts of sites at which positive and negative trend directions were established with confidence for each variable within each ETI class, and group these results according to trend magnitude. Our assessment method presents general change for each variable but leaves interpretation of the importance of these trends to later consideration.

We have interpreted decreasing concentrations of nutrients, ENT, FC, SS, CHLA, TURB and increases in CLAR, and DO as improving water quality. We have stopped short of classing trends in PH, SAL and TEMP as 'improving' or 'degrading' as we cannot say with confidence that trends in these variables reflect changes in ecosystem health. For example, eutrophication can cause both increases (e.g., in surface waters when photosynthesis increases) and decreases in pH of water (Cai et al. 2011). Salinity and temperature changes in estuaries may be caused by natural changes in flow patterns and movements in river mouth position and trends may be affected by long-term climate cycles (e.g., Interdecadal Pacific Oscillation (IPO)).

4 Results

4.1 Coastal water quality trends

4.1.1 Trade off analysis

The trade-offs between the number of qualifying monitoring sites (i.e., sites that met our filtering rules) and the time period represented by those sites are shown for each water quality variable in Figure 4-1. Trend periods of ten years (2008-2017) and 12 years (2006-2017) were used. The ten-year period coincided with the start of regular coastal water quality monitoring by some councils; for example, regular coastal water quality monitoring for a number of variables began at NRC and CRC in 2007. Multiple trends with different magnitudes and directions may be nested within the ten and 12-year trend periods which we do not resolve. Site-specific time-series plots are supplied as supplementary files to this report (Appendix A).

4.1.2 Ten-year trends (2008-2017)

Between 25 and 156 monitoring sites met the filtering rules for the ten-year trend analyses of the 15 water quality variables (Table 4-1). The qualifying sites were reasonably well-distributed geographically for some variables (such as TEMP), with gaps in the south of the North Island, and the South Island west coast (Figure 4-2). For other variables, such as CLAR, FC and ENT, sites that met the filtering rules were restricted to a small number of regions and ETI classes; these trends cannot be expected to be representative of national-scale trends.

Across the improving and degrading categories, almost all sites where trends could be confidently detected showed improving trends in TP, ENT, FC and DRP over the past ten years. There were also more sites with improving trends in SS, NOXN, CHLA and TURB than degrading trends. In contrast, there were a greater number of sites with degrading trends in NHXN and TN, and around three times as many sites with degrading trends in DO as improving trends. There were a greater number of sites with increasing trends in pH and TEMP, than decreasing trends. There were many sites and variables for which we could not confidently determine a trend direction. These data are summarised in Table 4-2. Trends grouped by ETI class are shown in Figure 4-3. For nutrient and microbiological variables that showed improvement at most sites (NOXN, TP, DRP, ENT and FC) these improvements appear relatively consistent in magnitude across ETI classes. Trend results partitioned by council are presented in Figure 4-4.

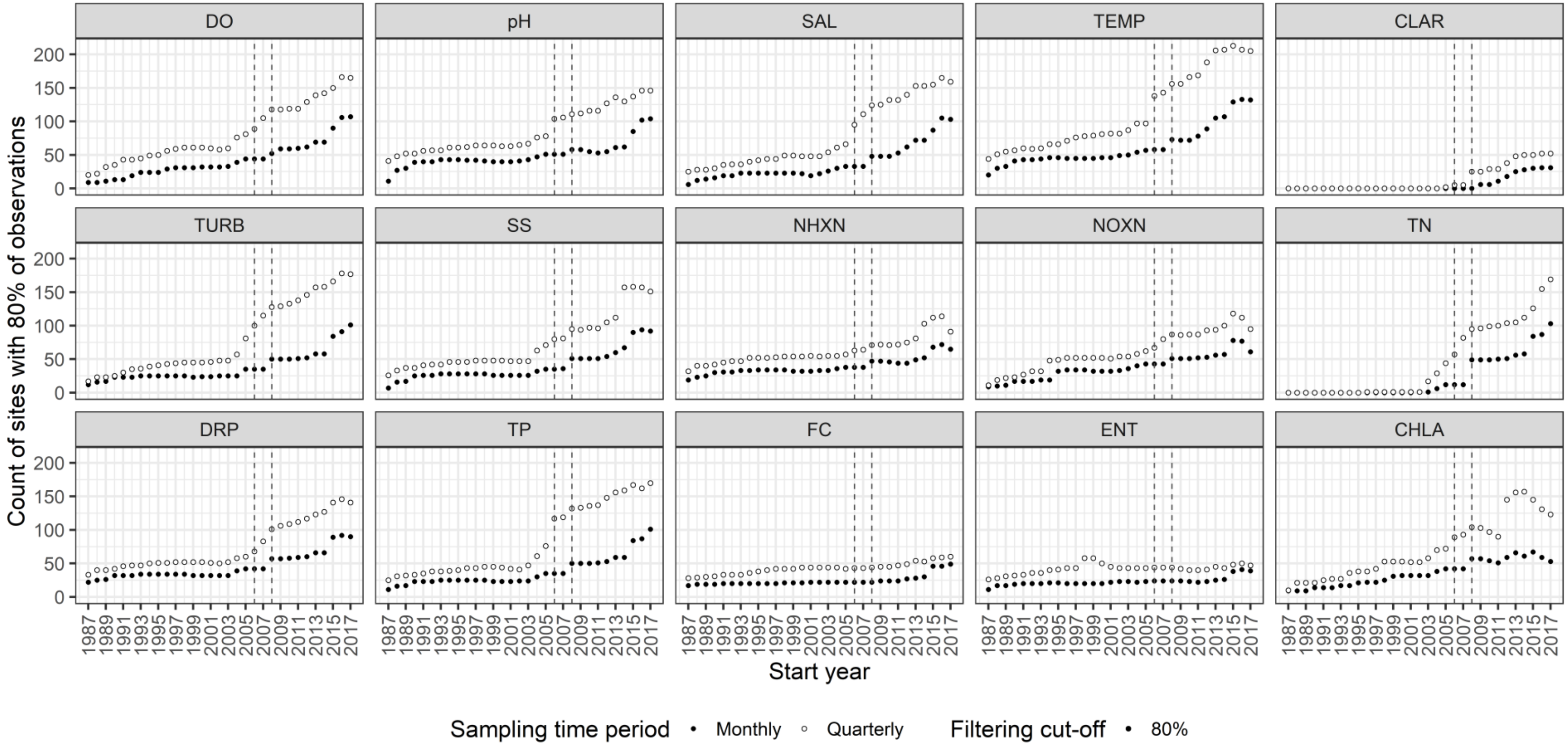

Figure 4-1: Changes in the number of monitoring sites that met the filtering rules for each water quality variable versus the period of site operation. Open circles: monthly data, filled circles: quarterly data. Dashed vertical lines give start dates of 10- and 12-year trend analyses in this report.

Table 4-1: Number of monitoring sites by ETI class and variable that were included in the 10-year trend analyses of water quality.The site numbers shown refer to sites where 80% of the sampling dates and seven of the years in the 2008-2017 period had observations, and less than 15% of the data for each variable consisted of censored values. Classification abbreviations are: shallow, short residence-time tidal river estuaries (SSRTREs), shallow intertidal-dominated estuaries (SIDEs), and deep subtidal-dominated estuaries (DSDEs). See section 3.2 for classification rationale.

Variable type	Variable	Total	ETI class			
			SSTRE	SIDE	DSDE	Open Coast
Physico-chemical	DO	118	6	51	23	38
	pH	111	7	39	47	18
	SAL	124	3	42	35	44
	TEMP	156	7	52	53	44
Optical	CLAR	25	0	5	2	18
	TURB	128	6	41	41	40
	SS	95	5	33	36	21
Nutrients	NHXN	71	4	43	10	14
	NOXN	87	5	47	20	15
	TN	95	5	33	35	22
	DRP	101	4	50	10	37
	TP	132	5	42	41	44
Microbiological	FC	44	5	24	15	0
	ENT	44	4	24	16	0
	CHLA	104	3	41	37	23

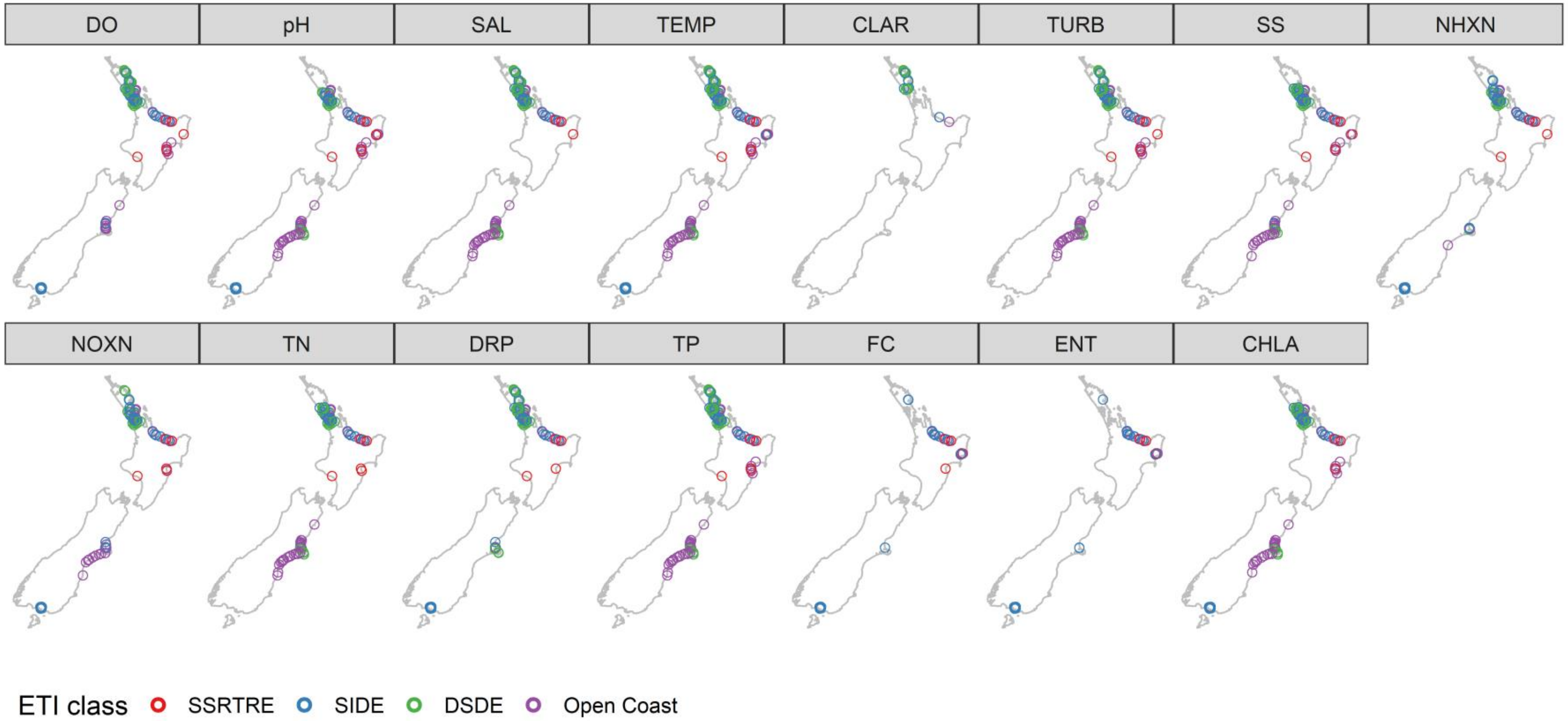

Figure 4-2: Locations of monitoring sites used for 10-year trend analyses of water quality variables. Legend gives ETI class of each site. Classification abbreviations are: shallow, short residence-time tidal river estuaries (SSRTREs), shallow intertidal-dominated estuaries (SIDEs), and deep subtidal-dominated estuaries (DSDEs). See section 3.2 for classification rationale.

Table 4-2: Numbers of sites in trend categories for 10-year trends across ETI classes. Decreasing concentrations of nutrients, ENT, FC, SS, CHLA, TURB and increases in CLAR, and DO can be interpreted as improving trends. Environmental degradation/improvement is not implied by trends in PH, SAL and TEMP (see methods). Insufficient data implies not enough data to reveal a trend direction (see Section 1 above).

Variable type	Variable	Magnitude of 10-year trend								Totals		
		Decreasing > 5% p.a	Decreasing 3 - 5% p.a	Decreasing 1 - 3% p.a	Decreasing 0 - 1% p.a	Increasing 0 - 1% p.a	Increasing 1 - 3% p.a	Increasing 3 - 5% p.a	Increasing > 5% p.a	Decreasing	Increasing	Insufficient data
Physico-chemical	DO	0	0	17	30	13	1	0	0	47	14	57
	pH	0	0	0	15	44	0	0	0	15	44	52
	SAL	2	1	2	33	6	3	2	0	38	11	75
	TEMP	0	0	6	4	55	2	0	0	10	57	89
Optical	CLAR	1	2	1	0	0	0	5	0	4	5	16
	TURB	19	10	3	0	1	8	3	3	32	15	81
	SS	35	4	3	0	0	6	9	1	42	16	37
Nutrients	NHXN	13	2	1	0	8	5	5	11	16	29	26
	NOXN	21	8	2	0	0	1	0	4	31	5	51
	TN	7	4	6	0	2	5	4	22	17	33	45
	DRP	26	9	12	1	0	3	2	2	48	7	46
	TP	52	26	16	1	0	1	2	1	95	4	33
Microbiological	FC	9	4	3	0	0	0	1	1	16	2	26
	ENT	10	4	3	1	0	0	0	1	18	1	25
	CHLA	21	12	3	0	0	2	2	1	36	5	63

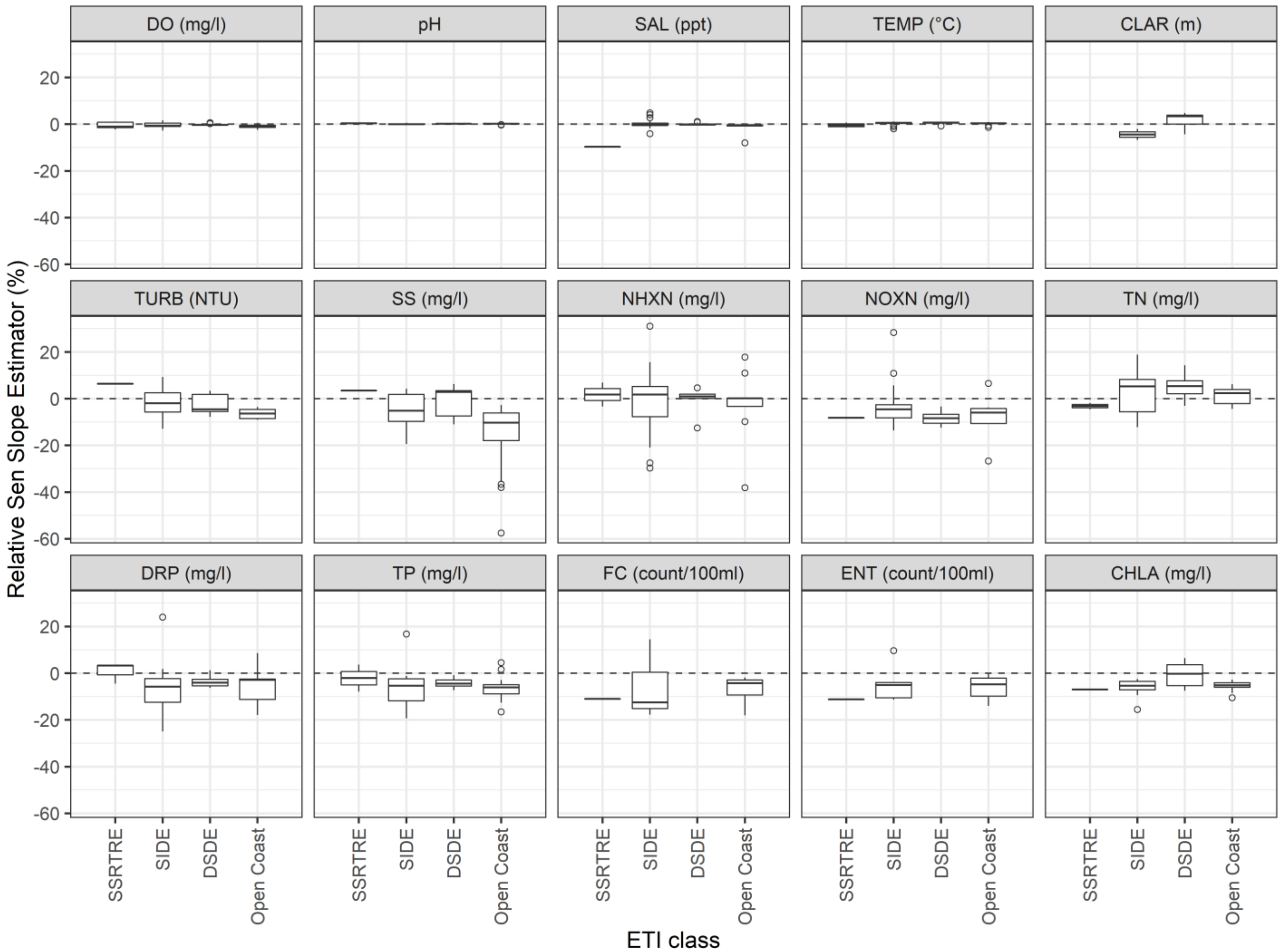

Figure 4-3: Summary of 10-year trends. Box-and-whisker plots show the distributions of site trends within ETI classes. The line within in each box indicates the median of site trends, the box indicates the inter-quartile range and the whiskers extend from the box to the largest value within 1.5 x the inter-quartile range. Outliers (any data beyond the whiskers) are indicated by open circles.

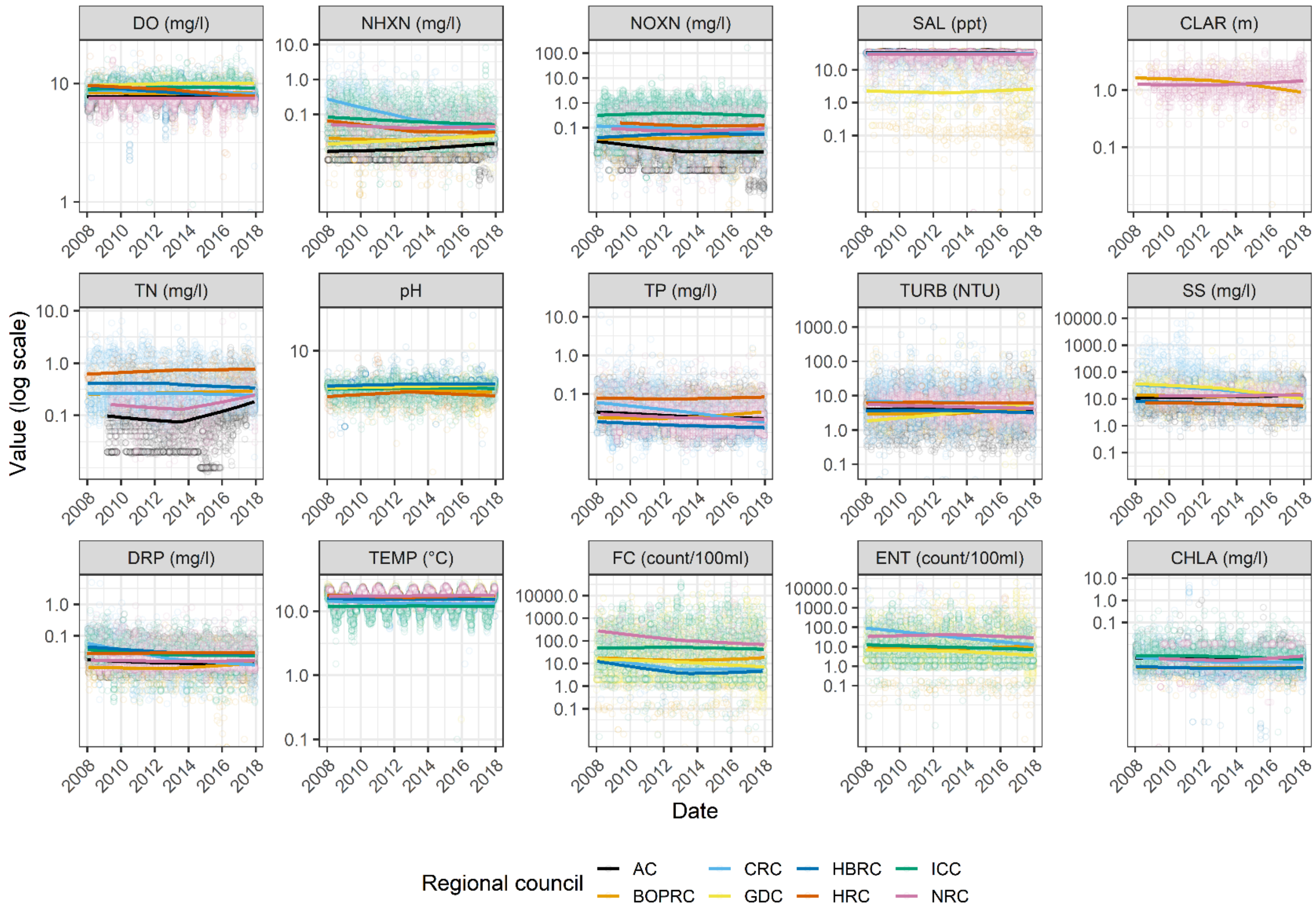

Figure 4-4: Trends in water quality variables over the 10-year period 2008-2017 partitioned by council. Note that the trendlines in each panel correspond to locally weighted (LOWESS) regressions, not seasonally adjusted trends. We suggest that care needs to be taken when interpreting differences in trends between regions due to inherent geographic variability, variation in numbers of sites between regions and differing site selection criteria (This topic is covered in detail in Section 5 of Dudley et al. (2017)).

4.1.3 Twelve-year trends (2006 – 2017)

Between five and 138 monitoring sites met the filtering rules for the 12-year trend analysis of water quality variables (Table 4-3). The numbers of sites varied substantially by ETI class, and there were few or no qualifying sites for some variables in some ETI classes.

The analysis of 12-year trend categories is shown in Table 4-4. Notably, as with the 10-year dataset, there were temperature increases at many more sites than registered decreases. DO, SAL and PH changes were slight if present across all ETI classes. There were improving trends in nutrient (NHXN, NOXN, TN, DRP and TP), and microbiological variables (FC, ENT and CHLA) at most sites. ENT and FC concentrations trended downwards across all site classes.

As noted in Dudley et al. (2017) care should be taken when comparing water quality trends between time periods at a national scale. To illustrate why, we have presented the non-monotonic 12-year trends for each council in Figure 4-7, and the relative proportions of data derived from each council in Figure 4-8. These plots show, for example, the relative dominance of the AC datasets in the 10-year TN trends, for which more sites showed degradation than improvement. In the 12-year dataset for the same variable, there are no qualifying sites from the Auckland dataset, and the counts of changing sites register more improvements than degrading sites. Notably however, some variables show little regional bias in the datasets, such as bacterial data (ENT and FC) which are relatively consistent in their origin between the 10- and 12-year time periods. For these bacterial data, trends appeared consistent showing mostly improvement through both time periods.

Table 4-3: Number of monitoring sites by ETI class and variable that were included in the 12-year trend analyses of water quality. The site numbers shown refer to sites where 80% of the sampling dates and seven of the years in the 2006-2017 period had observations, and less than 15% of the data for each variable consisted of censored values. Classification abbreviations are: shallow, short residence-time tidal river estuaries (SSRTREs), shallow intertidal-dominated estuaries (SIDEs), and deep subtidal-dominated estuaries (DSDEs). See section 3.2 for classification rationale.

			ETI class			
Variable type	**Variable**	**Total**	**SSTRE**	**SIDE**	**DSDE**	**Open Coast**
Physico-chemical	DO	89	6	44	16	23
	PH	104	7	37	14	46
	SAL	95	3	35	22	35
	TEMP	138	7	46	34	51
Optical	CLAR	5	0	2	1	2
	TURB	100	6	34	19	41
	SS	80	5	27	12	36
Nutrients	NHXN	63	5	38	10	10
	NOXN	67	5	36	8	18
	TN	57	4	16	6	31
	DRP	68	4	41	12	11
	TP	117	5	36	35	41
Microbiological	FC	43	5	23	0	15
	ENT	44	4	24	0	16
	CHLA	89	3	35	13	38

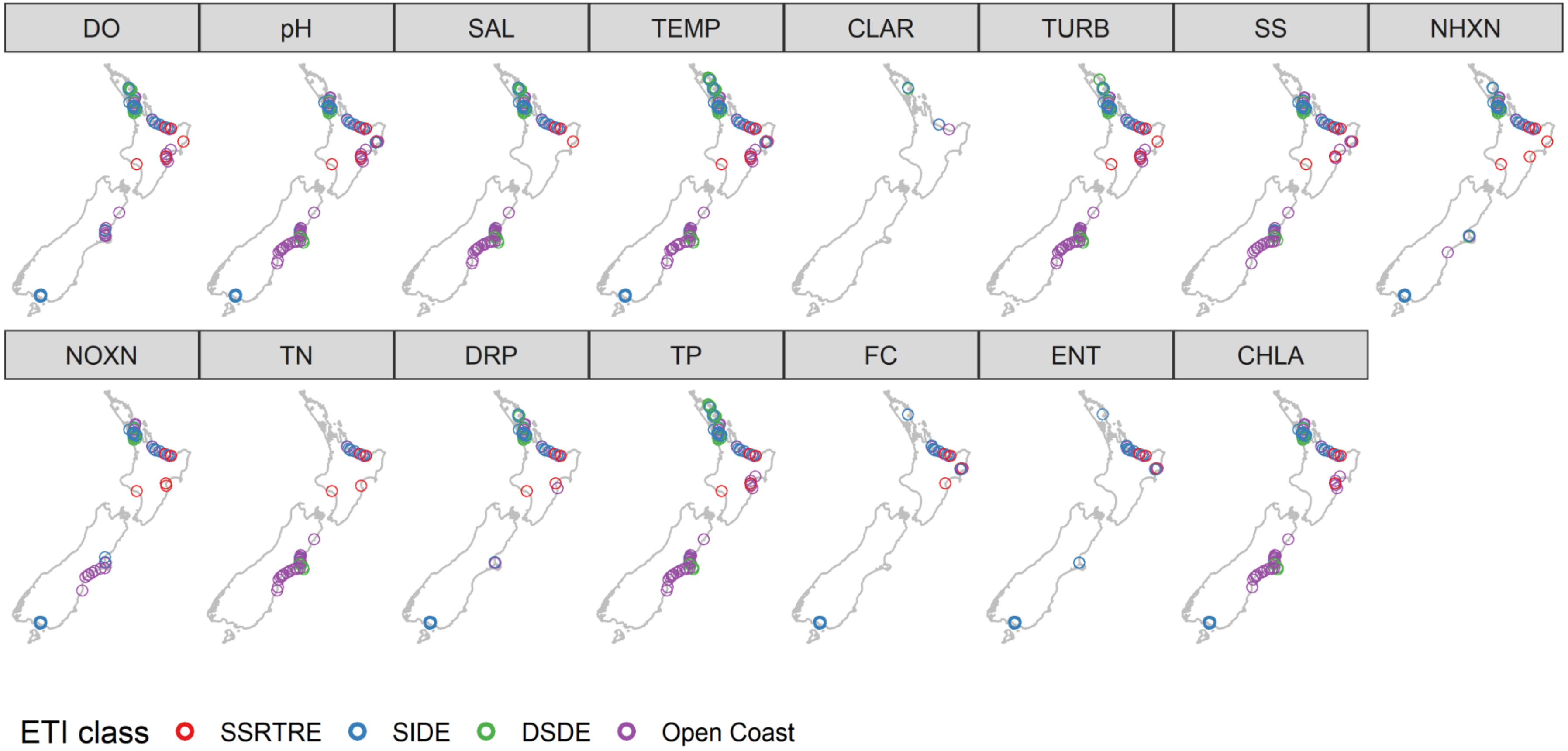

Figure 4-5: Locations of monitoring sites used for 12-year trend analyses of coastal water quality variables. Legend gives ETI class of each site. Classification abbreviations are: shallow, short residence-time tidal river estuaries (SSRTREs), shallow intertidal-dominated estuaries (SIDEs), and deep subtidal-dominated estuaries (DSDEs). See section 3.2 for classification rationale.

Table 4-4: Numbers of sites in trend categories for 12-year trends across ETI classes. Decreasing concentrations of nutrients, ENT, FC, SS, CHLA, TURB and increases in CLAR, and DO can be interpreted as improving trends. Environmental degradation/improvement is not implied by trends in PH, SAL and TEMP (see methods). Insufficient data implies not enough data to reveal a trend direction (see Section 3.4 above).

		Magnitude of 12-year trend								Totals		
Variable type	Variable	Decreasing > 5% p.a	Decreasing 3 - 5% p.a	Decreasing 1 - 3% p.a	Decreasing 0 - 1% p.a	Increasing 0 - 1% p.a	Increasing 1 - 3% p.a	Increasing 2 - 3% p.a	Increasing > 3% p.a	Decreasing	Increasing	Insufficient data
Physico-chemical	DO	0	0	5	15	25	0	0	0	20	25	44
	pH	0	0	0	27	44	0	0	0	27	44	33
	SAL	2	0	1	10	10	2	2	1	13	15	67
	TEMP	0	0	5	6	43	1	0	0	11	44	83
Optical	CLAR	1	1	1	0	0	0	0	0	3	0	2
	TURB	10	5	7	0	0	4	2	1	22	7	71
	SS	32	7	3	0	0	4	3	0	42	7	31
Nutrients	NHXN	12	3	7	0	5	3	2	5	22	15	26
	NOXN	23	7	5	0	1	0	0	3	35	4	28
	TN	6	5	6	1	0	2	4	1	18	7	32
	DRP	17	11	9	0	0	1	1	1	37	3	28
	TP	48	28	10	0	0	2	1	1	86	4	27
Microbiological	FC	14	4	6	0	0	0	1	0	24	1	18
	ENT	11	6	4	1	0	0	0	1	22	1	21
	CHLA	11	16	11	0	0	5	2	0	38	7	44

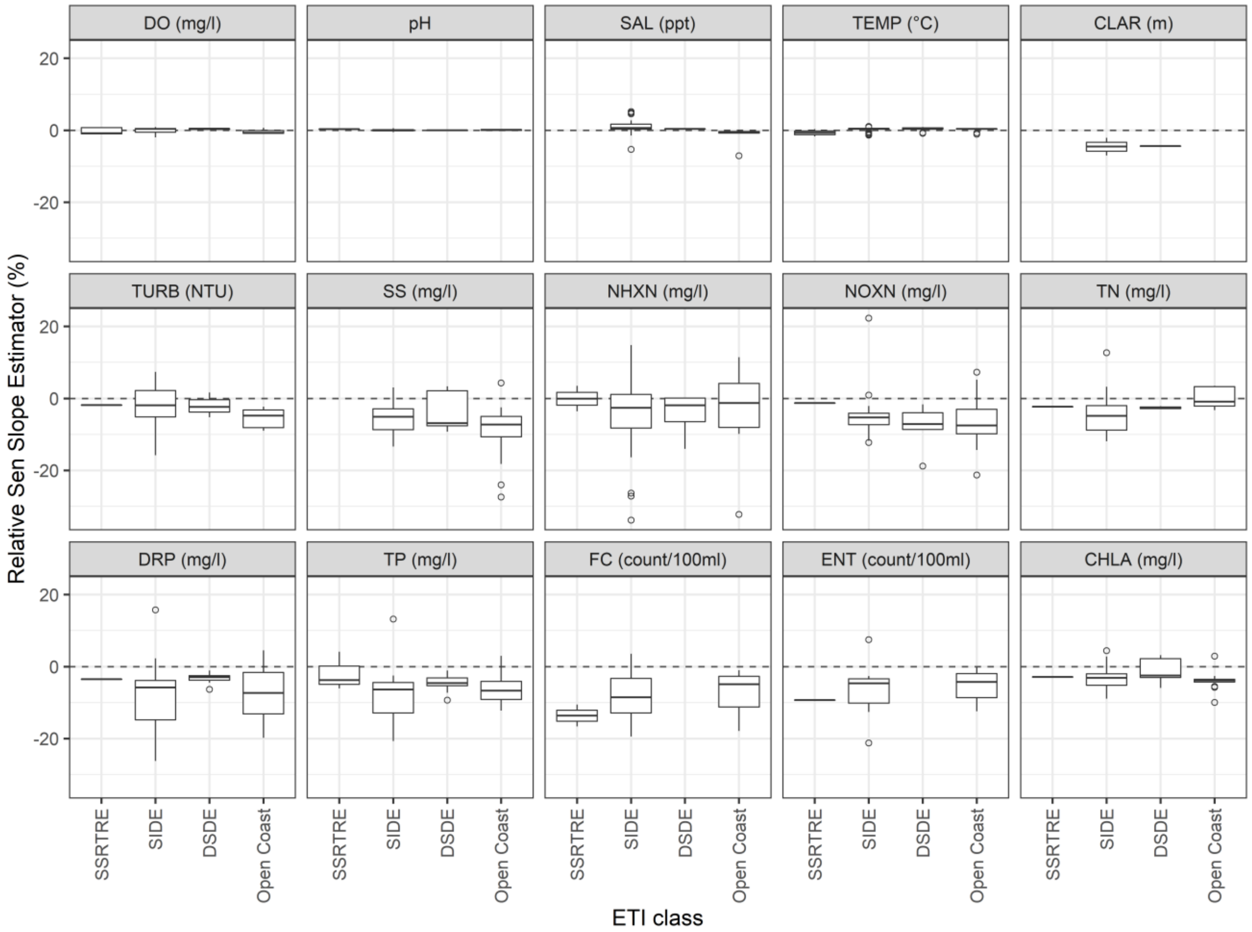

Figure 4-6: Summary of 12-year trends. Box-and-whisker plots show the distributions of site trends within ETI classes. The line within in each box indicates the median of site trends, the box indicates the inter-quartile range and the whiskers extend from the box to the largest value within 1.5 x the inter-quartile range. Outliers (any data beyond the whiskers) are indicated by open circles. Classification abbreviations are: shallow, short residence-time tidal river estuaries (SSRTREs), shallow intertidal-dominated estuaries (SIDEs), and deep subtidal-dominated estuaries (DSDEs). See section 3.2 for classification rationale.

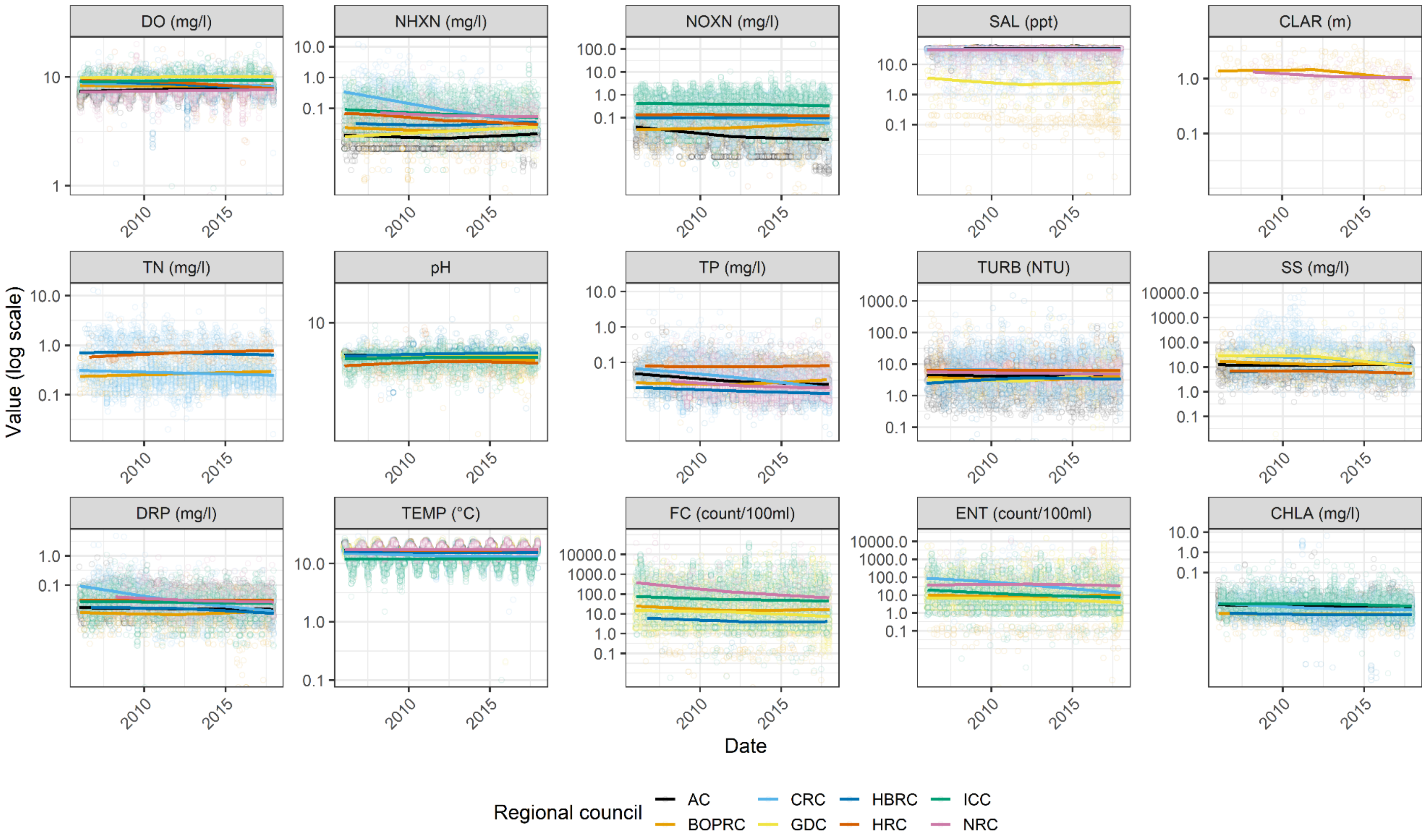

Figure 4-7: Trends in water quality variables over the 12-year period 2006-2017, partitioned by council. Note that the trendlines in each panel correspond to locally weighted (LOWESS) regressions, not seasonally adjusted trends. We suggest that care needs to be taken when interpreting differences in trends between regions due to inherent geographic variability, variation in numbers of sites between regions and differing site selection criteria. (This topic is covered in detail in section 5 of Dudley et al. (2017)).

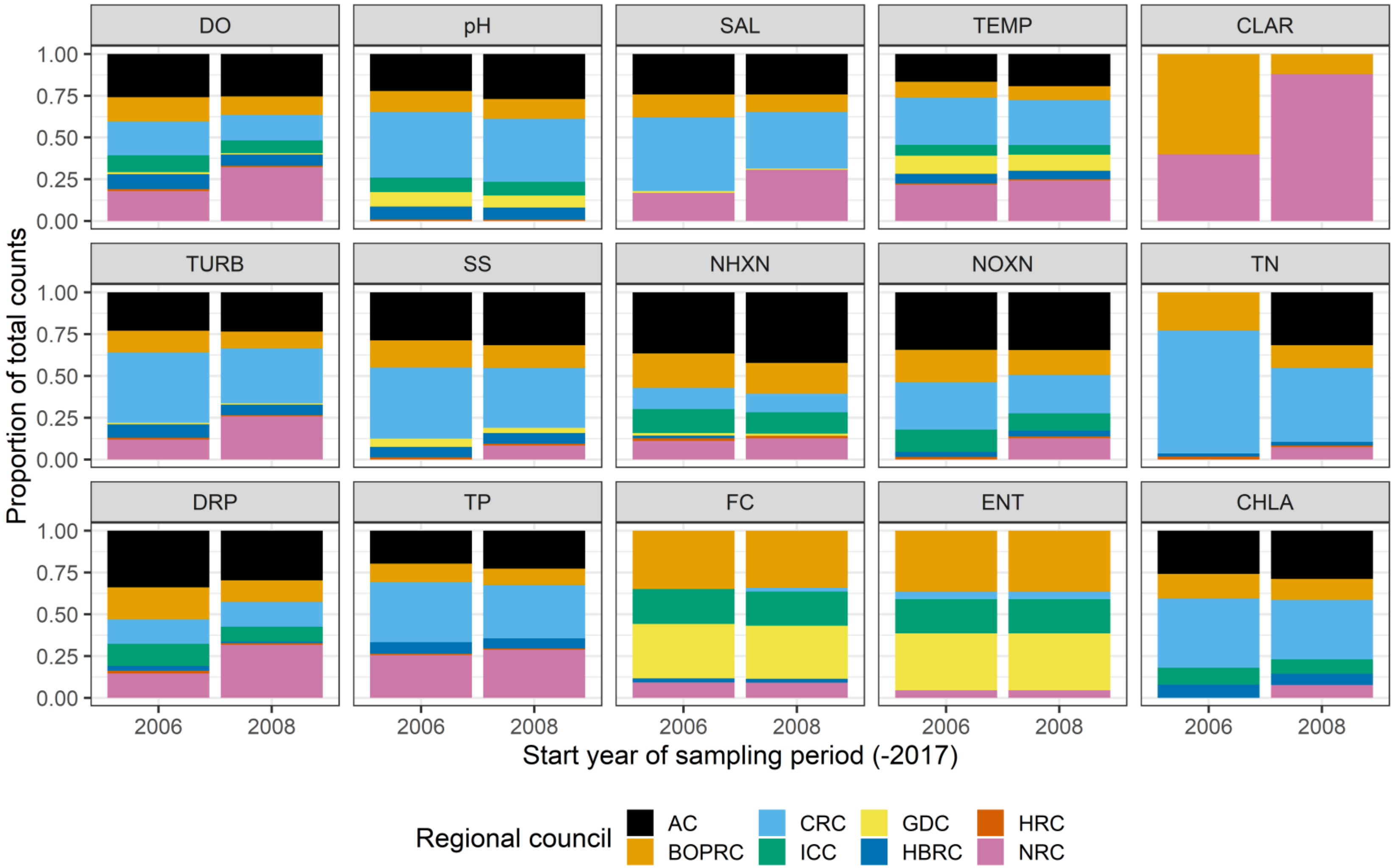

Figure 4-8: Origin of sites included in 10- and 12-year trend analyses. Bars show proportion of total sites for each variable derived from each council in 12-year (2006-2017) and 10-year (2008-2017) trend analyses.

4.2 Coastal water quality trend summary

As well as the summary statistics and plots above, detailed information for each coastal water quality monitoring site is contained in the supplementary files that accompany this report. The sites and corresponding water quality conditions can be aggregated in different ways to suit further reporting (e.g., by region, environmental class, nation-wide).

The 10- and 12-year trend analyses indicated that except for TN and NHXN over the 10-year trend period, more monitoring sites have improving trends in nutrients, FC and ENT than degrading trends. Trends for TP and DRP showed particularly strong declines. These phosphorus patterns are consistent with freshwater concentrations over the last 20 years (Larned et al. 2015), and may in part reflect reductions in freshwater phosphorus enrichment. However, it appeared that nutrient and bacterial reductions in coastal waters were also strong in high salinity site classes. Reductions in these waters may also reflect improvement in point-source (sewage) discharges from urban areas. Of the observed trends in nutrients, changes in nitrogen containing compounds are most likely to drive changes in land-driven impacts on coastal waters; N is the nutrient most commonly limiting to peak seasonal growth of coastal marine plants and algae (Hanisak 1983, Howarth and Marino 2006). Increases in water temperature were a dominant feature of both 10- and 12-year trend analyses.

The maps above (Figures 4-2 and 4-5) and the origin of data used in trend analyses (Figure 4-8), show large disparities in the spread of sites around New Zealand's coastline, and numbers of sites from each council contributing to analyses. We would therefore urge caution when using data from these areas for reporting at a national scale. Because of these representativeness issues, the state and trend results in this report appear to be most appropriate as 'case study' indicators of coastal water quality (as defined by Statistics New Zealand[3]). It is not within the scope of this report to make a detailed analysis or comparison of regional water quality trends; these may be affected by (for example) land use changes, changes in site selection, and climatic factors such as ENSO cycles. For detailed information on regional trends we direct the reader to environmental monitoring sections of council websites. All site locations, ETI classes and trend data are included in the supplementary file to this report "all_results_by_site_2018.csv".

[3] http://www.stats.govt.nz/browse_for_stats/environment/environmental-reporting-series/environmental-indicators/Home/About.aspx#topics (accessed 31/10/16).

5 Acknowledgements

We thank the many council staff who provided data and information about monitoring programmes. We thank Pierre Tellier (Ministry for the Environment) and the regional sector's Coastal Special Interest Group for support, feedback, enthusiasm, and patience during the production of this report and it's 2017 predecessor. Amy Whitehead helped greatly with coding for data preparation and analysis. John Zeldis reviewed the report.

6 References

Cai, W.J., Hu, X.P., Huang, W.J., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W.C., Zhai, W.D., Hollibaugh, J.T., Wang, Y.C., Zhao, P.S., Guo, X.H., Gundersen, K., Dai, M.H., Gong, G.C. (2011) Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience* 4, 766-770.

Davies-Colley, R.J., Vant, W.N., Smith, D.G. (2003). Colour and clarity of natural waters. Science and management of optical water quality. Reprinted by Blackburn Press, Caldwell, New Jersey.

Gall, M. P., Swales, A., Davies-Colley, R. J., and Bremner, D. (*in review*) Light penetration and optical water quality northern North Island, New Zealand estuaries. Estuarine, coastal and shelf science.

GESAMP (2001). Protecting the Oceans from Land-based Activities. Land-based Sources and Activities Affecting the Quality and Uses of the Marine, Coastal and Associated Freshwater Environment. United Nations Environment Program, Nairobi.

Hanisak, M.D. (1983). The nitrogen relationships of marine macroalgae. In: Carpenter, E.J., Capone, D.G. (Eds.), Nitrogen in the Marine Environment. Academic Press, New York.

Helsel, D.R. (1990). Less than obvious-statistical treatment of data below the detection limit. Environmental Science & Technology, 24(12): 1766-1774.

Helsel, D.R. (2012). Statistics for Censored Environmental Data Using Minitab® and R. Wiley, New York.

Hewitt, J.E., Bell, R., Costello, M., Cummings, V., Currie, K., Ellis, J., Francis, M., Froude, V., Gorman, R., Hall, J., Inglis, G., MacDiarmid, A., Mills, G., Pinkerton, M., Schiel, D., Swales, A., Law, C., McBride, G., Nodder, S., Rowden, A., Smith, M., Thompson, D., Torres, L., Tuck, I., Wing, S. (2014). Development of a National Marine Environment Monitoring Programme (MEMP) for New Zealand. New Zealand Aquatic Environment and Biodiversity Report No. 141.

Hume, T., Snelder, T., Weatherhead, M., Liefting, R. (2007). A controlling factor approach to estuary classification. Journal of Ocean and Coastal Management 50, 905–929.

Hume, T. (2016). The fit of the ETI trophic state susceptibility typology to the NZ coastal hydrosystems typology. Prepared by Hume Consulting Ltd for NIWA Christchurch.

Howarth, R.W. and Marino, R. (2006). Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades. *Limnology and Oceanography* 51, 364–376.

Karez, R., Engelbert, S., Kraufvelin, P., Pedersen, M.F., Sommer, U. (2004). Biomass response and changes in composition of ephemeral macroalgal assemblages along an experimental gradient of nutrient enrichment. *Aquatic Botany* 78, 103–117.

Larned, S.T., Snelder, T., Unwin, M. J., McBride G. B., Verburg, P., McMillan H. K. (2015). Analysis of Water Quality in New Zealand Lakes and Rivers. New Zealand Ministry for the Environment. *NIWA Client Report* CHC2015-033.

Law, C.S., Bell, J.J., Bostock, H.C., Cornwall, C.E., Cummings, V.J., Currie, K., Davy, S.K., Gammon, M., Hepburn, C.D., Hurd, C.L., Lamare, M., Mikaloff-Fletcher, S.E., Nelson, W.A., Parsons, D.M., Ragg, N.L.C., Sewell, M.A., Smith, A.M., Tracey, D.M. (2018). Ocean acidification in New Zealand waters: trends and impacts. New Zealand Journal of Marine and Freshwater Research, 52(2): 155-195.

Lowe, M.L., Morrison, M.A., Taylor, R.B. (2015). Harmful effects of sediment-induced turbidity on juvenile fish in estuaries. *Marine Ecology Progress Series* 539, 241–254. doi: 10.3354/meps11496.

McBride, G.B., Cole, R., Westbrooke, I., Jowett, I.G. (2014). Assessing environmentally significant effects: a better strength-of-evidence than a single *P* value? *Environmental Monitoring and Assessment* 186, 2729–2740.

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

Sharp, J.H. (1983). The distributions of inorganic nitrogen, and dissolved and particulate organic nitrogen in the sea. In: Carpenter, E.J., Capone, D.G. (Eds.), Nitrogen in the Marine Environment. Academic Press, New York.

Zeldis J, Plew D, Whitehead A, Madarasz-Smith A. Oliver M, Stevens L, Robertson B, Burge O, Dudley B. (2017). The New Zealand Estuary Trophic Index (ETI) Tools: Tool 1 - Determining Eutrophication Susceptibility using Physical and Nutrient Load Data. Ministry of Business, Innovation and Employment Envirolink Tools Contract: C01X1420. https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/.

Appendix A

All the following files are available on the MfE data service[4]:

Accompanying figure file 1: Ten-year trend plots for each site, grouped by variable. Trendline is a lowess smoother, not seasonally adjusted. See 'coastal-water-quality-10-year-trends.pdf' for these figures.

Accompanying figure file 2: Twelve-year trend plots for each site, grouped by variable. Trendline is a lowess smoother, not seasonally adjusted. See 'coastal-water-quality-12-year-trends.pdf' for these figures.

Accompanying data file: Twelve-year and Ten-year trends at each site, grouped by variable. See 'all_results_by_site.csv' for these data.

Accompanying data file: All raw data. See 'MFE_rawdata_table_2018.csv' for these data.

Accompanying metadata files: Metadata 2018. See ' metadata_rawdata_table_2018.xlsx' and 'metadata_all_results_by_site.xlsx' for these data.

[4] https://data.mfe.govt.nz/group/environmental-reporting/data/category/environmental-reporting/marine/water-quality/