Marlborough Sounds Water Quality Monitoring

review of Marlborough District Council monitoring data 2011-2018

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Prepared by:
Niall Broekhuizen
David Plew

For any information regarding this report please contact:

Niall Broekhuizen
Ecological modeller
Coastal & Estuarine Processes
+64-7-856 1798

National Institute of Water & Atmospheric Research Ltd
PO Box 11115
Hamilton 3251

Phone +64 7 856 7026

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	Formatting checked by:	Alison Bartley
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Executive summary

Marlborough District Council have monitored water quality approximately monthly at 11 stations in Queen Charlotte Sound/Tory Channel since July 2011 (Figure 2-1a) and at 11 stations in Pelorus Sound since July 2012 using a CTD (conductivity-temperature-depth) device and associated fluorometer (Figure 2-1b). At subsets of these 22 stations (five in Queen Charlotte Sound, seven in Pelorus Sound), the CTD sampling has been augmented with water-samples collected near-surface and near-bed. The water-samples are returned to the laboratory for chemical analyses and for determination of phytoplankton composition and abundance (by cell counts).

Marlborough District Council originally commissioned NIWA to prepare only a summary of their monitoring data. Subsequently, the contract was extended to require us to also reporting of temporal auto-correlation and spatial-cross correlation patterns for particulate carbon (PC), particulate nitrogen (PN) and chlorophyll. In addition, we were also asked to comment upon the distributions of dissolved oxygen saturation and near-surface chlorophyll concentration relative to thresholds that have been nominated to ensure that New Zealand King Salmon Ltd (NZKS) salmon farms are not causing undue water-quality changes. This bears on other work in which Marlborough District Council, NIWA and other parties are reviewing the provisional water-quality standards which govern operation of three New Zealand King Salmon Ltd farms within the Sounds.

The Queen Charlotte data-set now spans seven years and the Pelorus one spans six years. Near-surface dissolved oxygen saturations have invariably been high (usually, >80%) in both sounds but near-bed saturations tend to drop during late summer/autumn. In Pelorus Sound, the lowest recorded near-bed saturation has been around 68% and in Queen Charlotte, around 48%. The lowest saturations are found in the two inner-most stations of Queen Charlotte Sound (which are in the main-stem of Queen Charlotte Sound close to Christy's Bay and Okahu Bay) and in Endeavour inlet. Species which are especially sensitive to (low) oxygen concentrations (some fish and some crustacea) may be beginning to exhibit signs of chronic stress (i.e., some aspects of their performance may be temporarily harmed) at saturations below around 60%. It is unlikely that any would have been asphyxiated even when the saturation fell to 48%.

There have been five sequences where DO has fallen below 90% somewhere within Pelorus Sound on three or more successive sampling occasions. In contrast, saturation fell below 70% on only three isolated occasions. In Queen Charlotte/Tory, DO saturation has been below 90% in five distinct sequences of three or more sequential sampling occasions. It has been below 70% on eleven sampling dates (incl. one sequence of three successive occasions).

The water quality data include measurements of concentrations of dissolved inorganic and dissolved organic nutrient (N, P, Si), chlorophyll, particulate carbon and nitrogen, chlorophyll, turbidity and total suspended solids and taxon-specific algal cell counts. Nitrate (in particular) shows a strong seasonal cycle (being less abundant during the summer months). Other nutrients show less seasonal variation. Chlorophyll also shows some seasonal variation – but the seasonal cycles vary amongst sites. Concentrations of suspended solids tend to be greater in the inner parts of both Sounds (esp. Mahau and Kenepuru Sounds within Pelorus).

For most water-quality variables at most sites, the signs of the linear trend lines (calculated using the Sen-slope method) cannot be reliably determined (i.e., the 95% confidence interval for the slope spans zero; see Table 8-1 for a summary of the trend-characteristics associated with each variable). There is however, some evidence that the concentration of suspended inorganic solids (and turbidity – which measures a similar property) have risen since mid-2014 in Pelorus Sound. Similarly, there is some evidence that nitrate concentrations have risen in both Sounds whilst ammonium concentrations have dropped – such that trends of change of total dissolved inorganic nitrogen (DIN) cannot be reliably determined at most sites. The nutrient and chlorophyll concentrations are consistent with the view that these sounds are near the oligotrophic-mesotrophic boundary, in terms of trophic classification.

There provisional water-quality standards governing the operation of some NZKS farms require that a review be undertaken if chlorophyll concentration exceeds 3.5 mg m^{-3} in the upper 15 m of the water-column on three or more sequential sampling occasions at any of the sampling locations within a Sound. In Pelorus Sound, there have been three sequences where chlorophyll (determined from the water-samples) has exceeded 3.5 mg m^{-3} in the upper 15 m of the water column for three or more months but no such sequences as inferred from the fluorometer data. In Queen Charlotte Sound there has been one such sequence as inferred from the water samples, but no such sequence inferred from the fluorometer. The highest individual chlorophyll concentrations have been recorded at the two inner-most stations in Queen Charlotte Sound.

Patterns of temporal auto-correlation and spatio-temporal cross-correlation amongst variables were examined after deseasonalizing the data (by subtracting the medians calculated for each month-of-year). The values remaining after deseasonalizing represent a time-series of anomalies from the multi-year median-monthly-states. The chlorophyll anomalies rarely exhibited significant auto-correlation across time. In contrast, PC and PN anomalies do often exhibit weak temporal auto-correlations at lags up to several sampling intervals. These observations suggest that non-seasonal chlorophyll fluctuations occur over time-scales that are shorter that the sampling interval (i.e., shorter than about one month), whereas non-seasonal fluctuations of particulate organic matter (POM) have a longer period. This is not a surprising result. Phytoplankton growth rates can be very high – but so can their loss rates. Thus, populations can 'boom and bust' over the course of a few days. In contrast, whilst POM stocks may sometimes increase rapidly (e.g., during development of a phytoplankton bloom), detrital organic matter tends to decay only slowly – such that POM variation (esp. declines) is slower than that of living phytoplankton (as indexed by viable chlorophyll) (Zeldis, J.R., Howard-Williams et al. 2008). Living phytoplankton (of which chlorophyll is an indicator) is one component of POM – but it is not the dominant one. Other components will include dead phytoplankton, faecal material originating from zooplankton grazing and organic matter originating from the catchment. This means that while much POM may have originated in phytoplankton production, living phytoplankton are rarely the dominant component of POM in Pelorus Sound (Zeldis, J.R., Howard-Williams et al. 2008; Zeldis, J.R., Hadfield et al. 2013).

For each of the variables: chlorophyll, PC and PN, the strongest spatial cross-correlations amongst stations were usually evident at lag zero (sampling intervals) in Queen Charlotte Sound. This is also true of Pelorus Sound, but in that sound, correlations amongst stations in the main stem of the system (PLS-1 (Mahau), PLS-2 (Kenepuru), PLS-3 (Yncyca) , PLS-6 (mid-Waitata), PLS-7 (Ninepin)) were stronger than those between the main-stem and major side-bays (PLS-4 (Beatrix) & PLS-5 (Tawhitinui)). At time-lag 0, the spatial cross-correlation coefficients were around 0.4 for chlorophyll anomaly and around 0.6 for PC and PN anomalies.

Correlations between chlorophyll and PC or PN tend to be strongest at lag zero (in time). They also weaken with increasing distance between the stations at which chlorophyll and PC (PN) concentrations are measured. The correlation between chlorophyll and PC (or PN) measured one month earlier is stronger than the converse correlation. Collectively, these two observations suggest that, (i) short-term peaks and troughs in the abundance of phytoplankton are also evident as corresponding peaks and troughs in total particulate organic matter (even though living phytoplankton are not a dominant component of particulate organic matter) and (ii) nutrients stored within detrital particulate organic matter are more important in fuelling future phytoplankton growth than phytoplankton mortality is in fuelling production of detritus.

During our analyses, we discovered a small number of inconsistencies in the data-files that were provided to us (see Table 7-1). We recommend that MDC ensure that their internal database is updated to reflect the corrections.

1 Introduction

In July 2011 Marlborough District Council (MDC) initiated a regular water-quality monitoring program for Queen Charlotte Sound and Tory Channel. From July 2012, this was extended to include Pelorus Sound. These were based on the water quality monitoring programme design of (Zeldis, J., Plew et al. 2011).

The data that were collected between 2011 and 2015 were presented in an earlier report (Broekhuizen and Plew 2015). This new report includes both those original Queen Charlotte and Pelorus data and data collected at the MDC monitoring sites in the two sounds since then (to June 2018).

"Water-quality" is a term that has no unique or formal definition. The individual characteristics which contribute to water-quality can often be considered as falling into one (or both) of two categories: (a) those relating to the suitability of the water for direct human use (presence/absence of pathogens and toxins that might be harmful to humans (or marine species exploited- or otherwise valued- by humans)), (b) those relating to aspects of 'ecosystem health'. The latter category can include concentrations of suspended solids, nutrients, oxygen and plankton. It is important to realise that all of the latter materials are present even in pristine/unimpacted waters. Furthermore, the 'natural' abundance of any one characteristic may vary across differing 'pristine' systems. A concentration that might be deemed to be unusually high (or low) in one (modified/stressed) system might be entirely natural for some other pristine system.

A water-body may have low turbidity and colour but high concentrations of faecal contaminants. In that situation, those whose interest is in 'sea-scape' might consider the water-quality to be high, but those interested in contact recreation or shellfish farming are likely to consider the water quality to be low. Conversely, turbid water that is free of pathogens and toxins may remain safe for shellfish farming and swimming but of lesser value from a sea-scape perspective. Statements about water-quality are usually made with respect to an accompanying purpose/value: *this water is suitable for contact recreation*, or *these waters are not nutrient-enriched, so is unlikely to exhibit excessively large/frequent algal blooms or other unwanted symptoms of eutrophication.*

The MDC water-quality monitoring program was designed to monitor the trophic status of the Sounds. Thus, whilst water-quality characteristics such as clarity and concentrations of suspended solids, nutrients, oxygen and plankton are measured, there are no measurements of faecal contaminants, heavy metals or organic contaminants[1].

1.1 Water Quality Standards (for trophic status)

A full review of water quality standard for coastal waters is beyond the scope of this report. Nonetheless, we offer a few relevant examples to provide some context that will help the readers to interpret the MDC Marlborough Sounds water-quality monitoring data in Table 1-1.

[1] Marlborough District Council does monitor faecal contaminants at some bathing sites. The locations of those monitoring sites differ from those used for the water-quality monitoring described in this report.

Table 1-1: Examples of coastal water-quality thresholds and/or standards relevant to the Marlborough Sounds. Note that where standards are attributed to Morrisey, Anderson et al. (2015), that document (rather than this table) provides the definitive description of the standard.

Property	Threshold(s)	Description of threshold(s)/band(s)	Comments	Reference
Ammoniacal nitrogen concentration.	460 µg L^{-1} total NH_3-N	Updated ANZECC marine guideline value (low risk of chronic or acute effects for human health).	At pH=8.0, and 20 °C.	(Batley and Simpson 2009)
Total nitrogen (dissolved and particulate).	300 mg N m^{-3} in near surface waters	Threshold concentration in NZKS farm-management protocols (recent agreement between NZKS & MDC).	Three sequential near-surface TN concentrations > 300 mg N m^{-3} (in monthly monitoring and beyond 250 m from farm perimeter) will trigger an investigation as to the cause. If the farms are deemed to be the cause an intervention may be required to reduce TN concentrations.	(Morrisey, Anderson et al. 2015).
Chlorophyll concentration (seemingly, based upon highest values recorded during the 'annual bloom period' in near surface water).	5 µg chl L^{-1}	Consent condition for three recently approved NZKS salmon farms in the Marlborough Sounds.		EPA Board of Inquiry consent conditions for new NZKS fish farms.
Chlorophyll concentration.	3.5 µg chl L^{-1}	Threshold concentration in NZKS farm-management protocols (recent agreement between NZKS & MDC).	Three sequential chlorophyll exceedances (in monthly monitoring) will trigger an investigation as to the cause (farm or other) and, if the farms are deemed to be the cause an intervention may be required to reduce phytoplankton concentrations.	(Morrisey, Anderson et al. 2015).
Dissolved oxygen concentration.	4.2 mg L^{-1} (to graphical accuracy, see Fig 3B of Vaquer-Sunyer & Duarte (2008))	Median concentration for sub-lethal effects in most sensitive taxonomic grouping examined (fish).		(Vaquer-Sunyer and Duarte 2008).

Property	Threshold(s)	Description of threshold(s)/band(s)	Comments	Reference
Dissolved oxygen concentration.	70% at any location within the water-column at locations within 250 m of farm perimeter.	Threshold concentration in NZKS farm-management protocols (recent agreement between NZKS & MDC). Oxygen saturation should not drop below 70% at all sampling depths (but may drop below 70% at some depths).	More than three sequential breaches (in monthly monitoring) will trigger an investigation as to the cause. If the farms are deemed to be the cause an intervention may be required to reduce phytoplankton concentrations.	(Morrisey, Anderson et al. 2015).
Dissolved oxygen concentration.	90% at any location within the water-column at locations beyond 250 m of farm perimeter.	Threshold concentration in NZKS farm-management protocols (recent agreement between NZKS & MDC). Oxygen saturation should not drop below 90% at all sampling depths (but may drop below 90% at some depths).	More than three sequential breaches (in monthly monitoring) will trigger an investigation as to the cause. If the farms are deemed to be the cause an intervention may be required to reduce phytoplankton concentrations.	(Morrisey, Anderson et al. 2015).

2 The monitoring programme

2.1 Monitoring locations & methods

MDC have sampled in Queen Charlotte Sound/Tory Channel on an approximately monthly basis since July 2011 and in Pelorus Sound since July 2012.

There are eleven sampling stations in each of the two sounds (Figure 2-1). Sampling usually occurs in the fourth week of the month. In general, Pelorus Sound is sampled on one day and Queen Charlotte/Tory on the subsequent one. Occasionally, adverse weather has delayed one or both sampling trips. Thus, Queen Charlotte sampling has not always been one day after the corresponding Pelorus sampling. Indeed, it has sometimes preceded the Pelorus sampling. Similarly, on rare occasions there was no sampling in one given month, but two samplings in the subsequent one (early in the month, one late in the month).

For both sounds, there are three distinct types of sampling:

1. A CTD (conductivity-temperature-depth) instrument is lowered through the water-column and then recovered. The instrument is equipped with additional sensors to measure dissolved oxygen (DO), turbidity and fluorescence. Thus, this operation yields vertical profiles for temperature and salinity, dissolved oxygen, turbidity and fluorescence (which tends to be dominated by fluorescence by phytoplankton pigments but can also be influenced by dissolved colours (tannins etc.)).

2. Secchi disk depth is measured (providing an index of water clarity). Secchi disk is a weighted white (or black+white) disk that is lowered into the water on a string. The Secchi disk depth is the depth at which the person who is lowering the disk determines that they can no longer see the disk.

3. Water samples are collected from close to the surface and close to the seabed. When recovered onto the boat, a sub-sample of the water is drawn and preserved with Lugols[2] solution. The remainder of the sample is retained in a sealed bottle and packed in ice. The chilled and preserved samples are couriered to the NIWA water-quality laboratory in Hamilton over-night. The raw water is filtered. The remaining raw water and the filters are then frozen until analysis of nutrients, suspended solids, chlorophyll etc. Table 2-1 provides a summary of the water-quality properties that are measured and of the methods involved to make the measurements.

CTD casts are made at all stations, but Secchi disk depth and water-sample collection occurs at only a subset of stations (four in Queen Charlotte, one in Tory, seven throughout Pelorus)[3].

Near-bed water-samples are collected using a Van Dorn bottle that is lowered to approximately two meters above the seabed before being closed[4]. Up to (and including) June 2014, a Van Dorn bottle

[2] Lugols is a preservative. These samples do not require freezing. Indeed, they cannot be frozen since this would disrupt the phytoplankton cells – hindering identification.

[3] The hand-held temperature, salinity and dissolved oxygen sensors are owned and maintained by Marlborough District Council. Up until July 2014 (incl), the Council used a NIWA CTD (with DO sensor and fluorometer) to make the vertical casts. From August 2014, they used a CTD of their own. They take responsibility for maintaining the sensors on that CTD.

[4] On rare occasions, the bottle has hit the seabed before being closed. Such events can stir sediments up off the bed such that anomalously high suspended sediment concentrations are measured. When the laboratory records unusually high suspended sediment concentrations, we have contacted MDC staff to determine whether the bottle was recorded as having hit the seabed. When this is confirmed the data are rejected,

was also used to collect the near surface water sample (from about 1 m below the sea-surface), but from July 2014 onward, MDC switched to using a hose sampler. A weighted hose pipe is lowered to approximately 15 m depth. It is then sealed and recovered. The hose is drained into a bucket. The bucket is stirred, and a sample is draw from the bucket. Thus, the water-sample represents a depth-average over the upper 15 metres of the water column. At the two inner-most sites in Pelorus Sound (PLS-1 and PLS-2), the hose sampler would reach to the seabed if fully extended. Thus, for these two sites, it was decided to cease collecting near-bed samples using the Van Dorn sampler. Thus, since the later part of 2014, there has only been one water-quality sample per month collected at these two sites. This has been a depth-averaging hose-sample.

Prior to July 2014, water samples were analysed for particulate organic carbon (POC) and particulate organic nitrogen (PON). From July 2014 onward, these characteristics were dropped in favour of particulate carbon (PC) and particulate nitrogen (PN). The change was made to render the MDC sampling more consistent with other historical data gathered in Pelorus Sound. The laboratory methods for sampling PC and PN are slightly simpler than those for POC and PON (the former requires less filtration, so may be less prone to laboratory error). Historical data from Pelorus Sound indicate that PON and PN have near 1:1 relationship with one another. The POC and PC values are also correlated with a slope that is close to 1.0 (Broekhuizen 2014). We therefore regard the two suites of measures as being quantitatively equivalent. We concatenate the POC and PC time-series to a single, composite time-series (that we will usually call particulate carbon (PC)). Similarly, we concatenate the PON and PN data to yield a single composite time-series ('particulate nitrogen' (PN)).

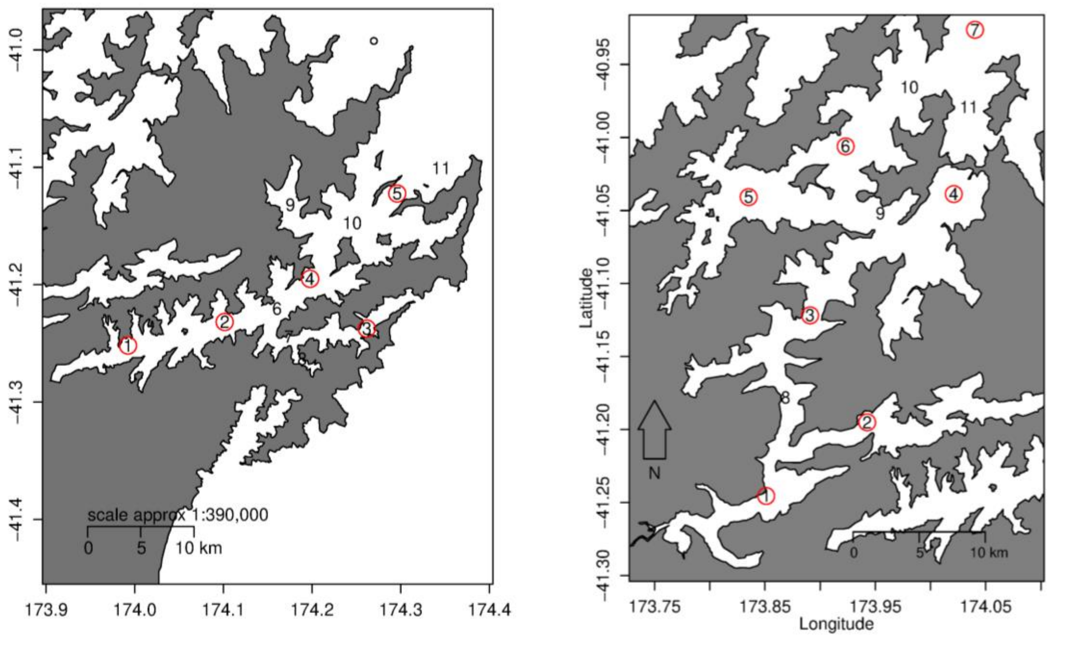


Figure 2-1: Locations of the Marlborough District Council sampling stations. (left) Queen Charlotte Sound/Tory Channel and Port Gore; (right) Pelorus Sound. Circled station-numbers denote water-quality sampling stations and unadorned numbers denote CTD-only stations.

Table 2-1: Characteristics measured in each water-quality sample. Each detection limit is expressed in the same units as the water-quality property is measured. Note that the device that was initially used to measure nutrient concentrations (an Astoria auto-analyser) failed irreparably in June 2017. A replacement (SEAL) analyser was purchased and used for all samples collected after that date. The failure precluded paired cross-validation on fresh water samples, but some cross-validation was conducted by running archived (frozen) water samples that had previously been run through the Astoria. This cross-validation suggested that both instruments yielded very similar concentrations for NH_x-N, NO_x-N, and DRP, whilst the SEAL yielded DRSi concentrations that were about 15% larger than those measured by the Astoria.

Quantity	Abbreviation	Units	Laboratory Method	Detection limit	Comment
Salinity	Sal	ppt		0.1	
Turbidity	Turbidity	Nephometric turbidity units (NTU)	Turbidimeter rated against Formazin standards (APHA2130B).	0.1	
Total suspended solids	TSS	g DW m^{-3}	Filtration (GF-C), drying at 104 C (APHA 2540D).	0.5	
Suspended inorganic solids	SIS	g DW m^{-3}	Filtration (GF-C), drying at 104 °C, followed by furnacing at 400 °C.	0.5	
Volatile Suspended solids	VSS	g AFDW m^{-3}	TSS-SIS	0.5	
Dissolved reactive silicon	DRSi	mg Si m^{-3}	Molybdosilicate / ascorbic acid reduction. APHA4500Si.	1	
Dissolved reactive phosphorus	DRP	mg P m^{-3}	Simultaneous Auto-analysis (Astoria, or SEAL).	1	
Total dissolved phosphorus	TDP	mg P m^{-3}	Persulphate digest, molybdenum blue, FIA (Lachat).	1	
Dissolved organic phosphorus	DOP	mg P m^{-3}	TDP-DRP	1	Derived from the TDP and DRP measurements. We present this in addition to the TDP and DRP measurements.
Ammoniacal nitrogen	NH_4N	mg N m^{-3}	Simultaneous Auto-analysis (Astoria or SEAL).	1	

Quantity	Abbreviation	Units	Laboratory Method	Detection limit	Comment
Nitrate+Nitrite	NO_3N	mg N m^{-3}	Simultaneous Auto-analysis (Astoria or SEAL).	1	
Total dissolved nitrogen	TDN	mg N m^{-3}	Persulphate digest, auto cadmium reduction, FIA (Lachat).	10	
Dissolved organic nitrogen	DON	mg N m^{-3}	TDN-NH_4N-NO_3N.	1 (if NH_4N+NO_3N> 10)	Derived from the TDN, NO_3N and NH_4N measurements. We present this in addition to those measurements.
Chlorophyll-a	Chl	mg Chl m^{-3}	Filter onto GF-C filter (approx. 1.2 µm pore size); Acetone pigment extraction, spectrofluorometric measurement.	0.1	
Particulate organic carbon	POC	mg C m^{-3}	Filtration onto GF-C, acidification, Catalytic combustion @900°C, sep, TCD, Elementar C/N analyser.	0.1	Prior to July 2014.
Particulate organic nitrogen	PON	mg N m^{-3}	Filtration onto GF-C, acidification, Catalytic combustion @900°C, sep, TCD, Elementar C/N analyser.	0.1	Prior to July 2014.
Particulate carbon	PC	mg C m^{-3}	Filtration onto GF-C, Catalytic combustion @900°C, sep, TCD, Elementar C/N analyser.	0.1	From July 2014.
Particulate nitrogen	PN	mg N m^{-3}	Filtration on GF/C, Catalytic combustion @900°C, sep, TCD, Elementar C/N analyser.	0.1	From July 2014.

Quantity	Abbreviation	Units	Laboratory Method	Detection limit	Comment
Taxon specific phytoplankton cell counts.		Cell L^{-1}		Variable, see Appendix A.	Cell counts; also converted to carbon biomass.
Taxon specific zooplankton cell counts.		Individuals L^{-1}			Until June 2014.

2.2 CTD data

Different CTD instruments have been used over the six-seven year monitoring period. This has some implications for some of the parameters reported in this study due to differences in sensor design, sensitivity and calibration. These are discussed later when reporting on the results.

From July 2011 to July 2013, a Seabird SBE19plus (serial number 4248) equipped with temperature, conductivity, PAR (photosynthetically active radiation), fluorescence and turbidity sensors was used with the exception of Sept 2011 when a Seabird SBE19plus (serial number 4337) with only temperature and conductivity sensors was deployed.

From August 2013 to March 2014, a YSI Sonde (serial number 13E101652) equipped with temperature, conductivity, fluorescence, BGA-PC fluorescence[5], turbidity and dissolved oxygen sensors was used. The conductivity sensor on this instrument proved to be unreliable with the calibration appearing to drift over time. Conductivity and derived salinity and density appeared lower than expected with the error increasing over time. It has not been possible to satisfactorily correct the conductivity measurements in post-processing therefore all conductivity measurements over this period are rejected. Temperature data appear consistent with those measured with the Seabird (a comparison between this Sonde and Seabird 4248 was conducted in March and June 2014).

For April and May 2014, the Seabird SBE19plus (serial number 4248) was used for sampling, with a dissolved oxygen sensor added to the instrument.

For June and July 2014, YSI Sonde serial number 14B100344 was used for sampling. However, the sensors from the original Sonde were moved over to this instrument, and again the conductivity data appear unreliable so have been rejected.

From August 2014 onwards, YSI Sonde serial number 14G100211 (owned by Marlborough District Council) has been used. This has the same array of sensors as described for the original Sonde except that the BGA-PC sensor is replaced with a BGA-PE sensor[6]. The data from this instrument appear to date to be generally consistent and reliable, although variations in salinity over time may indicate some calibration drift in the conductivity sensor.

[5] Phycocyanin Blue-Green Algae Sensor (BGA-PC) measures blue-green algae pigment fluorescence. The sensor has not been calibrated to field samples of blue-green algae. Furthermore this sensor is designed for freshwater and estuarine conditions.
[6] Phycoerythrin Blue-Green Algae Sensor (BGA-PE). This is similar to the BGA-PC sensor but intended for marine and estuarine conditions.

CTD data were post-processed to remove the up-cast (only the down-cast is used, most CTD instruments are optimised to sample on the downcast) and the period that the instrument is held at the surface. Any obvious spikes etc., were removed (see also Table 7-1). Salinity and density were calculated from temperature and conductivity. Salinity is reported here as practical salinity. Note that in scientific literature, the use of absolute salinity (ICOR, SCOR et al. 2010) is encouraged in place of practical salinity calculated. However, the YSI software[7] used by Marlborough District Council calculates practical salinity, and many historic or ongoing datasets continue to use practical salinity.

Data were binned (averaged) into 1m increments before generated the plots shown in this report.

[7] Absolute salinity (S_a) is defined as the mass fraction of dissolved solids within a kg of water (g kg^{-1}). This mass fraction is difficult to measure on a routine basis. For that reason, the practical salinity scale (S) has been widely adopted as a ready means making routine measurements measuring salinity. It is based upon a relationship between conductivity and salinity. Unfortunately, (i) conductivity is strongly influenced by temperature and, (ii) whilst non-ionic dissolved solids contribute to absolute salinity, they make no contribution to practical salinity. These factors limit the both the accuracy and the precision with which absolute salinity can be inferred from conductivity. Empirically, S_a=(1.0045 +/- 0.0005)S

3 Data Analysis & presentation

We will present the results from Queen Charlotte Sound / Tory Channel and Pelorus Sound in two separate sections. This reflects: (a) the differing durations of the time-series from each system, (b) the subtly different sampling dates for each sound, (c) a convenient sub-division of the data into manageable chunks, (d) a natural geographic and hydrographic distinction (for example, the influence of rivers upon flow and water-quality being of much greater importance in Pelorus Sound).

The data were gathered with a view to monitoring trophic status, but we have been asked only to present the monitoring data. Thus, whilst we present the time-series data in graphical form, we make no formal assessment of trophic status. We have, however chosen to super-impose 'best-fit linear trend lines' on many of the time-series graphs. Section 3.2 describes the means by which these were calculated. First, however, the method by which 'censored values' (those recorded as "below the instruments detection limit" were handled is described (section 3.1).

3.1 Imputation

Water-quality properties cannot be measured with infinite precision. Most are reported only to one decimal place or three-four significant figures. In particular, there is a lower limit (the so-called detection limit) below which the water-quality variable (e.g., a concentration) cannot be reliably distinguished from zero (i.e., reliably measured to be greater than zero). In such cases, the values are recorded as "< detection limit" by the laboratory. Such data are termed 'censored values'. Censored values create some problems when it comes to summarising data. A user is forced to substitute a precise numeric value in place of this 'band-score' value before calculating measures such as the mean. If the user elects to substitute censored-values with values that exactly equal the detection limit, the resultant mean will likely be an over-estimate of the true (but unknowable) sample mean. If the user chooses to substitute censored values with zeros, the mean will likely be under-estimated. If the user chooses to substitute censored values with values that are equal to 50% of the detection limit, the mean may be either over- or under-estimated. Helsel (2012) argues that a better approach is to adopt the so-called *regression-on-order* method to replace each censored value with an 'imputed value'. Each imputed value is drawn (at random) from the appropriate part of a probability distribution which has been parameterized to approximate the distribution of the uncensored values (with the implication that it may also adequately approximate the distribution of values which are below the detection limit). Collectively, the imputed values should have statistical properties (mean, standard deviation, skew etc.,) that are 'about right' (relative to the unknown true properties), but it is important to realise that the individual imputed values have much less meaning. Whilst each will be 'right' in the sense that it will, indeed, be less than the detection limit, it need not be close (in a relative or absolute sense) to the true (but unknowable) value that occurred at the date and location in question. Furthermore, sequential relativities amongst the imputed values need not be similar to those of the corresponding true (but unknown) values.

Imputation was implemented using a modified version of R-code originally developed by Ton Snelder (formerly of NIWA). In turn, that replies upon the R-package NADA (Lee 2017). First, the raw time-series was split into two sequential halves (by numbers of uncensored values). Secondly, any censored values within each half were replaced by imputation - using only the data from the half-series in question. This two-step imputation was adopted in order to reduce any bias (in the characteristics of the imputed values) that might arise if the underlying raw data exhibits long-term trend such that the probability distribution of the true (infinite-precision) time-series evolved through time. Note, however, that the imputation did take account of shorter-term (esp. seasonal-scale) variations in the probability distributions of the true data.

3.2 Calculation of the best-fit linear trend lines

The linear-trend lines which we have super-imposed upon many of the time-series graphs were calculated as follows:

1. After replacing censored values with imputed ones, the raw data were grouped by month-of-year and the median values were calculated for each month-of-year.
2. The raw time-series was deseasonalized by subtracting the appropriate monthly median value from each of the raw values. This yields a time-series of anomalies from the long-term monthly medians.
3. The Sen-slope of the and corresponding intercept were calculated for the deseasonalised time-series.
4. The mean of the aforementioned 12 month-by-month multi-year medians was added on to the intercept value in order to place the Sen-line back onto the raw-data-scale (rather than that of the deseasonalised data).

The Sen-slope is the median of the individual linear slopes calculated for each of the possible pair-wise combinations of the points in the time-series. The Sen-slope is less sensitive to missing values and outlying points than a least-squares slope and it is commonly used as a measure of trend in time-series data (Helsel and Hirsch 2002).

Whilst the Sen-slope is robust against outliers, this does not mean that the Sen-slope (or any other slope) that is calculated for data that have been drawn from a stationary probability distribution[8] will be exactly zero. Certainly, the Sen-slope (or any other slope) inferred from such a data-set will tend towards zero (perhaps, in an oscillatory manner) as the number of points in the time-series increases, but it is vanishingly unlikely that it will ever be exactly zero (or remain so as additional data accrue). This fact makes it inappropriate to test for the 'significance' of a trend-slope using a traditional two-sided test. In such tests, the null hypothesis is that the slope should be *exactly* zero – something that we know to be vanishingly unlikely even if the data are drawn from a trend-free probability distribution. A different approach is therefore required.

Recently, McBride (in review) proposed an alternative (more appropriate) means of evaluating trend. An earlier version of this new method was described and used in work that has been reported to the Ministry for the Environment (Larned, Snelder et al. 2015). This new method focusses upon determining how confidently the characteristics (absolute magnitude and sign direction) of the trend-slope can be determined from the available time-series data. It does not explicitly test any hypothesis. Thus, it does not promote naïve (i.e., inadequately qualified) dichotomous inferences (e.g., 'the trend-slope is (or is not) significantly different from zero'). Rather, it encourages the user to explicitly confront the question *'how much evidence of (adverse) trend do I require before I am prepared to intervene (or adapt)?*'. In turn, that forces questions such as: '*how much change do I consider to be acceptable?*' and *'what trade-offs am I prepared to make between: (a) the (uncertain) near-term costs associated with making an intervention that may be unwarranted (or unsuccessful) and (b) the (uncertain) future costs that will be incurred only if the trend-direction evident in the*

[8] i.e., one that genuinely embodies no time-trend.

historical data is maintained for sufficiently long into the future?'. Fortunately, answering those societal-level questions is not within the scope of this report!

The International Panel on Climate Change (DoE 2013) has proposed several qualitative terms to describe the likelihood that a trend-slope has been correctly determined (Table 3-1). In the IPCC parlance, when the probability associated with a calculated trend slope is 95% or greater, the direction of trend is deemed 'extremely likely' or 'virtually certain' to have been correctly determined. In the remainder of this document, we will refer to slope-signs that are deemed to have been correctly identified with 95% (or greater) probability as ones which have been 'confidently determined'. Slopes which are deemed to have been correctly identified with a probability of <95% will be described as 'uncertain'. The 95% confidence bounds on such slopes will both have the same sign (i.e., do not span zero).

Table 3-1: Qualitative descriptors for likelihood that a slope that carries a positive sign has been correctly identified as positive . Note that positive and negative trend direction inferences complement one another. If a trend slope is calculated to be positive and carries a probability of 0.98, there is only a 2% chance that an alternative sampling from the underlying process would yield a negative slope. The sign of the slope can be said to be 'extremely likely to be positive' (or, equivalently, 'Extremely unlikely to be negative'). Conversely, if a trend-slope is calculated to be negative with probability 0.7, it can be said to be 'likely to be negative' (or, equivalently, 'unlikely to be positive'). Table adapted from (McBride in review).

Qualitative descriptor	Percentile band for a positive slope
Virtually certain	99% <= percentile <= 100%
Extremely likely	95% <= percentile < 99%
Very likely	90% <= percentile < 95%
Likely	67% <= percentile < 90%
About as likely as not	33% <= percentile < 67%
Unlikely	10% <= percentile < 33%
Very unlikely	5% <= percentile < 10%
Extremely unlikely	1% <= percentile < 5%
Exceptionally unlikely	0 <= percentile < 1%

In instances where they are shown, the Sen lines are plotted as either dashed or solid lines. Use of a solid line indicates that the data are sufficient to enable the direction of any trend to be established with at least 95% certainty (i.e., the 95% confidence intervals for the slope-estimate both have the same sign – such that they do not span zero). Use of a dashed line implies that the data are insufficient to enable the direction of any trend to be determined with 95% (or greater) probability. The choice of 95% certainty is arbitrary – but consistent with common statistical practice. The R-package *Zyp* (Bronaugh and Werner 2013) was used to calculate the Sen-slope characteristics of the deseasonalized data (incl. the confidence bounds that are compared against zero to determine whether the direction of trend can be confidently determined).

3.3 Presentation of time-series results

The raw time-series results are presented in sections 4 (Queen Charlotte Sound) and 5 (Pelorus Sound). The same water-quality data are plotted against day of year (rather than calendar date) in Appendix B. The plots within Appendix B enable seasonal cycles to be more readily distinguished. Empirical probability and cumulative probability distributions of the recorded water-quality values are presented in Appendix C (Queen Charlotte Sound) and Appendix D (Pelorus Sound). These provide an alternative view of the data – one that might be more useful when endeavouring to define 'guard-values' for performing quality assurance on incoming data.

3.4 Assessment of water-quality relative to provisional water quality standards for New Zealand King Salmon farms

The consent conditions that govern three new NZKS farms (Ngamahau, Richmond Bay and Waitata South) required that provisional water-quality standards be nominated. Provisional standards were developed for: (i) dissolved oxygen saturation values (70% in the far-field), (ii) chlorophyll concentrations (3.5 mg m^{-3}) and (iii) total nitrogen (300 mg N m^{-3}) [see also Table 3-2].

The Marlborough District Council monitoring stations are 'far-field' stations in the context of the monitoring plan for the NZKS farms and we have been asked to assess the MDC monitoring data relative to the provisional standards for dissolved oxygen and chlorophyll. Therefore, we have added horizontal dashed lines to indicate the relevant thresholds in our time-series plots of chlorophyll, dissolved oxygen and total nitrogen (sections 4.3, 4.18, 4.20, 5.3, 5.18, 5.20).

In addition, in section 6.2, we have tabulated the dates (and station-locations) on which chlorophyll exceeded 3.5 mg m^{-3}, and the numbers of times this threshold was exceeded (at one or more MDC sites) on (a) an isolated sampling occasion, (b) two sequential sampling occasions (but not a third) and (c) three or more sequential sampling occasions). We have undertaken a similar exercise for dissolved oxygen saturation – adopting four different threshold saturations: 90%, 80%, 70% and 60% (section 6.1).

Table 3-2: A hierarchy of responses to potential breaches of the WQS for chlorophyll, total nitrogen and dissolved oxygen.(reproduced from Table 27 in Morrisey, Anderson et al. 2015).

Water-quality determinand	WQS measurement	Location	Tolerance of breach	First-level response	Second-level response
Chlorophyll-a	Must not exceed 3.5 mg/m^3 in an integrated 15 m deep sample for three successive months at any site(s).	One or more sampling sites around Richmond and Waitata, including far-field sites (MDC and NZKS).	Breach of WGS shall not exceed 3.5 mg/m3 for more than three successive months (time-wise, across all sites).	(a) Must notify MDC within 2 working days. Review of existing data for all stations (reported within 20 days). If cause uncertain, then RA may request (b) additional far-field sampling stations to better	If the first-level response identifies a breach of the WQS, reduced stocking* to achieve compliance will be required (as required by Condition 44dii). Post-breach WQ sampling will then be undertaken to determine that the resulting bloom has subsided and that no

Water-quality determinand	WQS measurement	Location	Tolerance of breach	First-level response	Second-level response
		One or more sites around Ngamahau, including far-field sites (MDC and NZKS).		map any indicators of a breach and (c) increased frequency of sampling to better resolve patterns of exceedance in WQS.	new blooms associated with the farm have been created. If the WQS is still breached, and the farm(s) are deemed to be a contributing factor, further mitigation* to achieve compliance will be required.
Total Nitrogen (TN).	near-surface not to exceed 300 mg TN/m^{3}.	Beyond 250 m from the edge of the net pens.	Breach of WGS shall not exceed a period of three consecutive months.	Timeframe for b-c, to be agreed upon by MDC.	* NZKS to propose a mitigation response and timeframes, via consultation with PRP and agreed upon by RA.
Dissolved oxygen (DO).	DO levels should not drop below 70%[9] at all depths.	Within 250 m of the net pens.	Breach of WGS shall not exceed a period of three consecutive months.		
	DO levels should not drop below 90%.	Beyond 250 m from the edge of the net pens.			

3.5 Auto-correlation and cross-correlation

The provisional water-quality standards that govern the operation of some of the NZKS salmon farms are being reviewed at present[10]. It has been noted that the correlation between mussel condition and particulate carbon (or particulate nitrogen) has proven to be stronger than the correlation with chlorophyll (Zeldis, J.R., Howard-Williams et al. 2008). With that in mind, the question 'should we adopt a threshold for PC (or PN) in place of (or in addition to) the one for chlorophyll?'. In response, Marlborough District Council asked NIWA to extend the work undertaken for this data-review in order that it could provide additional information that would be relevant to the NZKS water-quality-standards review.

In particular, we were asked to examine patterns of temporal auto-correlation and cross-correlation in the particulate carbon, particulate nitrogen and chlorophyll records.

[9] Vaquer-Sunyer, R. & Duarte C. (2008) provide an extensive review of the DO requirements (acute and chronic thresholds) of marine animals. Fish and crustacean are the least tolerant of hypoxia. The mean sub-lethal concentration for fish (the more sensitive of the two groups) is circa 4.4 mg O_2 L^{-1} (approx. 55% saturation at 15 C) and 75% of the records for chronic effect thresholds are < approx. 5.5 mg L^{-1} (approx. 70% saturation at 15 C). Vaquer-Sunyer, R. & Duarte C. (2008). Thresholds of hypoxia for marine biodiversity, Proceedings of the National Academy of Sciences 105 (40), 15452-15457.

[10] This data-review report was commissioned prior to the initiation of the review of NZKS water quality standards.

Particulate organic matter measures the abundance of both living and dead organic matter. Living phytoplankton (of which chlorophyll provides one, crude measure) is likely to be the dominant component of the living particulate organic matter (other components being protozoa and smaller meso-zooplankton). The dead organic matter will include dead phytoplankton, dead zooplankton, faecal material and fine particulate organic material that has been swept out of the catchment.

The raw time-series were deseasonalized by subtracting the medians of the multi-year respective month-of-year values to yield monthly anomaly values. The entire raw time-series was used (i.e., no distinction was drawn between the early sampling (which used a Van Dorn sampler for surface samples and measured POC and PON) and later sampling (hose sampler, PC and PN). We then sought to determine how persistent the anomalies were by calculating the temporal auto-correlation and partial auto-correlation coefficients on a station-by-station basis using the R functions *acf* and *pacf*. Results are presented in sections 6.3 - 6.5.

4 Results (Queen Charlotte Sound)

4.1 Temperature

4.1.1 Hand-held surface temperature

The phase/seasonal pattern of the annual temperature cycle is similar at all sites and in all years (Figure 4-1). The winter minimum occurs around August and the summer maximum around February. The winter minima are around 10-11 °C at all sites, but the summer maxima differ. The coldest summer-time surface water temperatures [14-15 °C] are found in Tory Channel (QCS-3). The warmest [approx. 18 °C] are found in inner Queen Charlotte (QCS-1, QCS-2).

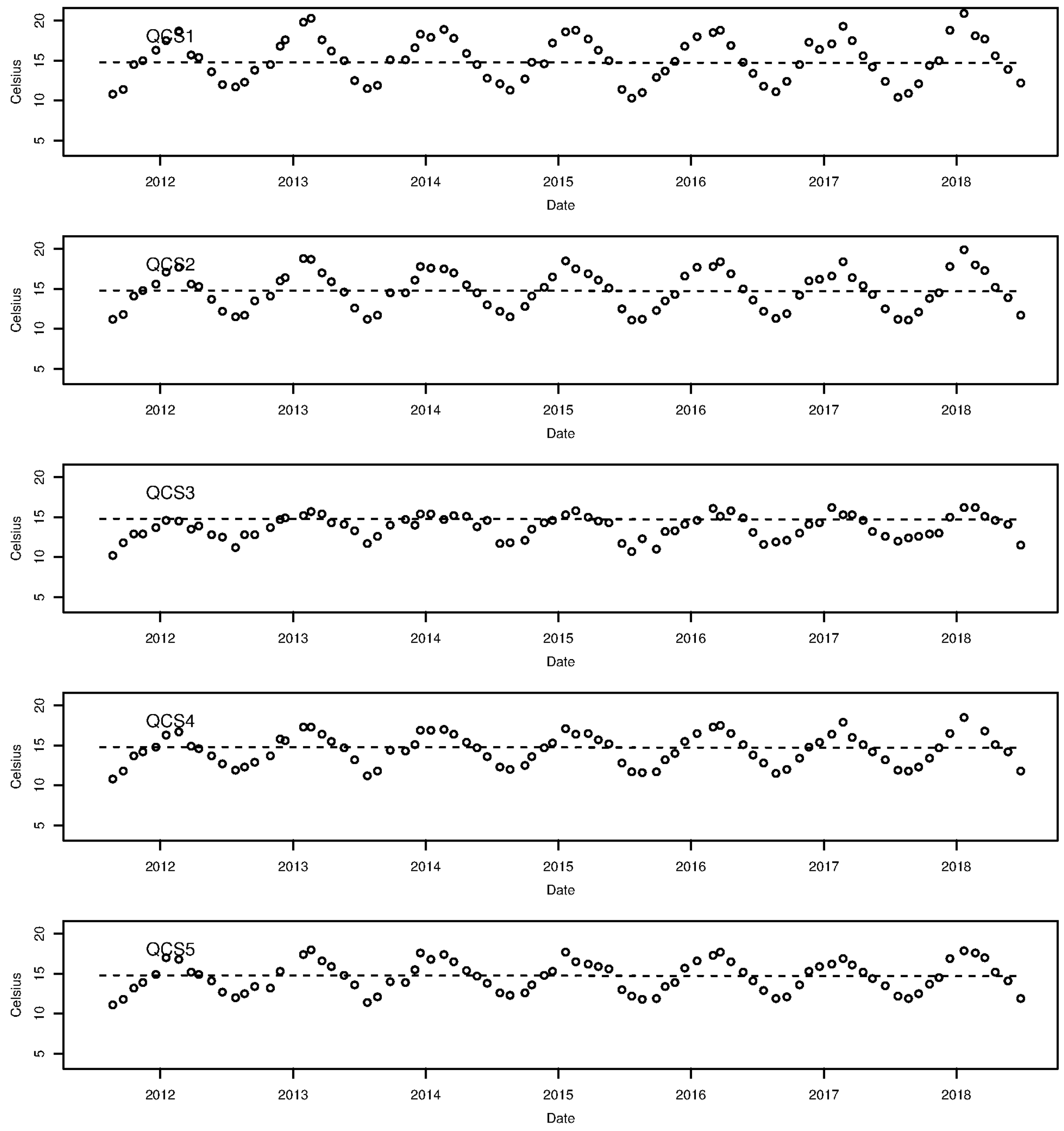
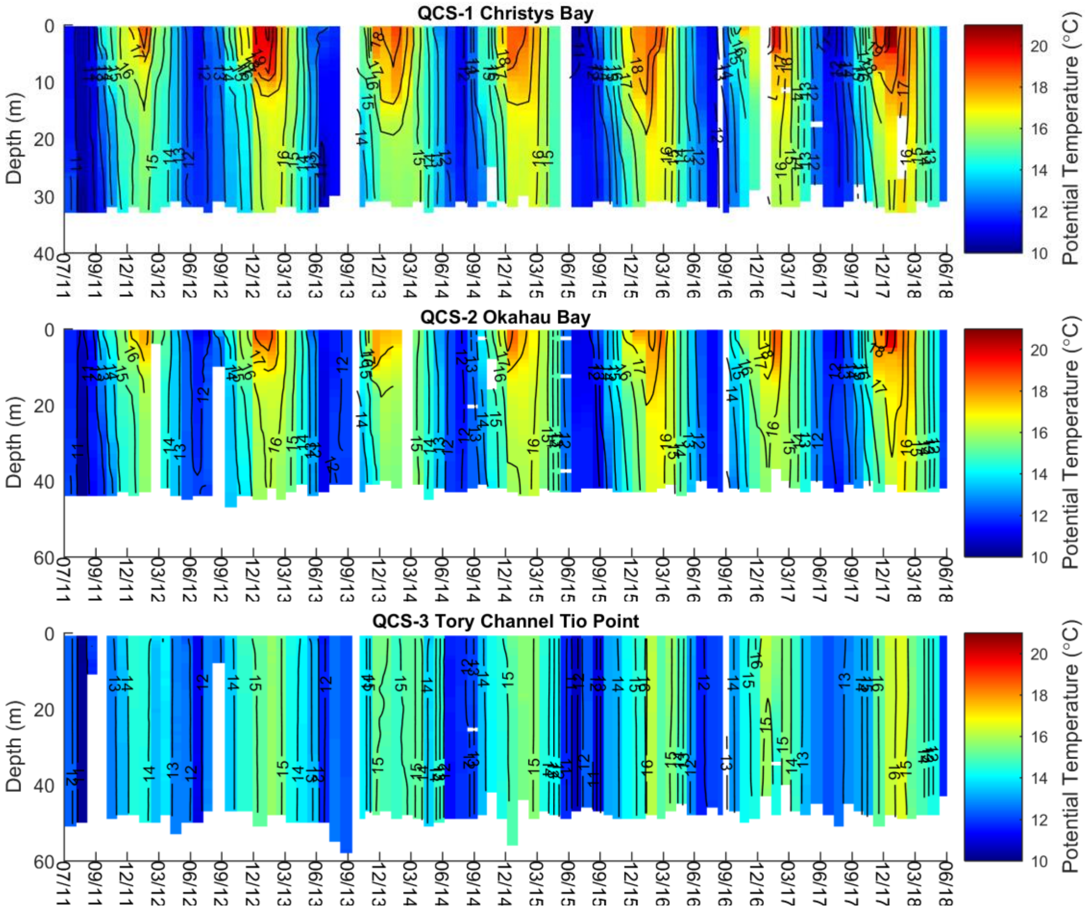


Figure 4-1: Queen Charlotte: Near surface water temperature measured with a hand-held probe at each of the five water quality sampling stations. The dashed line is a best-fit Sen line for the data from the hand-held device calculated after removing seasonal effects.

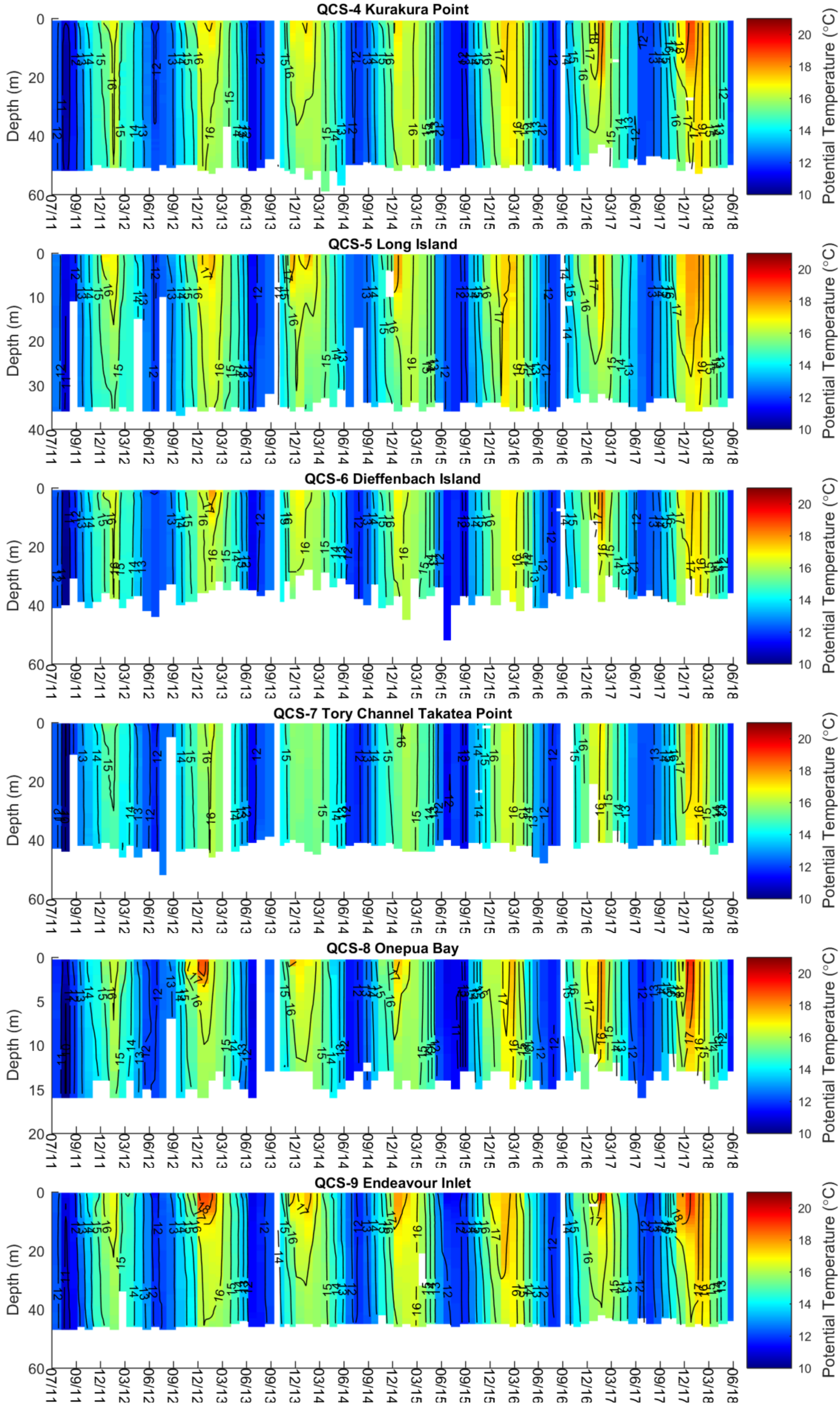
4.1.2 CTD temperature profiles

Depth-by-time colour contour plots of temperature show the seasonal variations in temperature, and also the development of summer-time stratification in the inner sound (particularly sites QCS-1, 2) and side bays (QCS-8, 9) (Figure 4-2). Stratification starts to develop around November, and generally breaks up in April. Surface waters are warmest at the innermost site (QCS-1) with the highest temperature of 20.9°C recorded in late Jan 2018. Winter water temperatures drop to ~11-12°C throughout the sound. The Tory Channel (QCS-3, 7) remains relatively well-mixed year-round.

The 2017-2018 summer was the warmest at all sites since the start of monitoring, with thermal stratification developing in October 2017, and breaking up in April 2018. This is consistent with climate reports that 2017-2018 was the hottest summer on record [11]. Persistence of high pressure over the Tasman Sea (a feature of La Nĩna) during November and early December 2017 had reduced mixing of cool, deeper water with the surface resulting in anomalously warm sea surface temperature in the region. This warmer surface water affected the Cook Strait, and in turn, the Marlborough Sounds region.



[11] https://www.niwa.co.nz/files/Climate_Summary_Summer_2018.pdf


QCS-4 Kurakura Point
QCS-5 Long Island
QCS-6 Dieffenbach Island
QCS-7 Tory Channel Takatea Point
QCS-8 Onepua Bay
QCS-9 Endeavour Inlet
Depth (m)
Potential Temperature (°C)

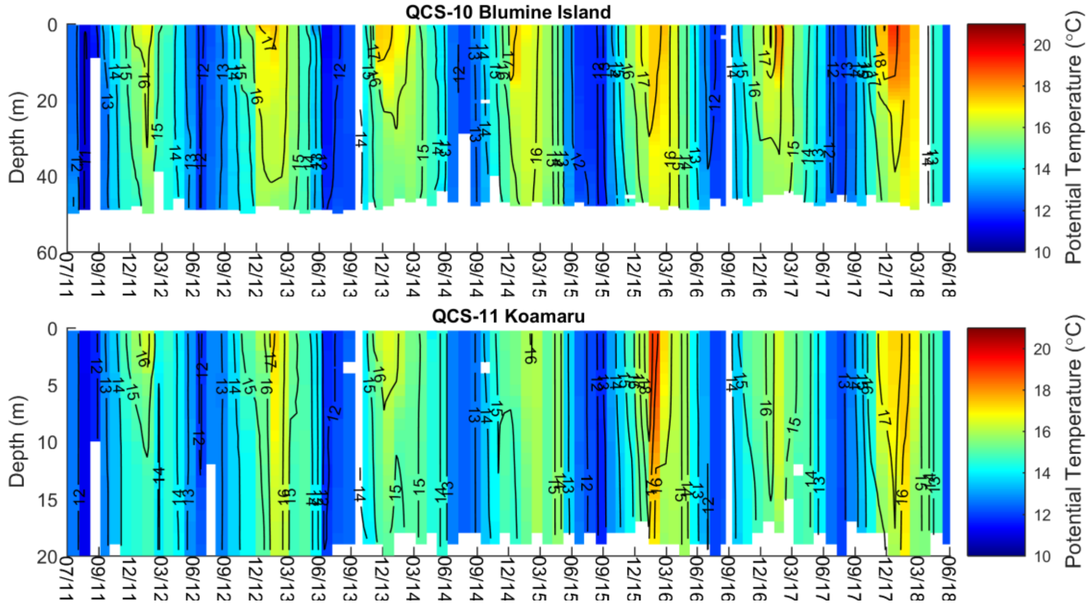


Figure 4-2: Contour plots of the evolving depth profiles of temperature through time at the Queen Charlotte and Tory stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended).

4.2 Salinity

4.2.1 Hand-held surface salinity & laboratory determinations

As one might expect, near surface salinities tend to be a little lower than near-bed ones because fresher water is more buoyant (Figure 4-3). Those measured in the laboratory tend to be a little higher than those measured at sea throughout the sampling period. This may indicate that the hand-held measurements and the Van Dorn bottle samples are made at slightly different depths, or it may indicate an inconsistency between the calibrations of the conductivity meters that are used in the field and in the lab. Near-surface salinities have invariably exceeded 30 PSU. Salinity minima tend to be lower within inner Queen Charlotte than in Tory Channel or central/outer Queen Charlotte. Whilst no formal cross-correlation tests have been made, salinities at different sites appear to be positively correlated – suggesting that the fluctuations at each site are all responding to one or more shared drivers (rainfall runoff, evaporation, intrusions from Cook Strait).

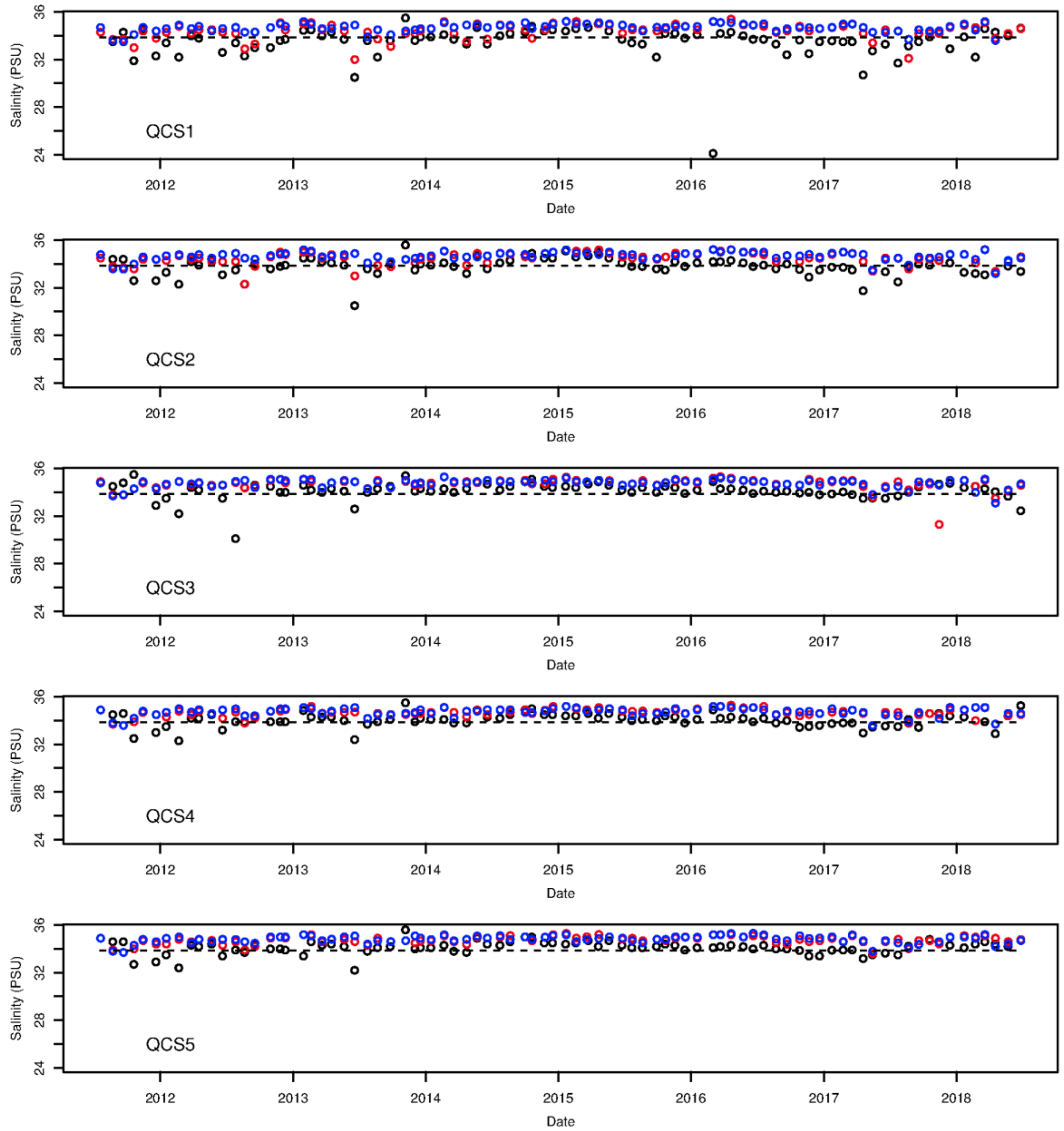
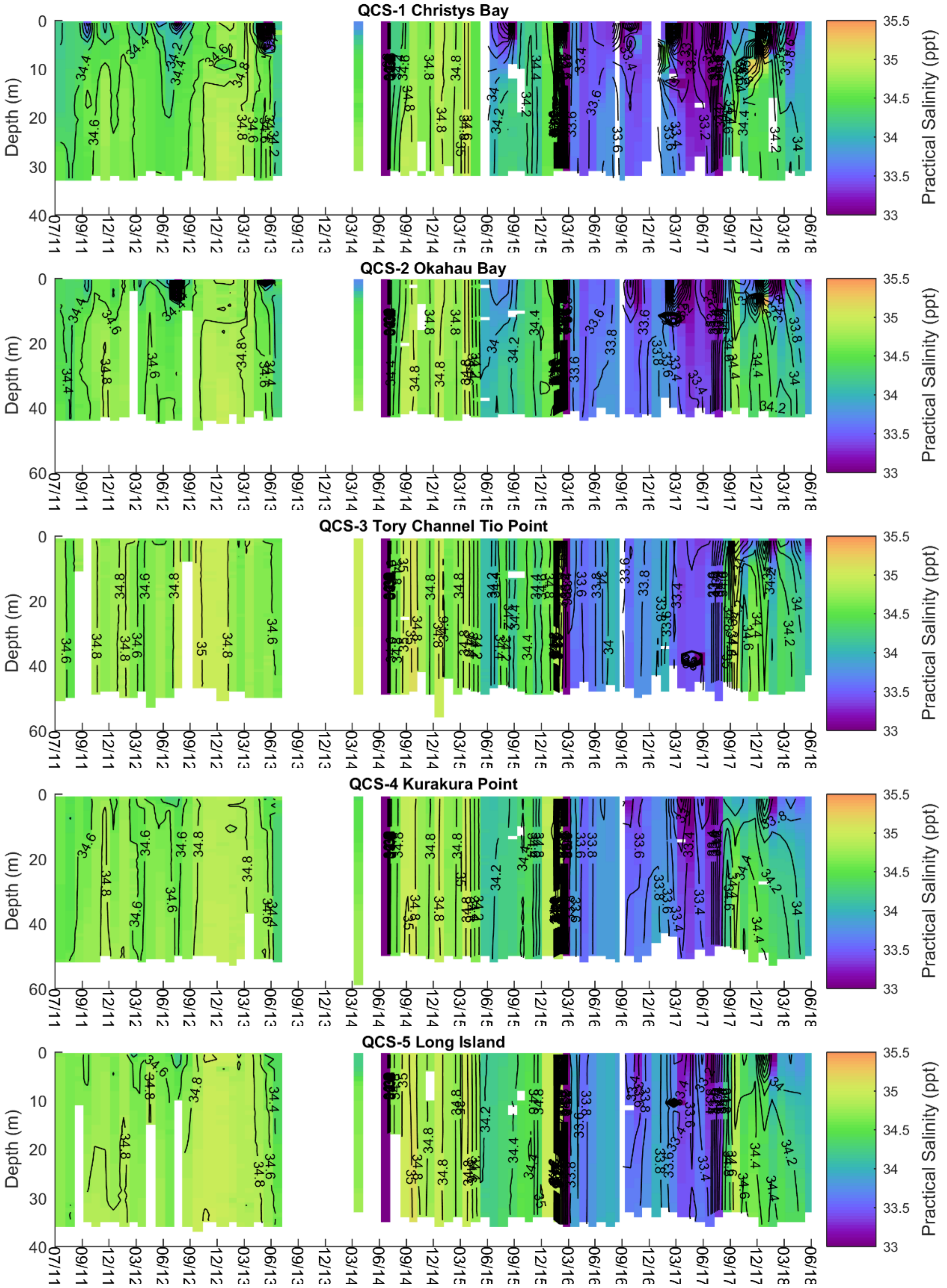


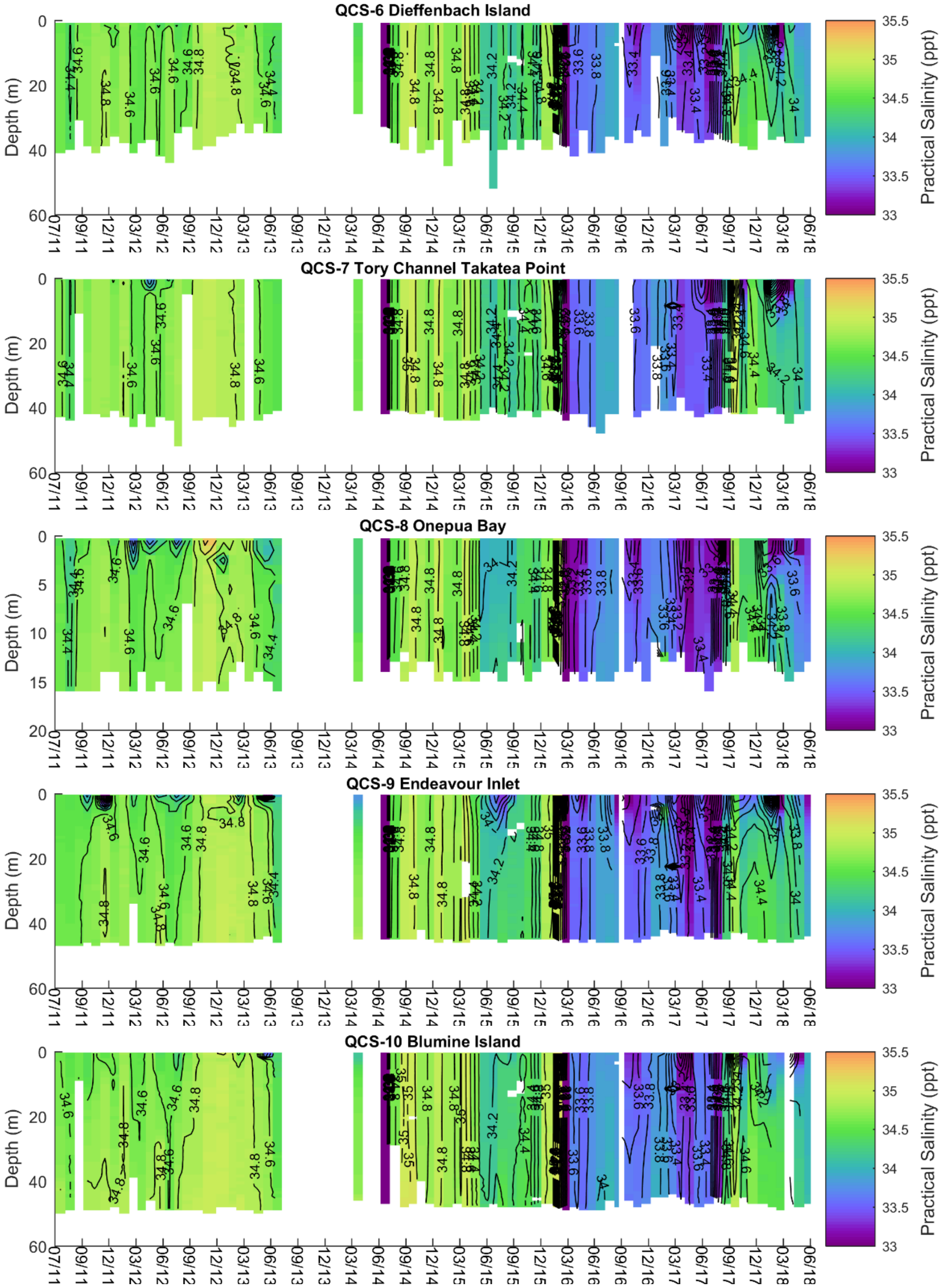
Figure 4-3: Queen Charlotte: Salinity measured at sea with a hand-held probe at 1 m depth (black circles) and in water-samples returned to the laboratory (red circles: near surface (1m or depth averaged to 15 m); blue circles: near-bed). Different instruments were used to measure salinity at sea and in the laboratory. The dashed line is a best-fit Sen line for the data from the hand-held device calculated after removing seasonal effects.

4.2.2 CTD salinity profiles

Contour plots illustrating the evolving depth profiles of salinity through time at the Queen Charlotte and Tory stations are shown in (Figure 4-4). Variations in salinity are small between sites and over time. There are episodic low salinity events seen in surface waters, particularly at sites QCS-1, 2, 7, 8 and 9; and to a lesser extent at other sites. We assume that these were caused by rainfall and runoff. There is no obvious seasonal pattern. Note that large periods of salinity data from Sept 2013 to August 2014 are not shown due to calibration drift of the conductivity sensor.

The contour plots also suggest there could be changes in calibration of conductivity sensors over the monitoring period. From March 2016 to August 2017, salinities at all sites were lower by approximately 0.5 to 1.2 ppt compared to earlier measurements. Salinities since Sept 2016 have increased but are still lower than during the start of the monitoring period. It may be possible to derive a correction for CTD observed salinity using the water samples, but we have not attempted to do so, and report the data as recorded.




QCS-6 Dieffenbach Island
QCS-7 Tory Channel Takatea Point
QCS-8 Onepua Bay
QCS-9 Endeavour Inlet
QCS-10 Blumine Island
Depth (m)
Practical Salinity (ppt)
07/11
09/11
12/11
03/12
06/12
09/12
12/12
03/13
06/13
09/13
12/13
03/14
06/14
09/14
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12/17
03/18
06/18

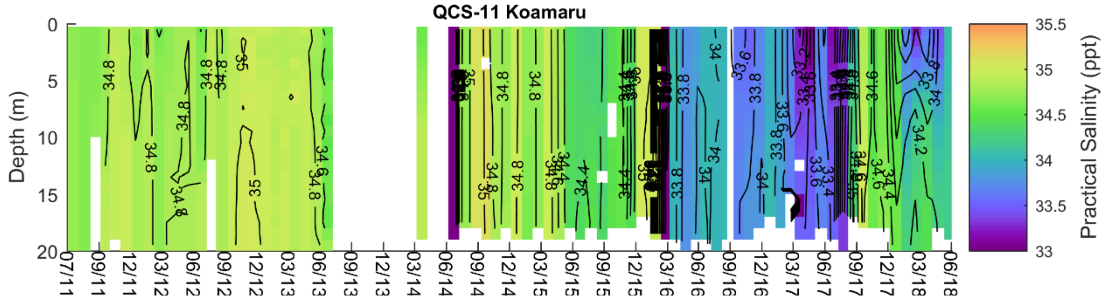


Figure 4-4: Contour plots of the evolving depth profiles of salinity through time at the Queen Charlotte and Tory stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended).

4.3 Dissolved oxygen

4.3.1 Hand-held surface oxygen saturation

Near-surface dissolved oxygen concentrations have been high (rarely <80% and always >75% saturation) at all stations throughout the sampling period (Figure 4-5). Concentrations tend to be highest in spring and lowest in late summer/early autumn. Whilst some particularly sensitive species may begin to exhibit signs of mild stress as oxygen levels progressively further below about 80% saturation, in the literature, the median concentration for sub-lethal effects is about 4.2 mg O_2 L^{-1} (around 50-60% saturation) for even the most sensitive taxa (fish and crustacean) (Vaquer-Sunyer and Duarte 2008).

Near-surface concentrations of dissolved oxygen concentration have been high enough to sustain a healthy biota at every site on every sampling occasion. Near surface waters are in close contact with atmospheric oxygen. Furthermore, the surface waters receive plentiful light, so photosynthetic oxygen production can also be significant (for example, leading to mild oxygen super-saturation). In general, therefore one should expect that they will have high oxygen concentrations. In contrast, deeper waters are less well connected to the atmosphere and experience lower light intensities (lesser photosynthesis). Furthermore, nearbed waters must withstand both local (pelagic net oxygen demand) and net demand arising from the adjacent seabed. Thus, oxygen concentrations often tend to decline with increasing depth into the water-column. Information concerning the vertical distribution of oxygen is available from the DO sensors mounted on the CTD. These data are presented in section 4.3.2.

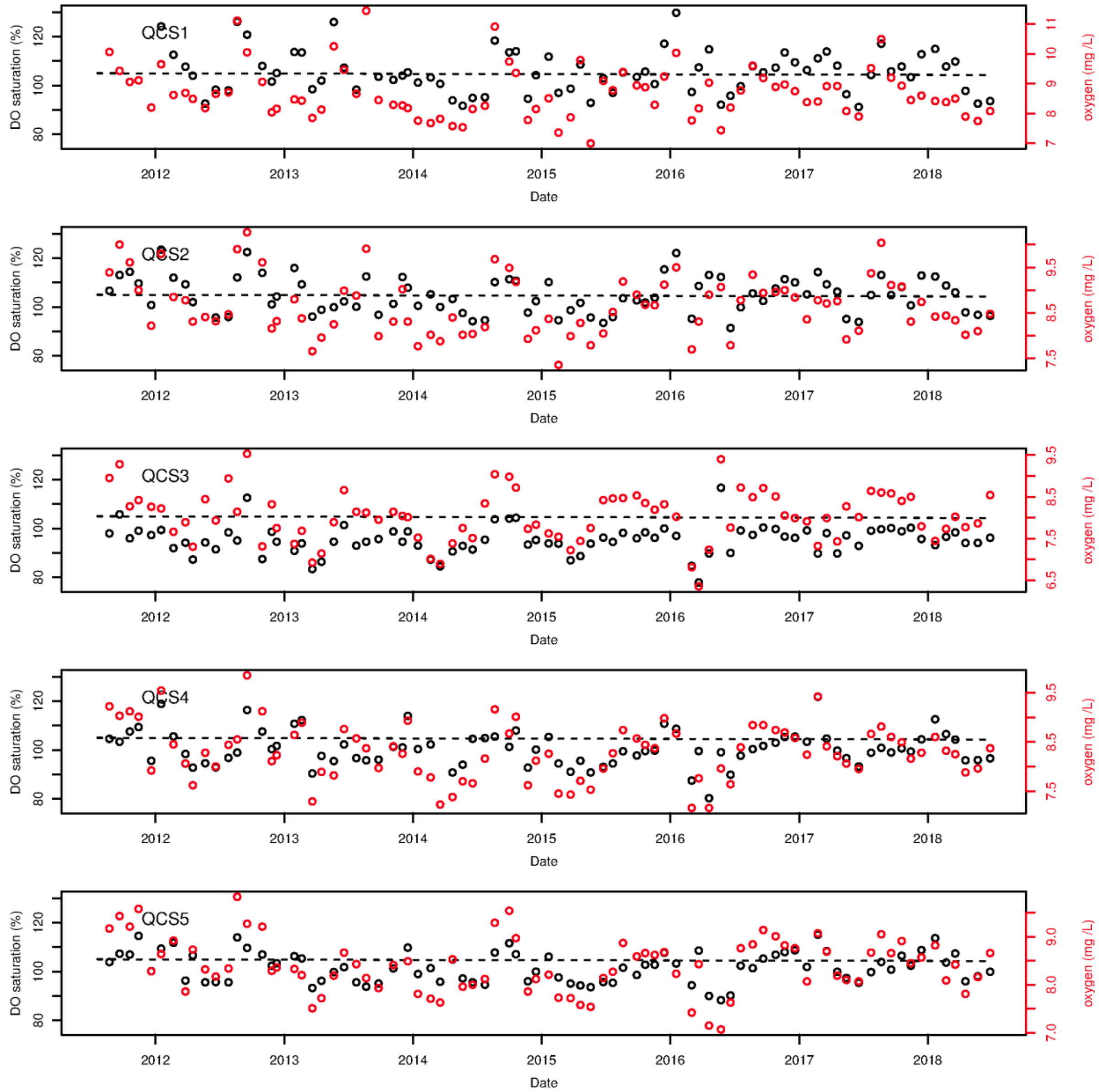
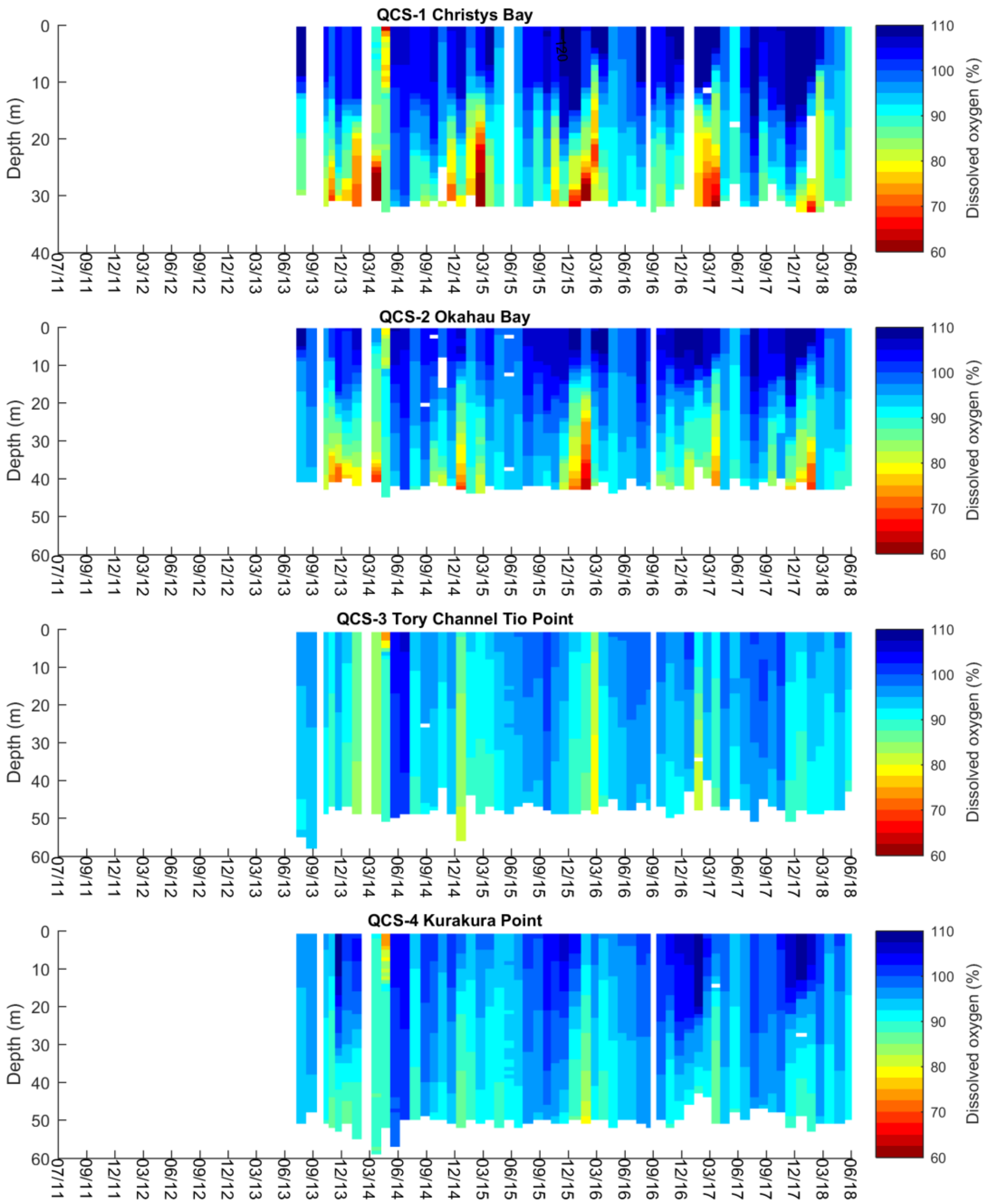
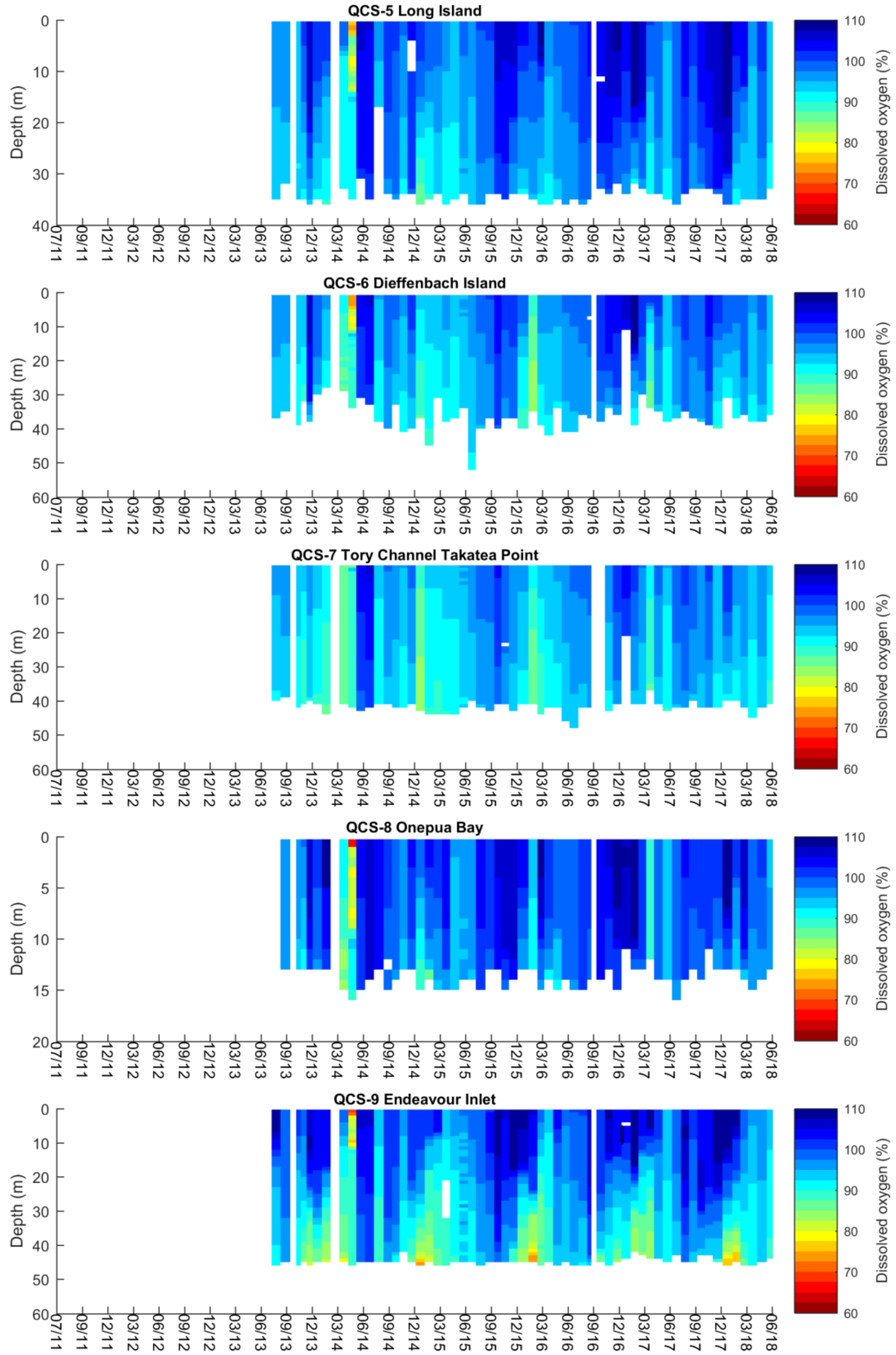


Figure 4-5: Dissolved oxygen measured at one metre below the sea-surface at the five Queen Charlotte water-quality monitoring stations. The dashed line is a best-fit Sen line for the data from the hand-held device calculated after removing seasonal effects. A small number of records from the hand-held sensor have been rejected as being implausibly high saturation (>140%) and concentration but others remain unresolved (see plots). Those records were replaced with near-surface readings from the CTD casts. Black symbols are oxygen saturation (left axis). Red symbols are absolute concentration (right axis). Oxygen saturation is a function of salinity, temperature (and air pressure) as well as absolute oxygen concentration. Thus, the correlation with absolute oxygen concentration is strong, but imperfect.

4.3.2 CTD oxygen profiles

Contour plots of the evolving depth profiles of oxygen saturation through time at the Queen Charlotte and Tory stations from monthly CTD casts are shown in Figure 4-6. Dissolved oxygen saturations are usually high (>80%) throughout the water-column, but near-bed saturations tend to drop during late summer/early autumn. The drops are greater in Endeavour inlet (site QCS-9) and inner Queen Charlotte (sites QCS-1 and QCS-2) than elsewhere. In particular, site QCS-1 has exhibited the lowest annual saturation minima (<70% in most years). The lowest DO saturation (48%) was recorded near-bed at QCS-1.




QCS-5 Long Island
QCS-6 Dieffenbach Island
QCS-7 Tory Channel Takatea Point
QCS-8 Onepua Bay
QCS-9 Endeavour Inlet
Depth (m)
Dissolved oxygen (%)
07/11
09/11
12/11
03/12
06/12
09/12
12/12
03/13
06/13
09/13
12/13
03/14
06/14
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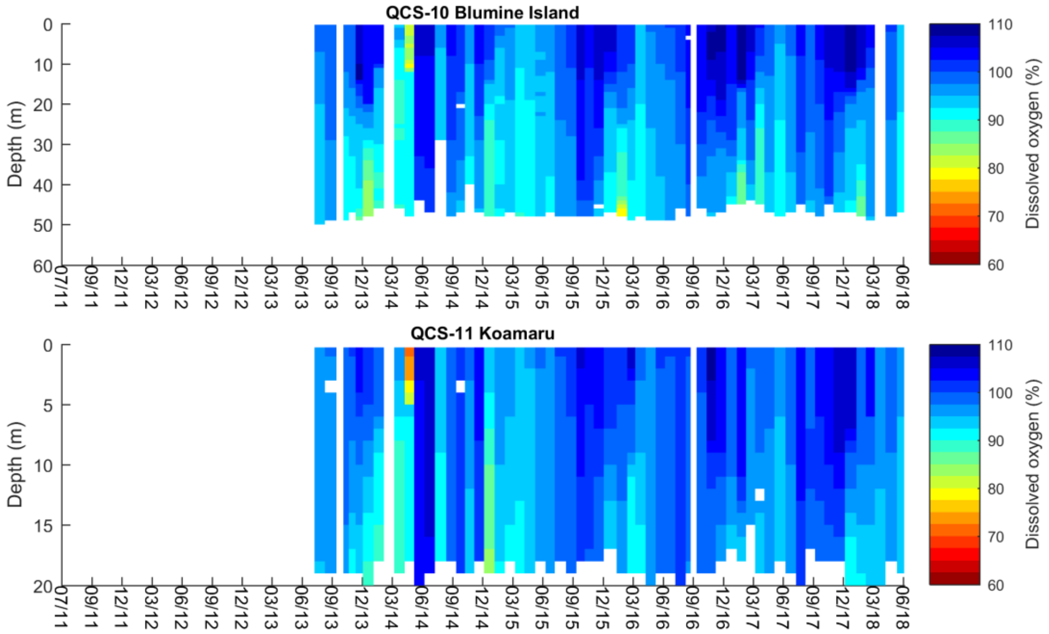


Figure 4-6: Contour plots of the evolving depth profiles of oxygen saturation through time at the Queen Charlotte and Tory stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended). The CTD instrument package did not include a DO sensor until July 2013.

4.4 Suspended inorganic solids

Concentrations of total suspended solids (TSS), suspended inorganic solids (SIS) and [12]volatile (i.e., organic) suspended solids (VSS) all derive from the same initial sample of material. This sample is first dried for several hours at 104 C. The dry material is weighed to yield a TSS-weight. It is then cooked at 400 C for several hours to burn off the organic material. The weight of the material that remains after cooking is the SIS-weight. The weight of volatile suspended solids is calculated as TSS-SIS.

SIS time-series for the 5 sites are plotted in Figure 4-7.

[12] Like particulate (organic) carbon and particulate (organic) nitrogen, volatile suspended solids provides an index of the abundance of particulate organic matter. It is easier to measure than PC or PN – but the detection limits of the technique are poorer (higher).

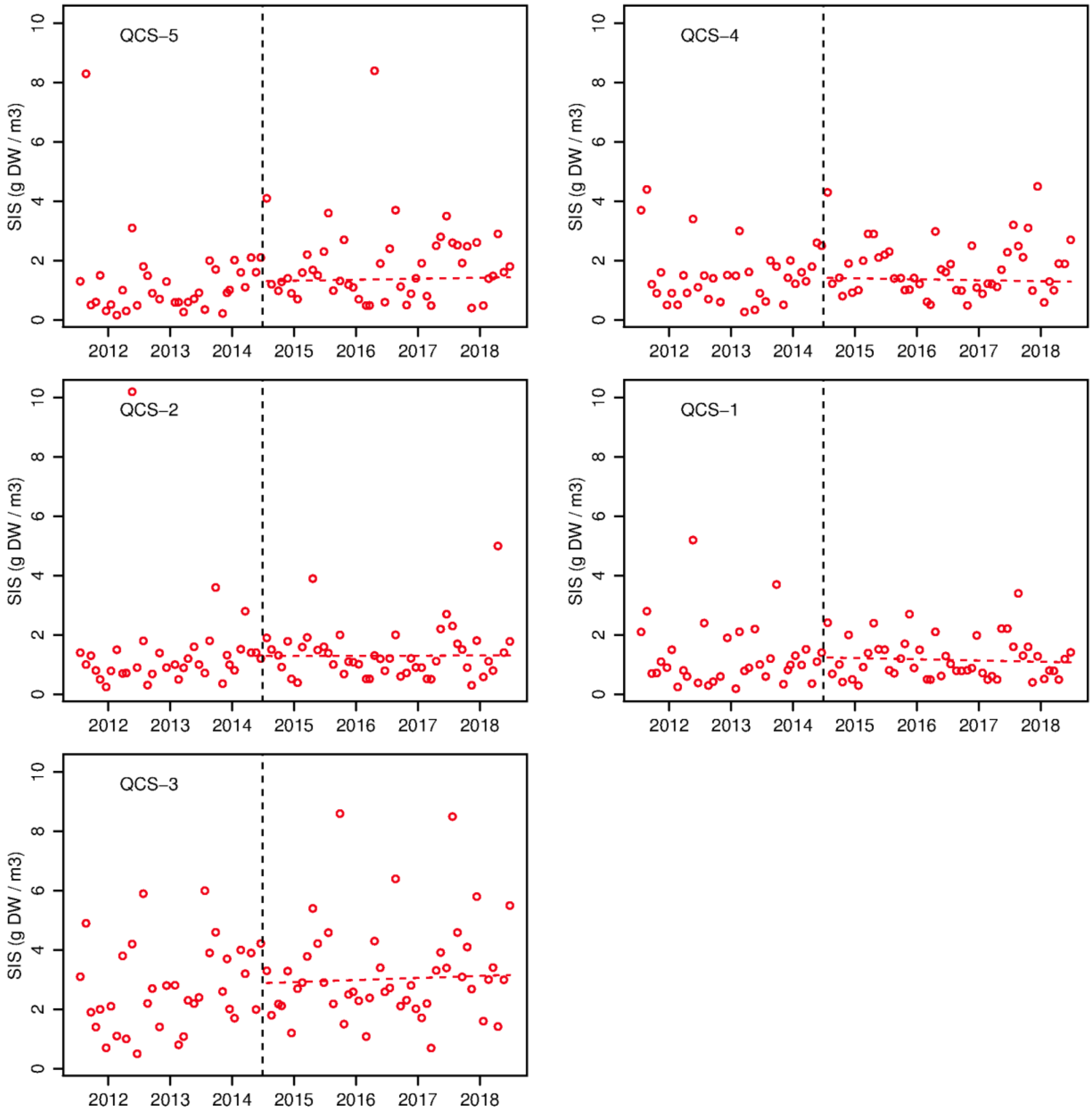


Figure 4-7: Concentrations of suspended inorganic solids measured in the near-surface water-samples of the five Queen Charlotte Sound/Tory Channel stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red line indicates the best-fit Sen-slope line fitted through the de-seasonalised data. If the line is solid, then the sign of the slope can be ascertained with probability >=95% (in this instance, there are no solid lines). If the line is dashed, the sign of this slope is less certain.

4.5 Turbidity

4.5.1 Hose & Van Dorn bottle samples

The majority of turbidity values measured in the upper 15 m of the water column has fluctuated between about 1 NTU and 4 NTU at all sites (Figure 4-8). The highest turbidity has been almost 8 NTU (measured at QCS-5 in outer Queen Charlotte). Turbidities tend to be a bit higher in Tory Channel (QCS-3) than at the remaining four water-quality sites within Queen Charlotte/Tory.

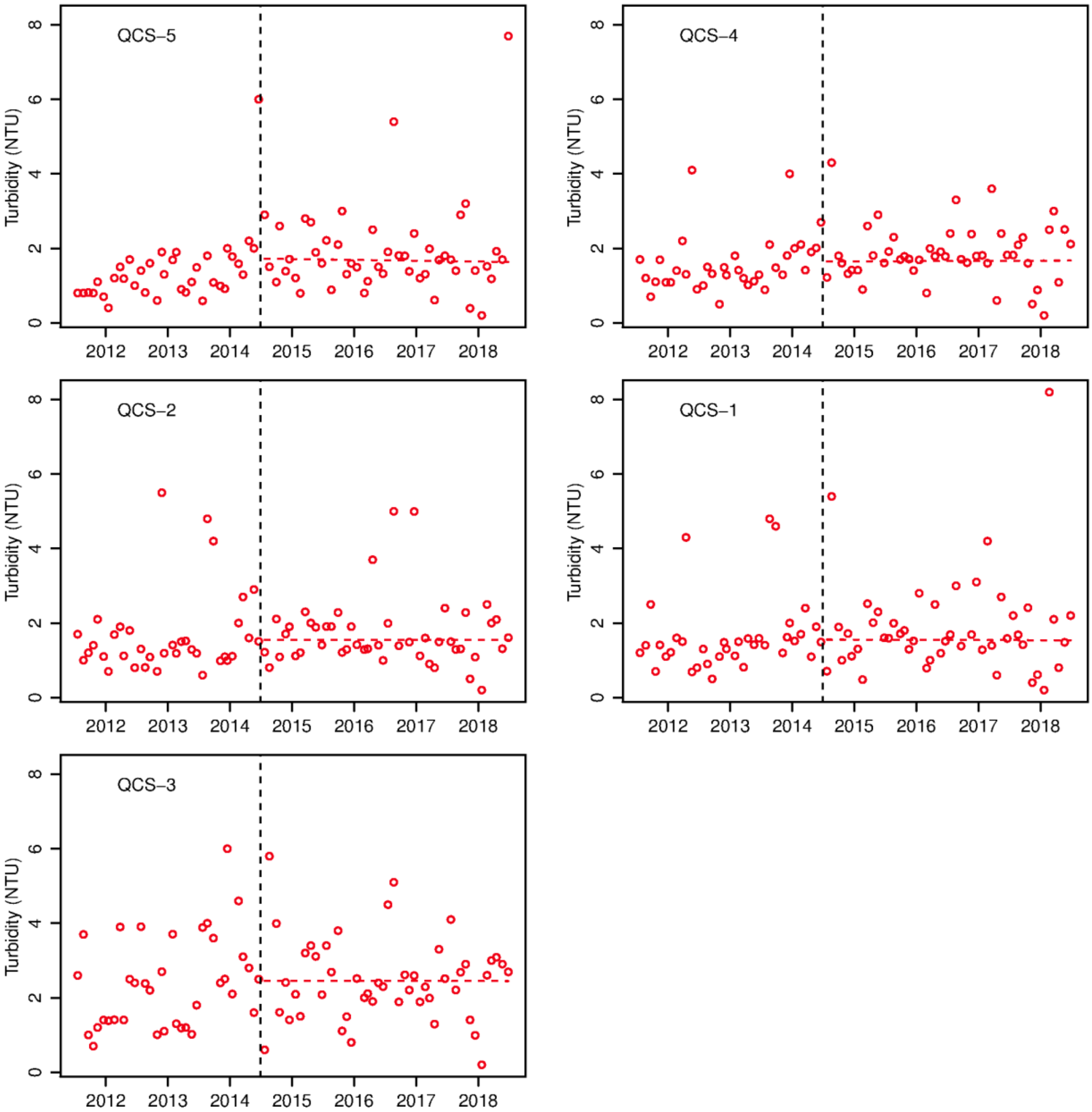
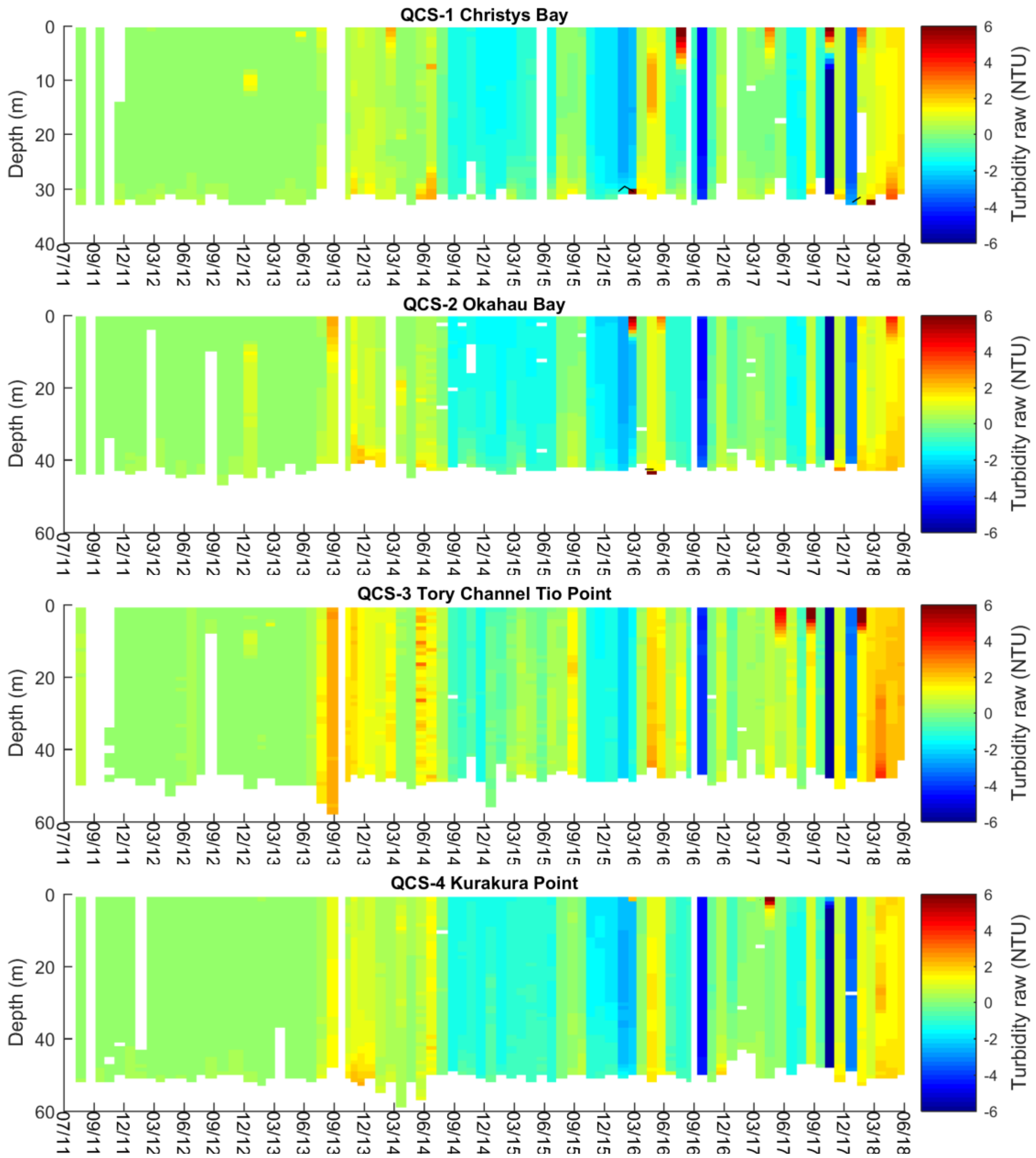
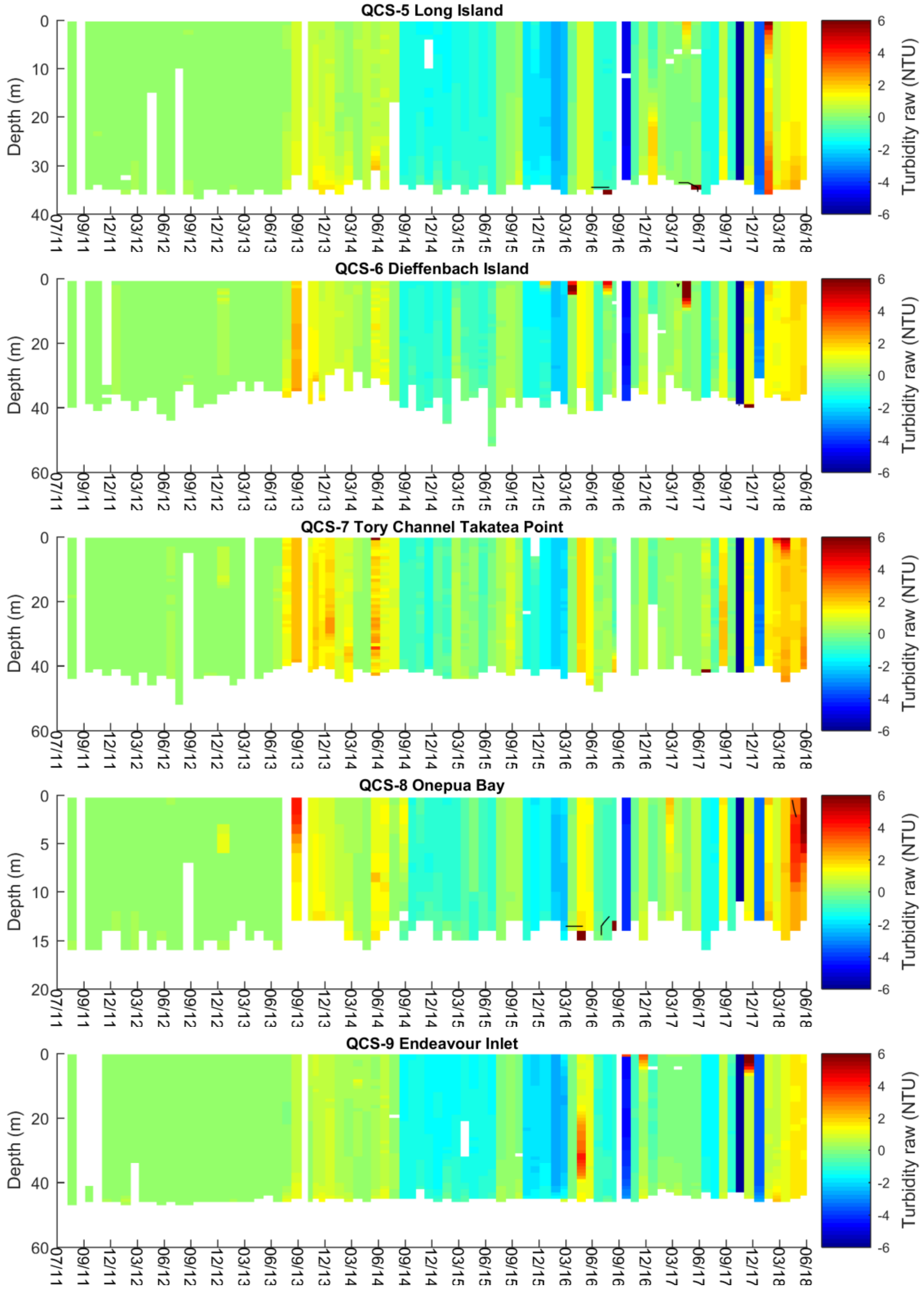


Figure 4-8: Near-surface turbidity measured at the five Marlborough District Council water quality monitoring sites in Queen Charlotte/Tory Channel. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red line indicates the best-fit Sen-slope line fitted through the de-seasonalised data. If the line is solid, then the sign of the slope can be ascertained with probability >=95% (in this instance, there are no solid lines). If the line is dashed, the sign of this slope is less certain.

4.5.2 CTD-turbidity

Contour plots of turbidity through time from the CTD profiles are shown in Figure 4-9. These data are of dubious quality. Frequently, negative turbidity values are obtained which are physically unrealistic. Furthermore, turbidities measured using the sensor that accompanied the CTD are often inconsistent with those measured in the water-samples that were returned to the laboratory. There is considerable variation over time at all sites. Between sites, turbidity values recorded at the same time generally have a similar range. This suggests changes in sensor calibration or performance over time. The CTD turbidity observations may be useful for comparing between sites, and over depth at a site, but not for comparing changes over time. CTD turbidity data may be improved by comparing to the water sample reported above, but a preliminary inspection showed that the relationship between CTD turbidity and water sample turbidity changes significantly over time, and a thorough analysis was beyond the scope of the present work. Turbidity monitoring may be improved by more frequent sensor calibration, and/or use of a calibration standard to reference data from each period.




QCS-5 Long Island
QCS-6 Dieffenbach Island
QCS-7 Tory Channel Takatea Point
QCS-8 Onepua Bay
QCS-9 Endeavour Inlet
Depth (m)
Turbidity raw (NTU)
07/11
09/11
12/11
03/12
06/12
09/12
12/12
03/13
06/13
09/13
12/13
03/14
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03/18
06/18

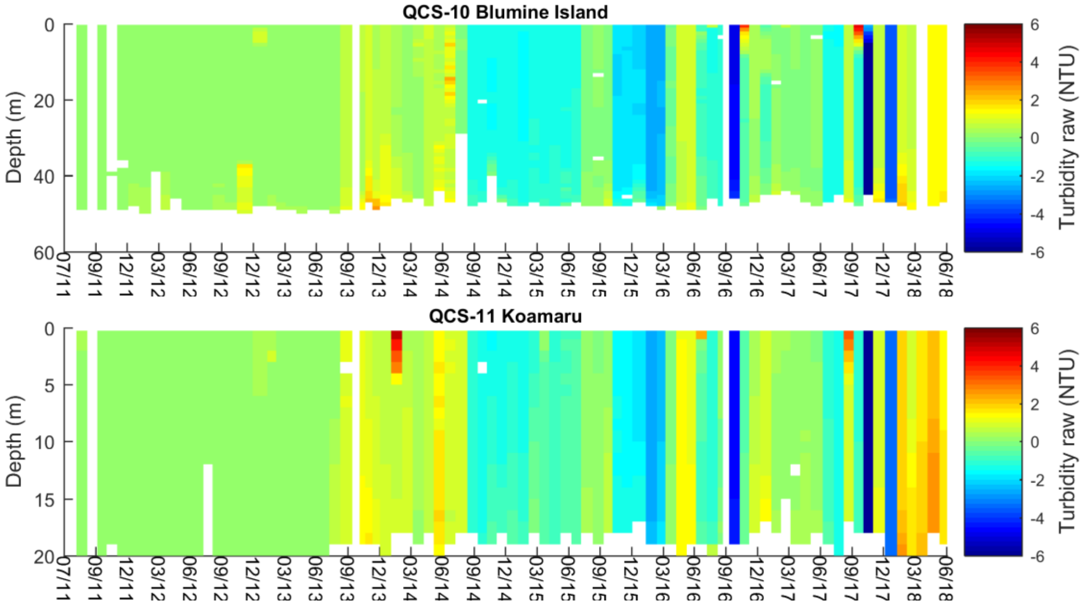


Figure 4-9: Raw turbidity from Queen Charlotte Sound as recorded by the turbidity sensor on the CTD probe. These data are of dubious quality. Negative turbidity values are physically unrealistic; furthermore, the turbidities measured using the sensor that accompanied the CTD are often inconsistent with those measured in the water-samples that were returned to the laboratory.

4.6 Dissolved reactive phosphorus

DRP fluctuates seasonally between about 5-10 mg P m^{-3} in summer and 15-20 mg P m^{-3} in the winter (Figure 4-10 and Table B-1). Near-bed concentrations tend to be higher than near-surface ones at stations QCS 1, 2, 4 & 5 – particularly during the summer months. The sign of the Sen-slope trend lines cannot usually be determined with great confidence, but DRP does appear to have trended downward in the surface waters of QCS-5 and upward in the near-bed waters at QCS-2.

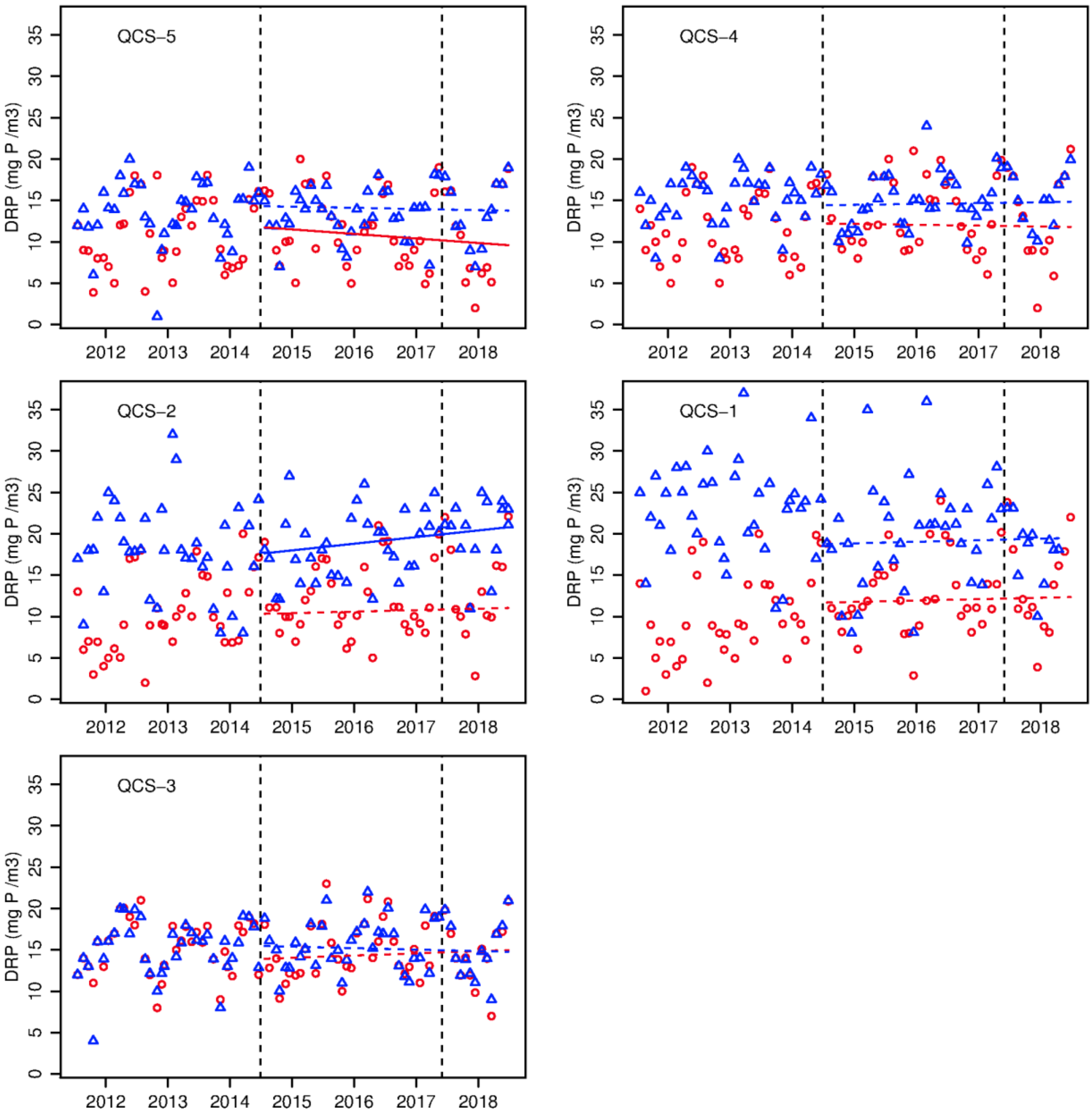


Figure 4-10: Time-series of dissolved reactive phosphorus measured near the surface (red) and near the seabed (blue) at the MDC sampling sites in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data collected after 1 July 2014. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.7 Total dissolved phosphorus

Like DRP, TDP shows an annual cycle (Figure 4-11 and Table B-1) and like TDP, there is little evidence of long-term trends – expect perhaps at QCS-2 (rising trend near-bed). TDP includes the organic forms of dissolved P, combined with inorganic dissolved P.

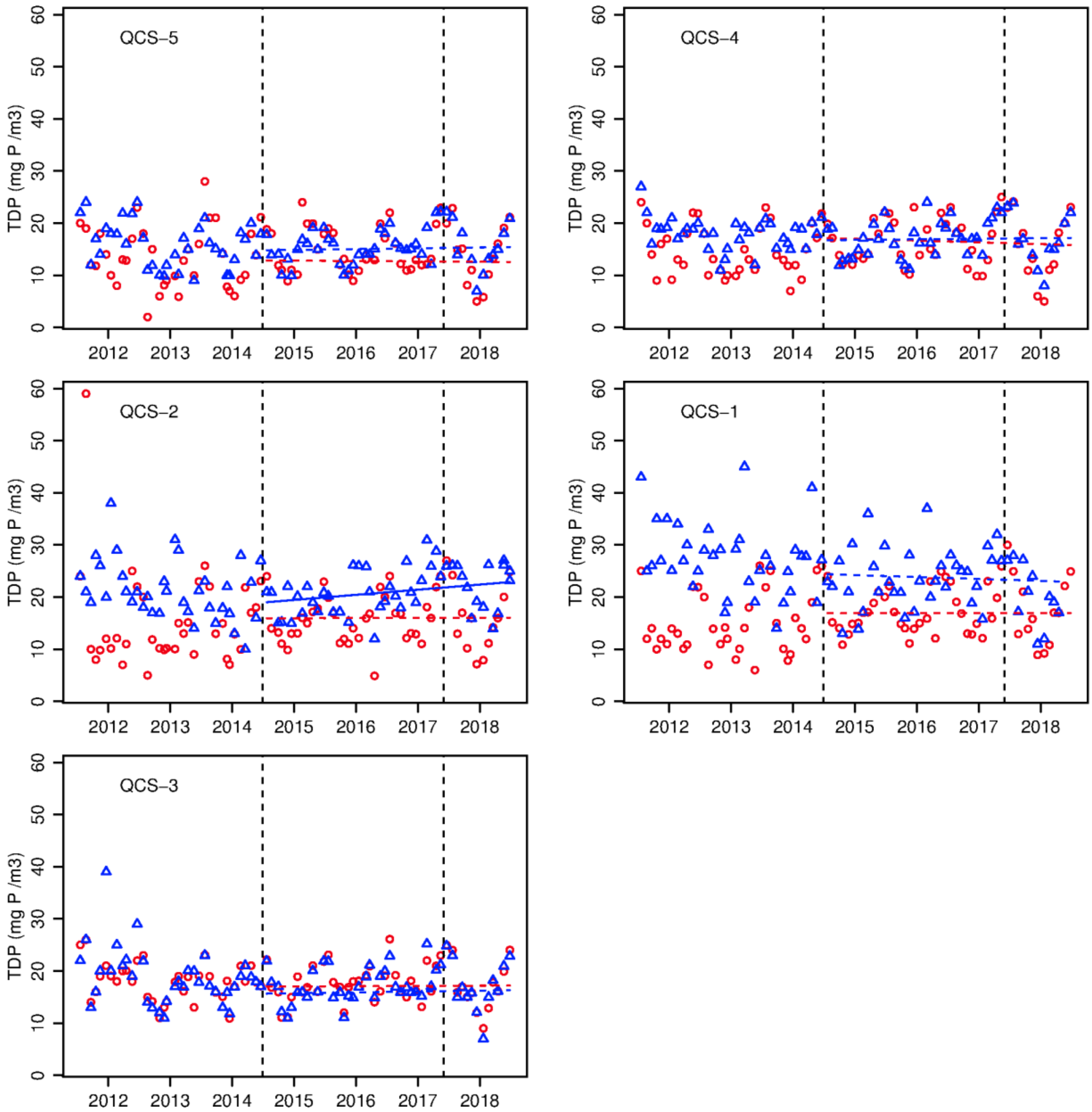


Figure 4-11: Total dissolved near-surface (red) and near-bed (blue) phosphorus measured at the five Marlborough District Council stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.8 Dissolved organic phosphorus

Dissolved organic phosphorus has been calculated by subtracting measured DRP concentrations from measured TDP concentrations. The inferred concentrations of dissolved organic phosphorus are usually low (Figure 4-12). Indeed, they are sometimes negative. In the real-world, negative concentrations are impossible. The negatives arise because of unavoidable sampling/measurement error (imprecision) associated with the measurements of DRP and TDP. The signs of the slopes of the trend-lines are uncertain everywhere but QCS-5 near-bed (where the trend appears to have been upward).

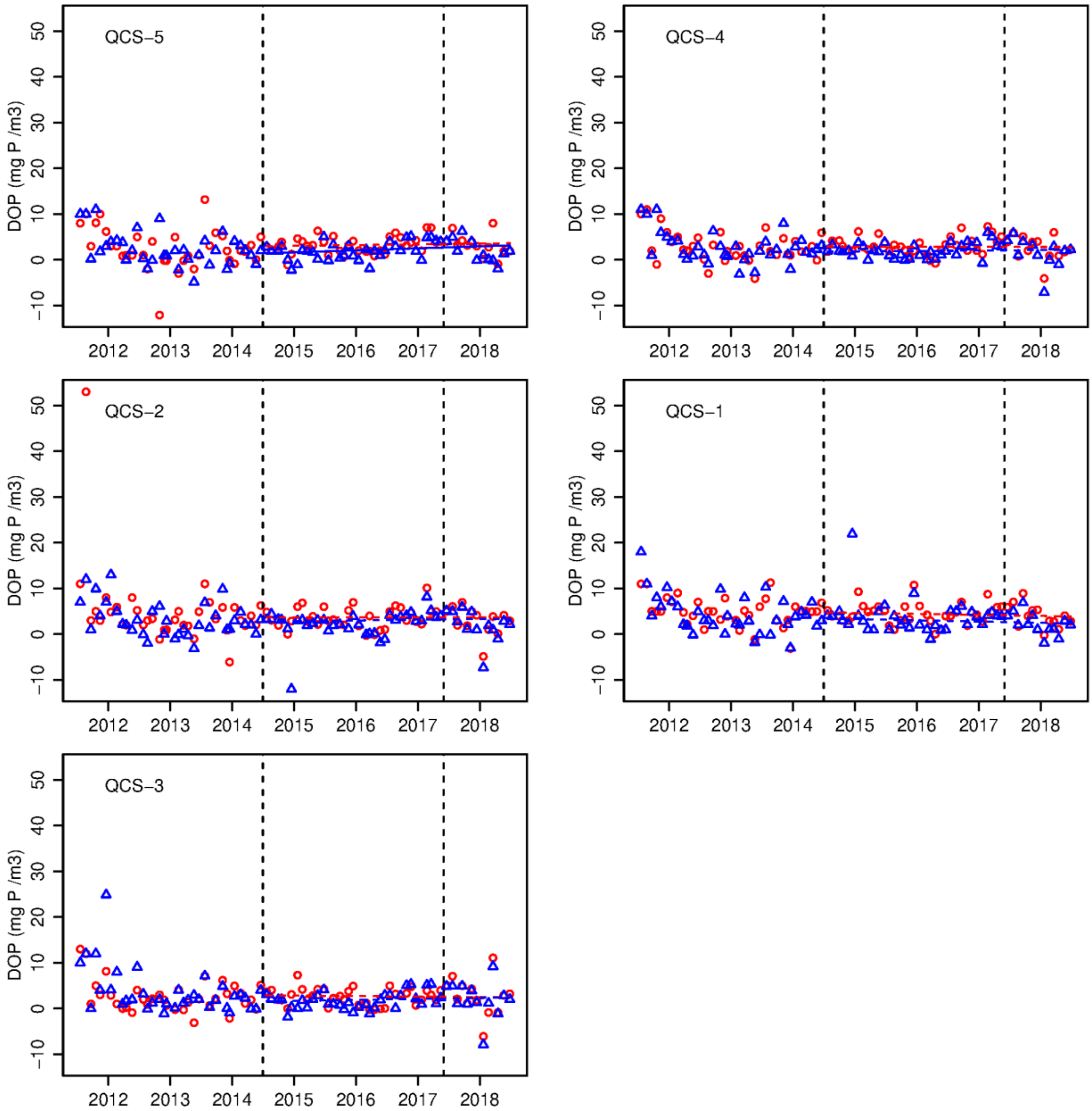


Figure 4-12: Inferred near-surface (red) and near-bed (blue) dissolved organic phosphorus (TDP-DRP) at the five Marlborough District Council water quality sites in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.9 Dissolved reactive silicon

Dissolved reactive silicon was not measured during the first 12 months of the program. DRSi concentrations exhibit weak annual cycles at all sites (Figure 4-13, Table B-1). Near-bed concentrations tend to be greater than near-surface ones (except at QCS-3). The signs of the Sen-slope trends can be confidently determined (to be positive) at sites QCS-3 (surface and bed) and QCS-2 (bed).

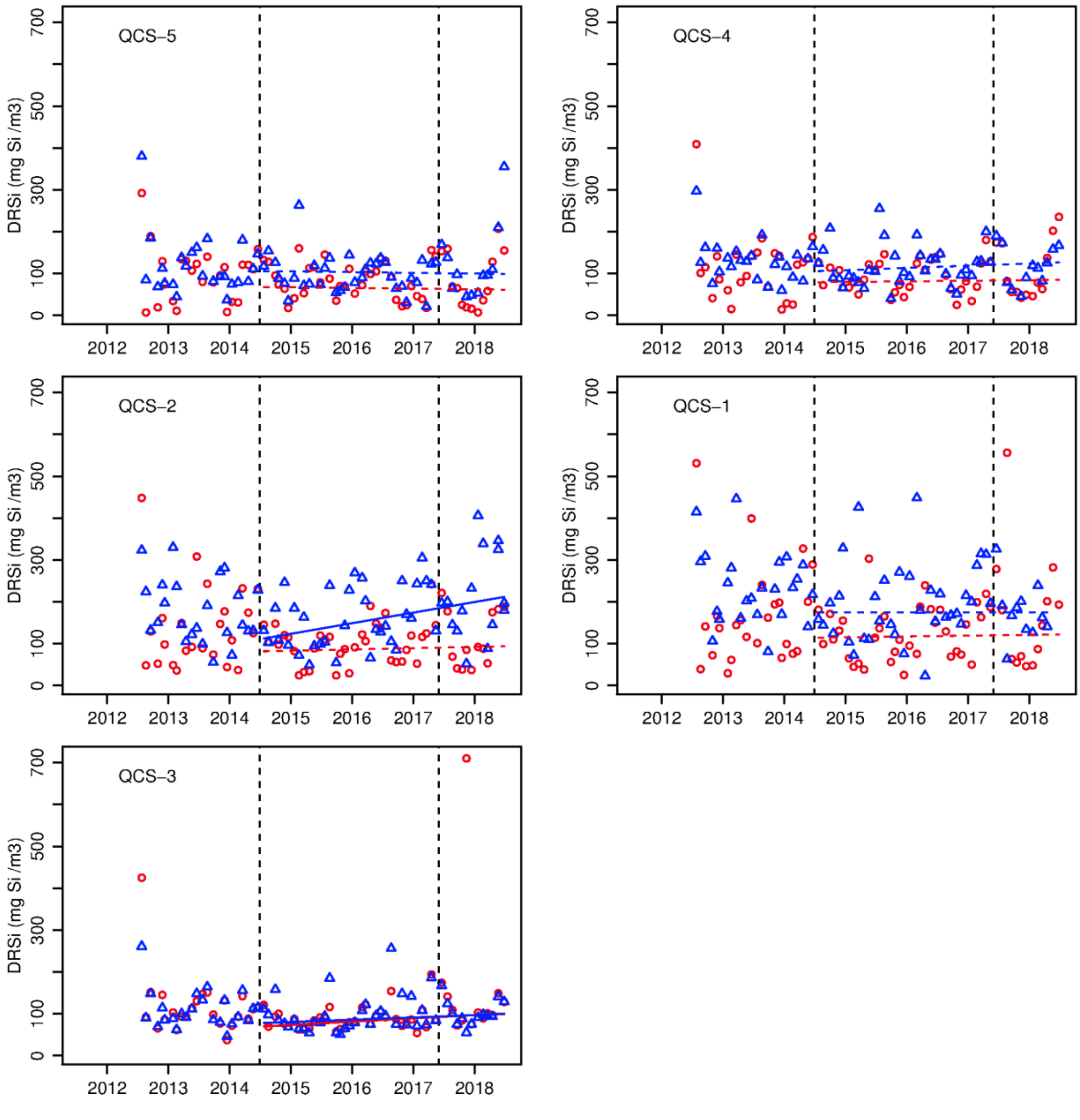


Figure 4-13: Dissolved reactive silicon concentrations near-surface (red) and near-bed (blue) at the five Marlborough District Council water quality stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.10 Total dissolved nitrogen

Total dissolved nitrogen concentrations have usually been <250 mg N m^{-3} (Figure 4-14). They exhibit an annual cycle at all sites (tending to be highest in late winter, Table B-1) and tend to be more abundant in the near-bed waters. The sign of the Sen-slopes can be confidently determined only in the near-bed data from site QCS-3 (where the sign is positive).

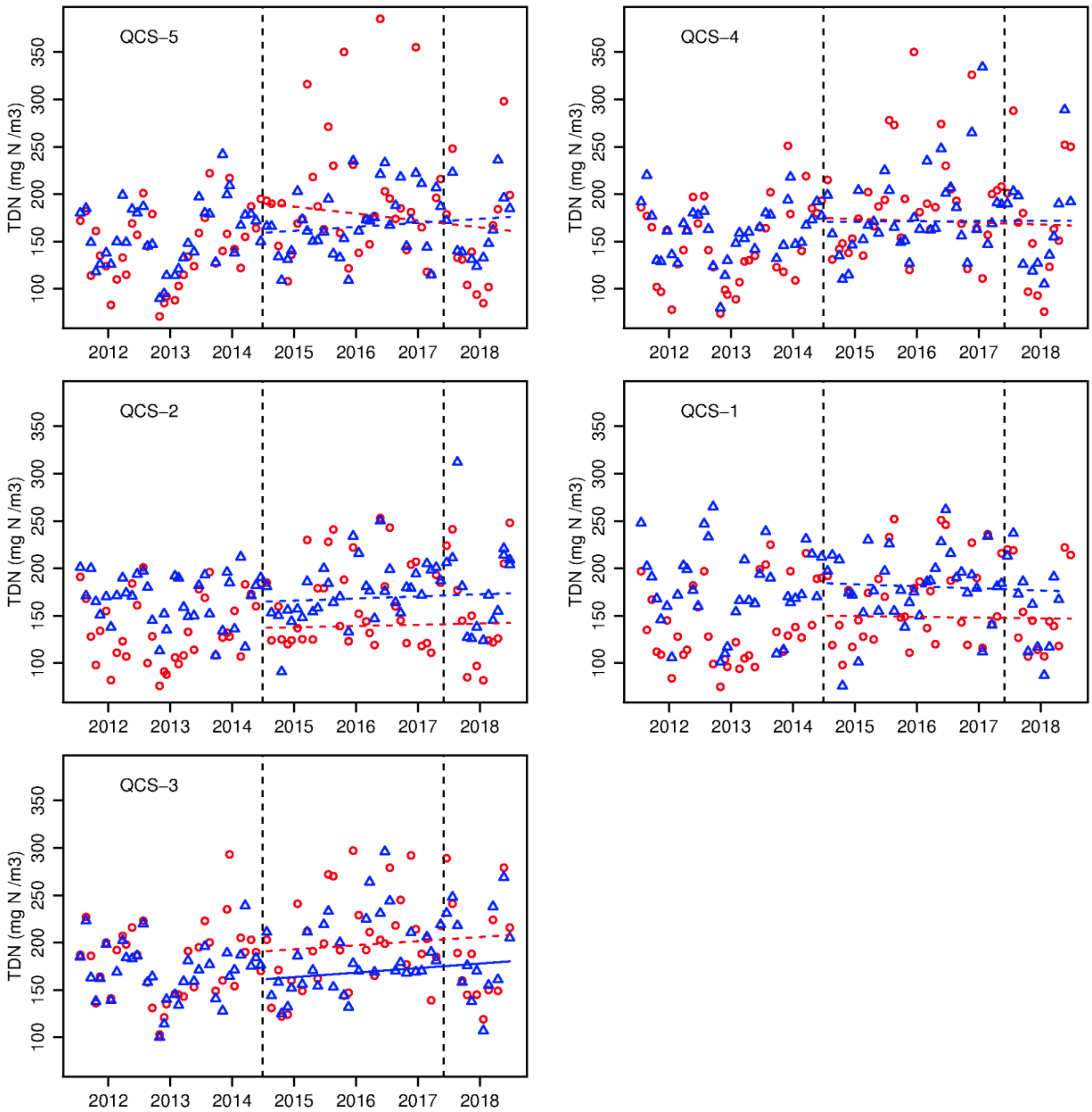


Figure 4-14: Total dissolved nitrogen near-surface (red) and near-bed (blue) measured at the five Marlborough District Council water-quality stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.11 Nitrate

Nitrate concentrations exhibit a large-amplitude annual cycle at all stations (Table B-1). Concentrations are higher during the winter than during the summer (Figure 4-15). Indeed, at stations QCS-1, 2, 4 & 5 the surface-water nitrate concentrations are often below the detection limit during the summer. The Sen-slope trend signs are positive at all sites, and these signs are deemed to have been confidently identified in six of the ten cases (five sites, two depth strata per site).

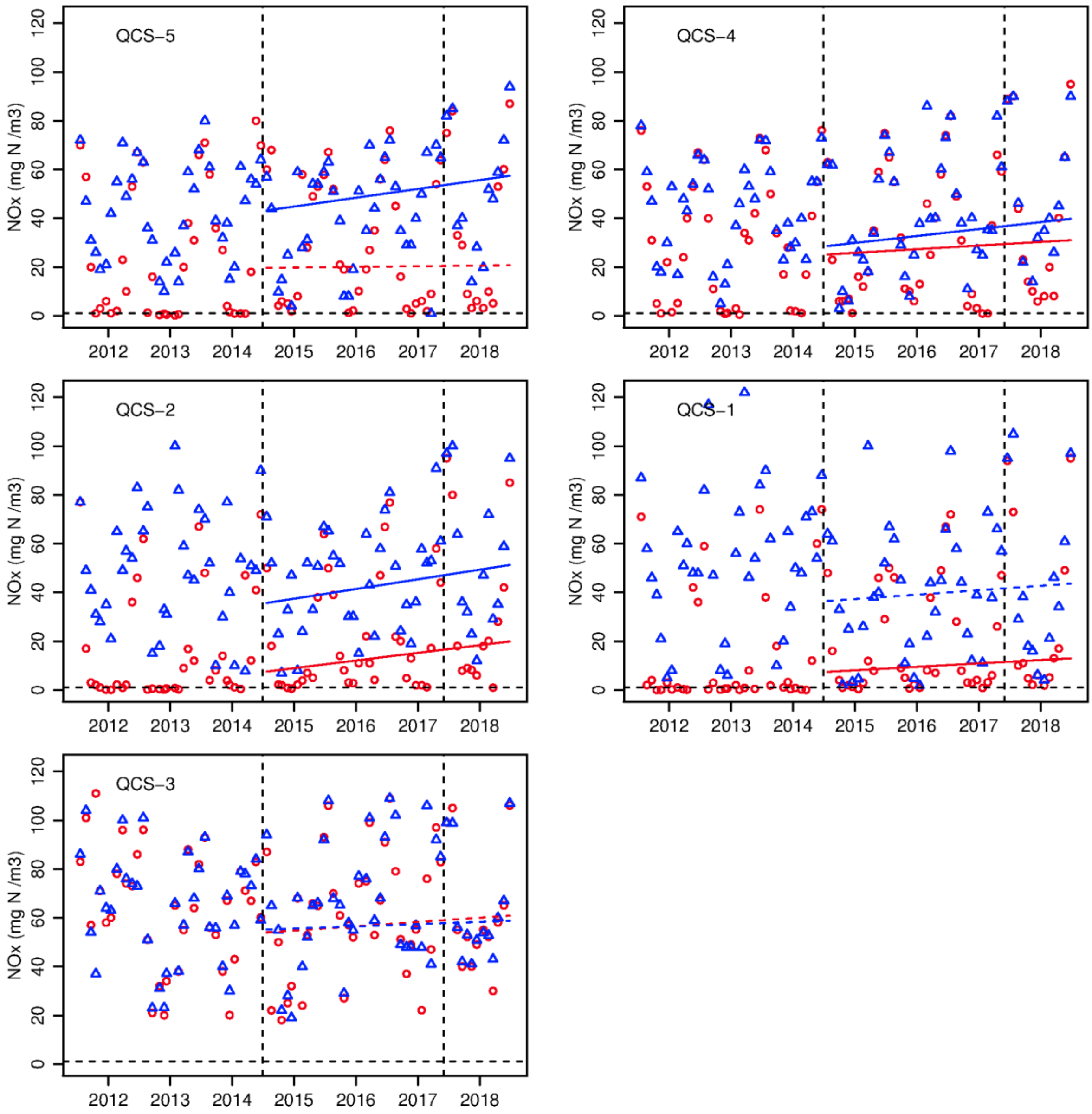


Figure 4-15: Nitrate concentrations near-surface (red) and near-bed (blue) measured at the five Marlborough District Council water-quality stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The detection limit is 1 mg N m^{-3} (horizontal dashed line). Values recorded as “<detection” have been replaced with imputed values calculated using regression-on-order methods. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.12 Ammoniacal nitrogen

Ammoniacal nitrogen concentrations tend to be highest during the summer months and lowest during the winter ones (Figure 4-16**,** Table B-1). All of the Sen-slopes are negative and nine out of the ten are deemed to have been confidently identified as such.

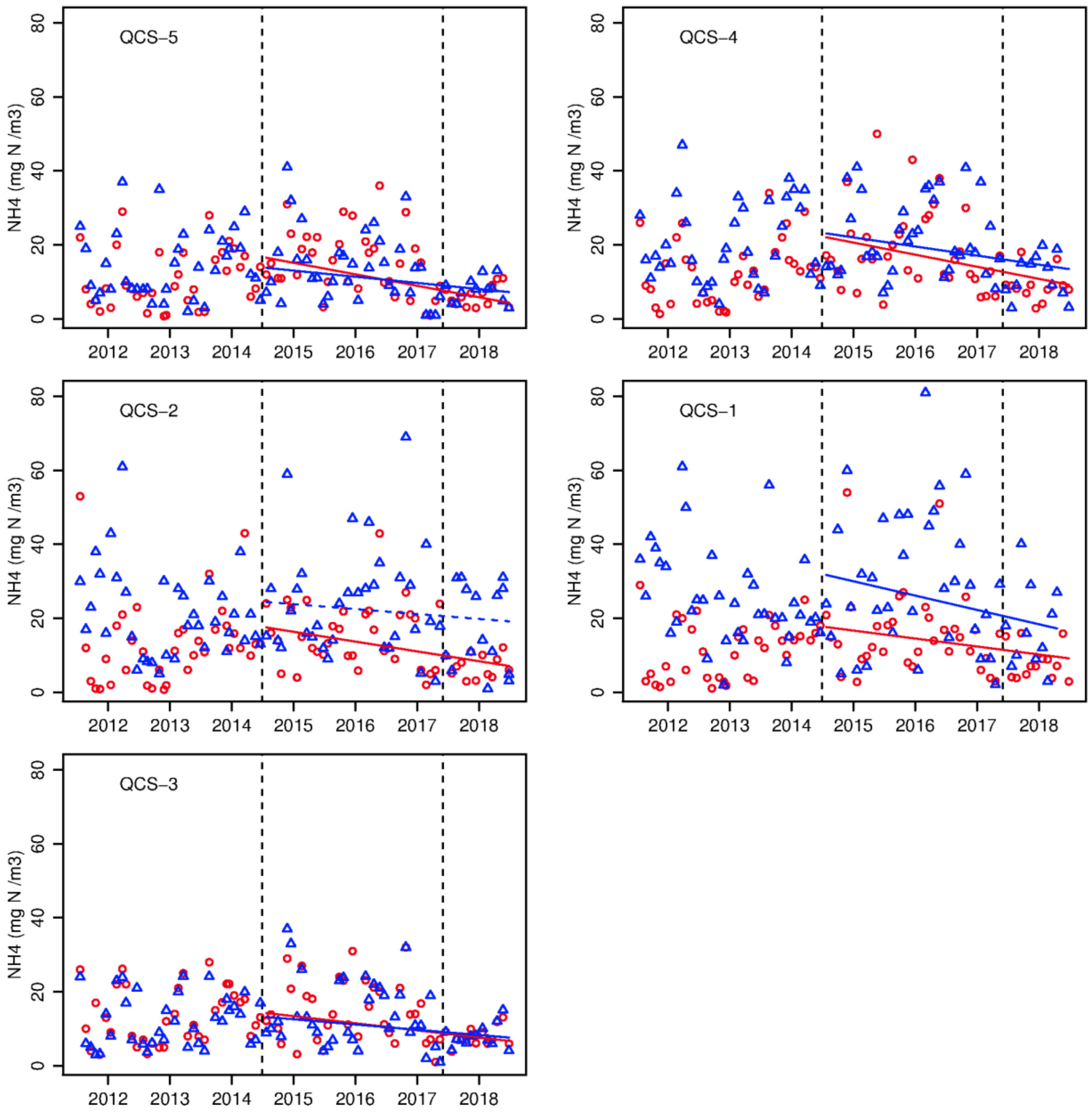


Figure 4-16: Ammoniacal nitrogen near-surface (red) and near-bed (blue) measured at the five Marlborough District Council water-quality stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.13 Dissolved inorganic nitrogen

Dissolved inorganic nitrogen (DIN) is the sum of oxidized nitrogen (section 4.11) and ammoniacal nitrogen (section 4.12). We have seen that oxidized nitrogen concentrations have tended to rise and that ammoniacal nitrogen concentrations have tended to fall. At most sites, the slope of concentration trend for DIN is close to zero and the sign of the slope cannot be reliably determined (Figure 4-17: Dissolved inorganic nitrogen concentrations measured near-surface (red) and near-bed (blue) measured at the five Marlborough District Council water-quality stations in Queen Charlotte Sound.).

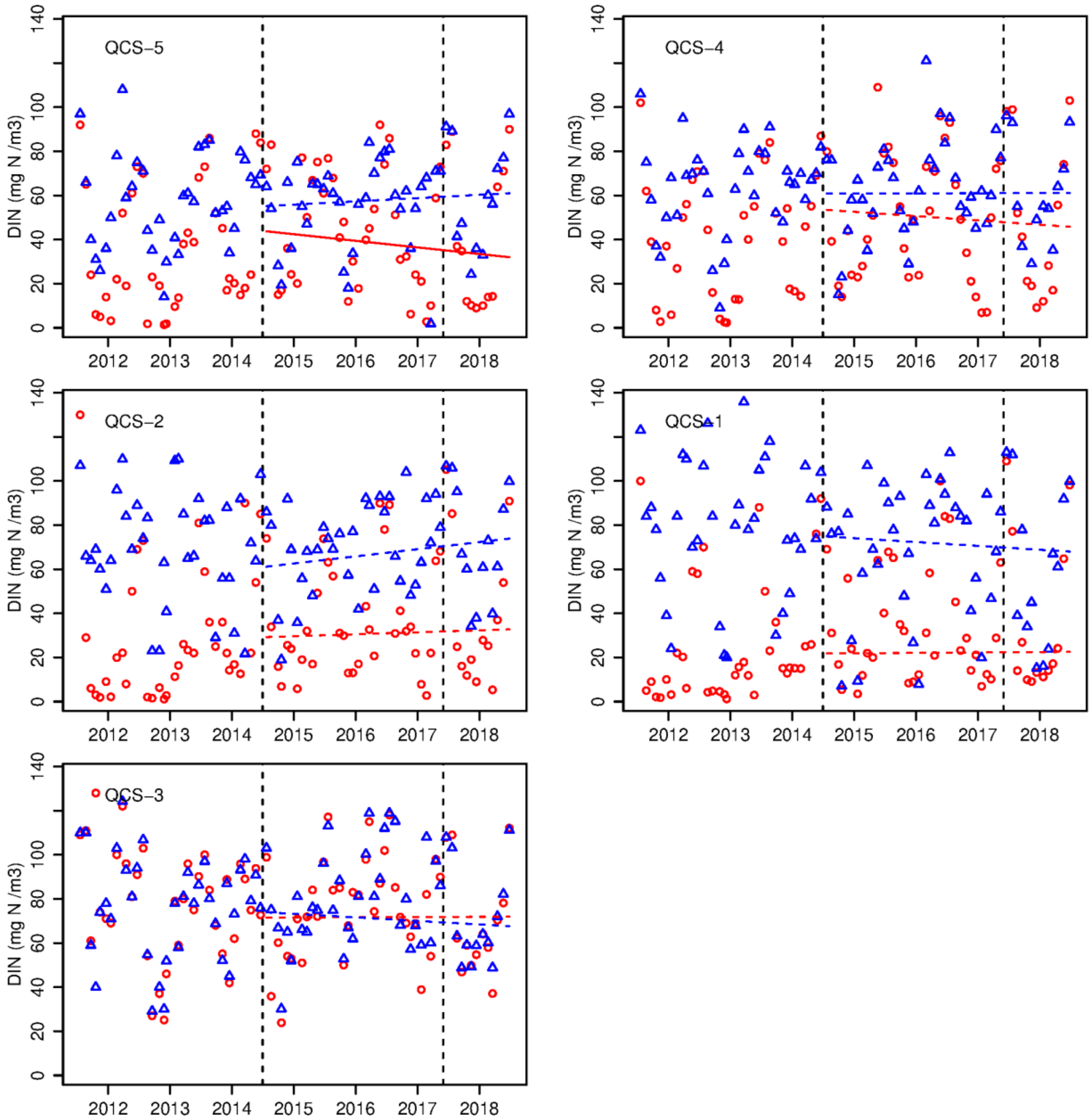


Figure 4-17: Dissolved inorganic nitrogen concentrations measured near-surface (red) and near-bed (blue) measured at the five Marlborough District Council water-quality stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical dashed line in mid-2017 indicates the date on which a new nutrient analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.14 Dissolved organic nitrogen

DON concentration is calculated by subtracting DIN from TDN. Near surface DON concentrations tend to be a little greater than near-bed ones (even at QCS-3), but unlike many of quantities, the annual cycles are weak or absent (Figure 4-18, Table B-1).

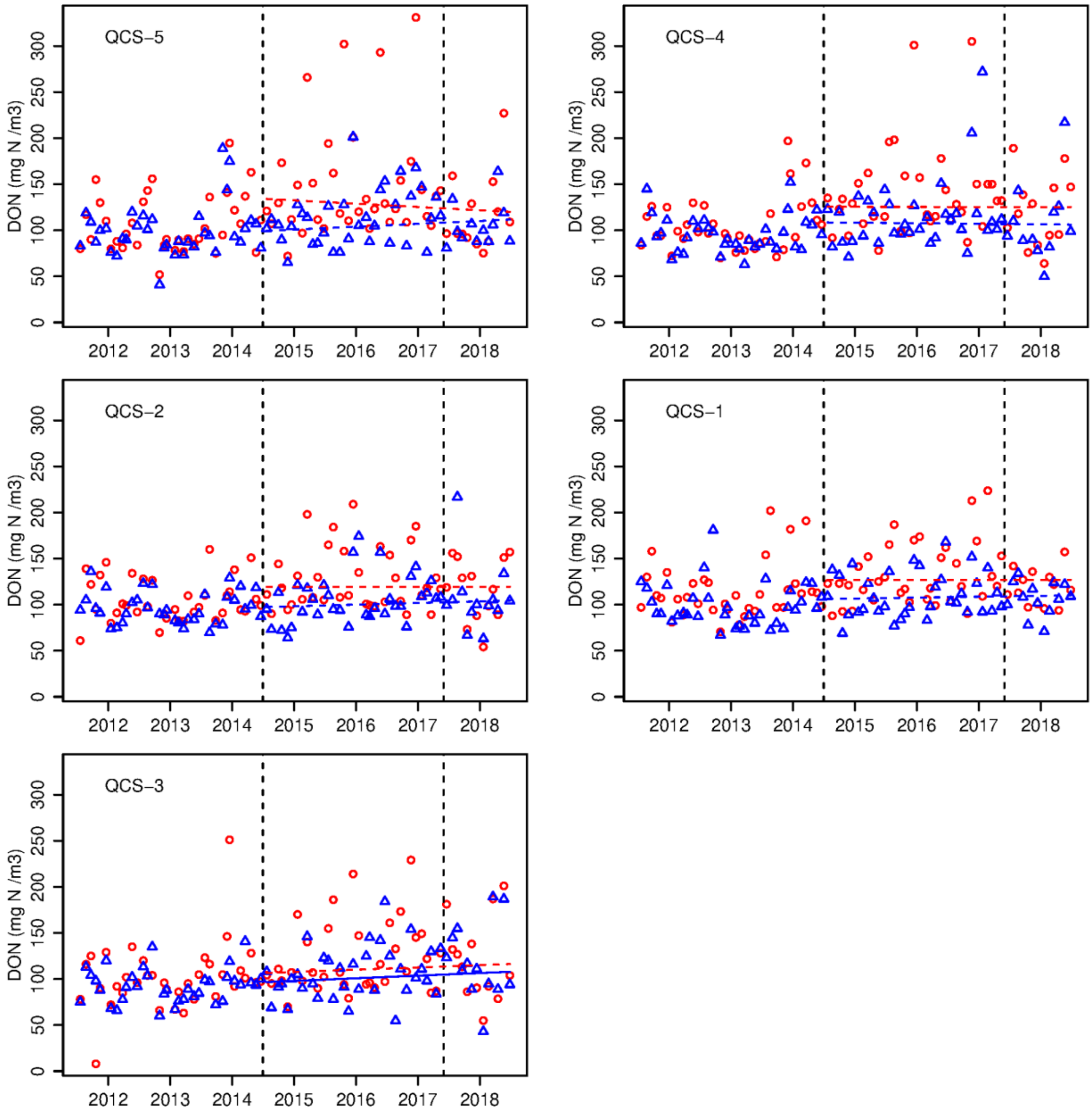


Figure 4-18: Inferred dissolved organic nitrogen concentrations near-surface (red) and near-bed (blue) at the five Marlborough District Council stations in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.15 Particulate nitrogen

Particulate nitrogen concentrations tend to peak in late spring/early summer and/or autumn (dep upon site) (Table B-1). In the surface waters, there is some evidence that concentrations measured since July 2014 tend to have been higher than those measured before then. We have not undertaken any statistical analysis to verify that impression. If real, we believe that reflects the switch from Van Dorn sampling at a fixed depth to hose sampling over the upper 15 m. PN concentrations are almost invariably higher in the near-surface samples than in the near-bed ones, and those measured in Tory Channel (QCS-3) tend to be lower than those measured elsewhere. At most sites, the sign of the Sen-slope trend line cannot confidently be determined but PN seems to have trended downward in the surface waters of QCS-5 and upward in the bottom waters of QCS-3.

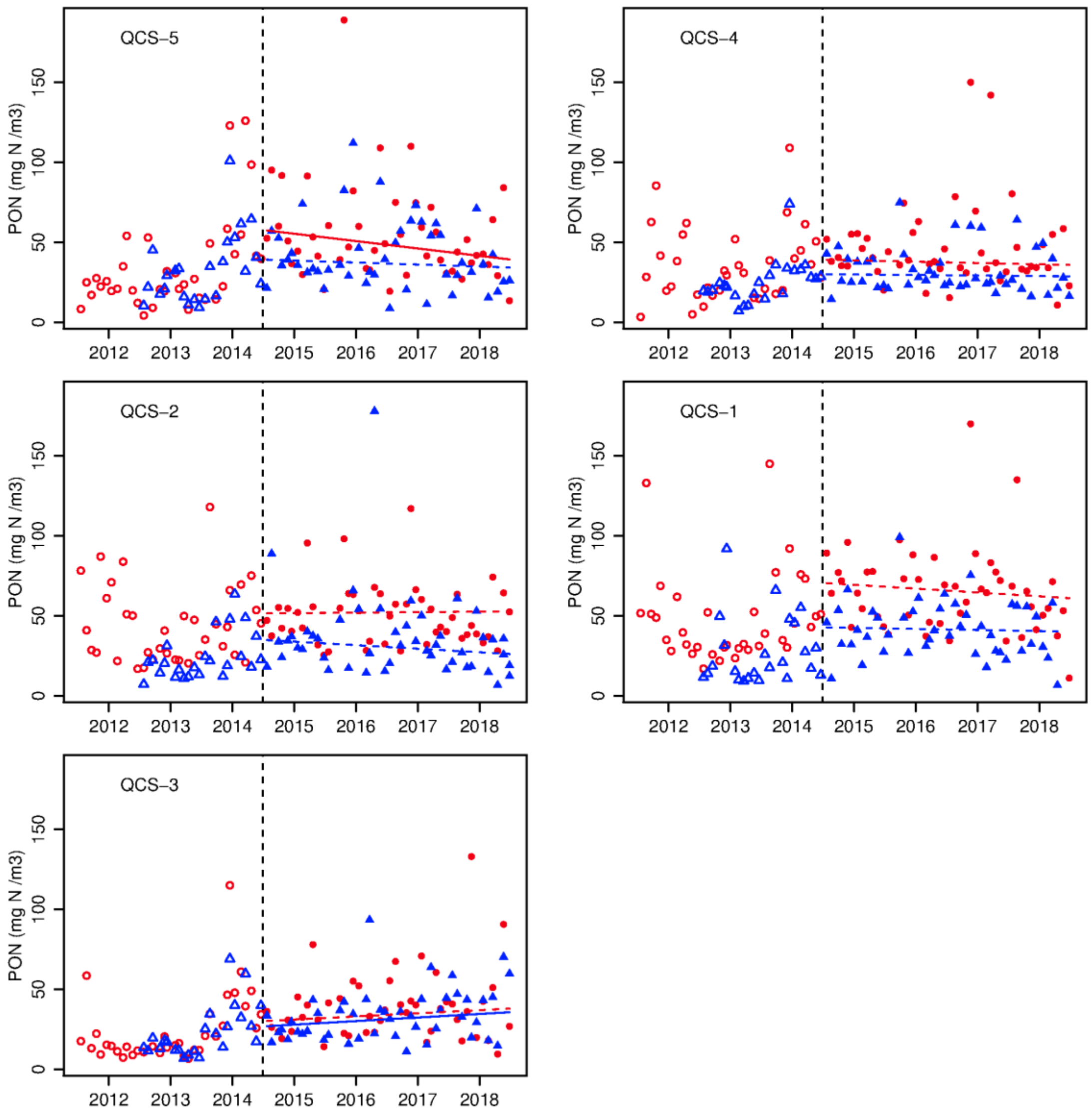


Figure 4-19: Particulate nitrogen near-surface (red) and near-bed (blue) at the five Marlborough District Council monitoring stations in Queen Charlotte Sound. The dashed vertical line (July 1, 2014) separates measurements of Particulate Organic Nitrogen sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Nitrogen measured sampled from the upper 15 using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.16 Particulate carbon

Particulate carbon concentrations rose relatively abruptly at all sites during the latter part of 2013 (Figure 4-20). The nature of the sampling and laboratory regimes did not change during the period of the rapid rise. Near surface concentrations tend to be greater than near-bed ones. The signs of the Sen-slopes can be confidently said to be negative in four of ten cases, but five of the remaining six signs are also negative (though their confidence bounds span zero). PC concentrations at QCS-3 show lesser trend than those at other sites.

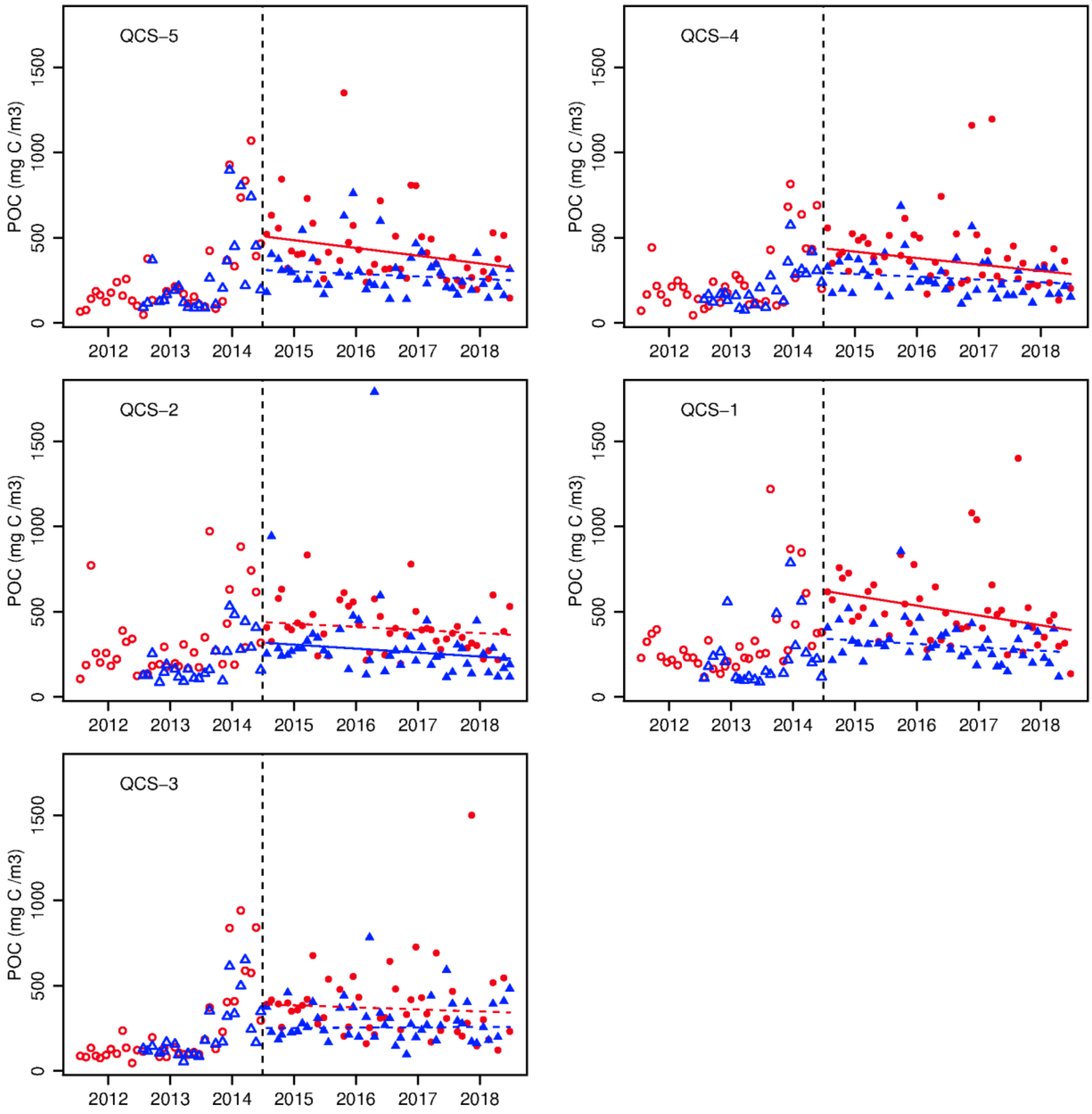


Figure 4-20: Particulate carbon near-surface (red) and near-bed (blue) at the five Marlborough District Council monitoring stations in Queen Charlotte Sound. The dashed vertical line (July 1, 2014) separates measurements of Particulate Organic Carbon sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Carbon measured sampled from the upper 15 using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.17 PN:PC

In comparison with terrestrial particulate organic matter, fresh marine particulates (living plankton and freshly dead plankton) tends to have a high N:C content. The majority of PN:PC ratios have fallen between about 0.05 and 0.15 Figure 4-21. There have been a few values greater than 0.2. Such large values are very improbable (and suggest that either the PN concentration has been over-estimated, or the PC concentration under-estimated in those instances). PN:PC ratios fell during the period 2011-2014 and have tended to climb since then. There is little, or no seasonality to the PN:PC ratios (Table B-1). The majority of PN:PC values are below (but often close to) the so-called 'Redfield ratio'. This ratio is an empirically determined ratio for the elemental content of phytoplankton in oceanic waters (16:106, by moles). The fact that the PN:PC ratio is close to the Redfield ratio suggests that a majority of the particulate matter in the water is derived from algal material (or, at least, protein rich material) rather than terrigenous leaf- and stick-litter etc., (Zeldis, J.R., Howard-Williams et al. 2008). This material is likely to decay moderately rapidly (Enríquez, Duarte et al. 1993).

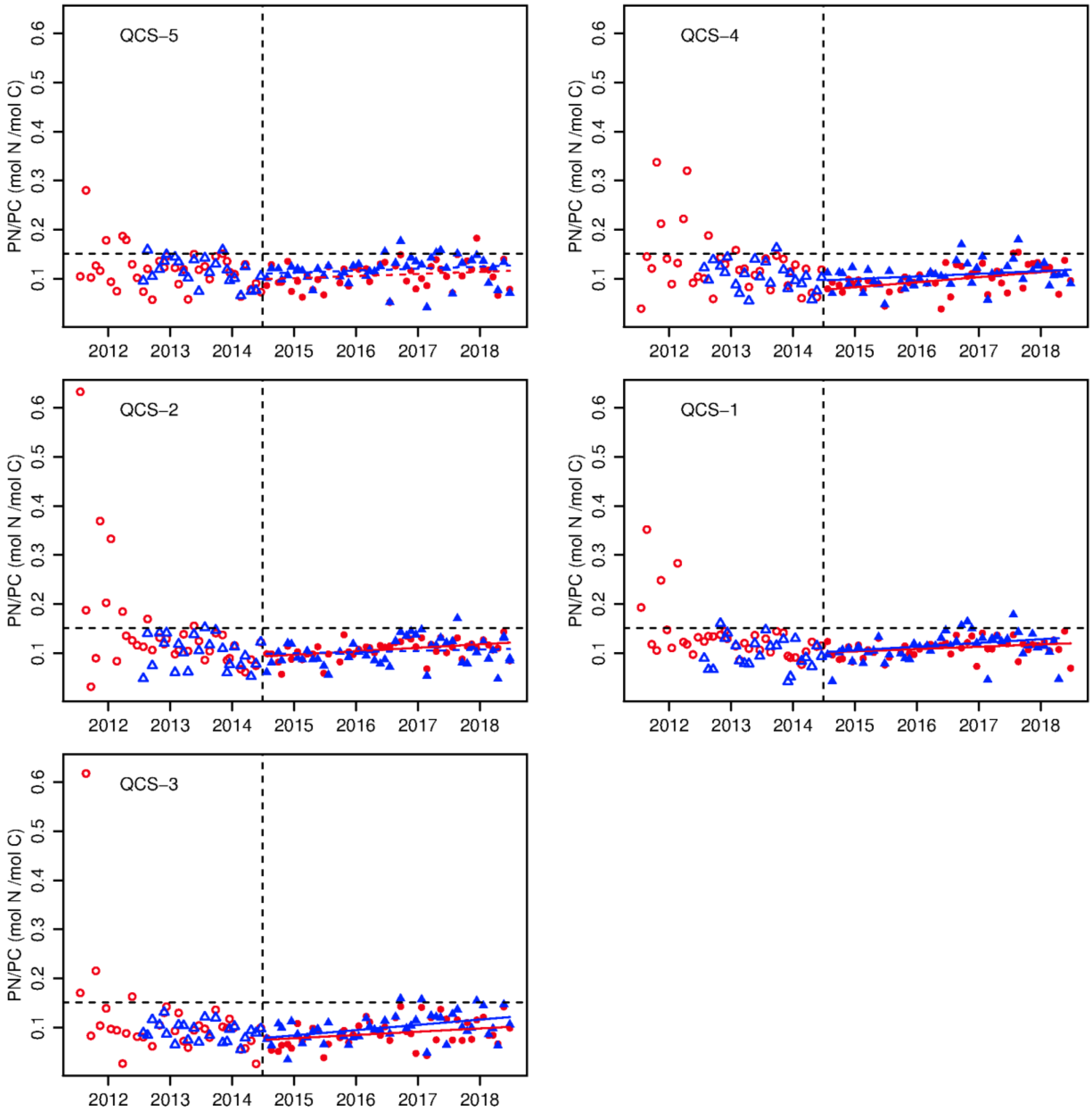


Figure 4-21: PN:PC ratios in near-surface (red) and near-bed (blue) samples at the five Marlborough District Council sampling sites in Queen Charlotte Sound. The vertical dashed line (1 July, 2014) separates measurements of Particulate Organic Carbon sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Carbon measured sampled from the upper 15 using a hose-sampler. The horizontal dashed line represents the so-called 'Redfield ratio' (empirically determined N:C ratio for particulate material in oceanic waters). The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.18 Total nitrogen

Here, total nitrogen is determined as the sum of particulate and total dissolved nitrogen. Total nitrogen concentrations have fluctuated between about 100 mg N m^{-3} and about 500 mg N m^{-3} but the vast majority of records are less than 300 mg N m^{-3}. 300 mg N m^{-}3 is a trigger-level associated with monitoring of NZKS salmon farms. There has been one period where this threshold has been exceeded at least one site on three sequential sampling occasions (May-July 2016).

The signs of the Sen-slopes for TN trend cannot be confidently determined from the data.

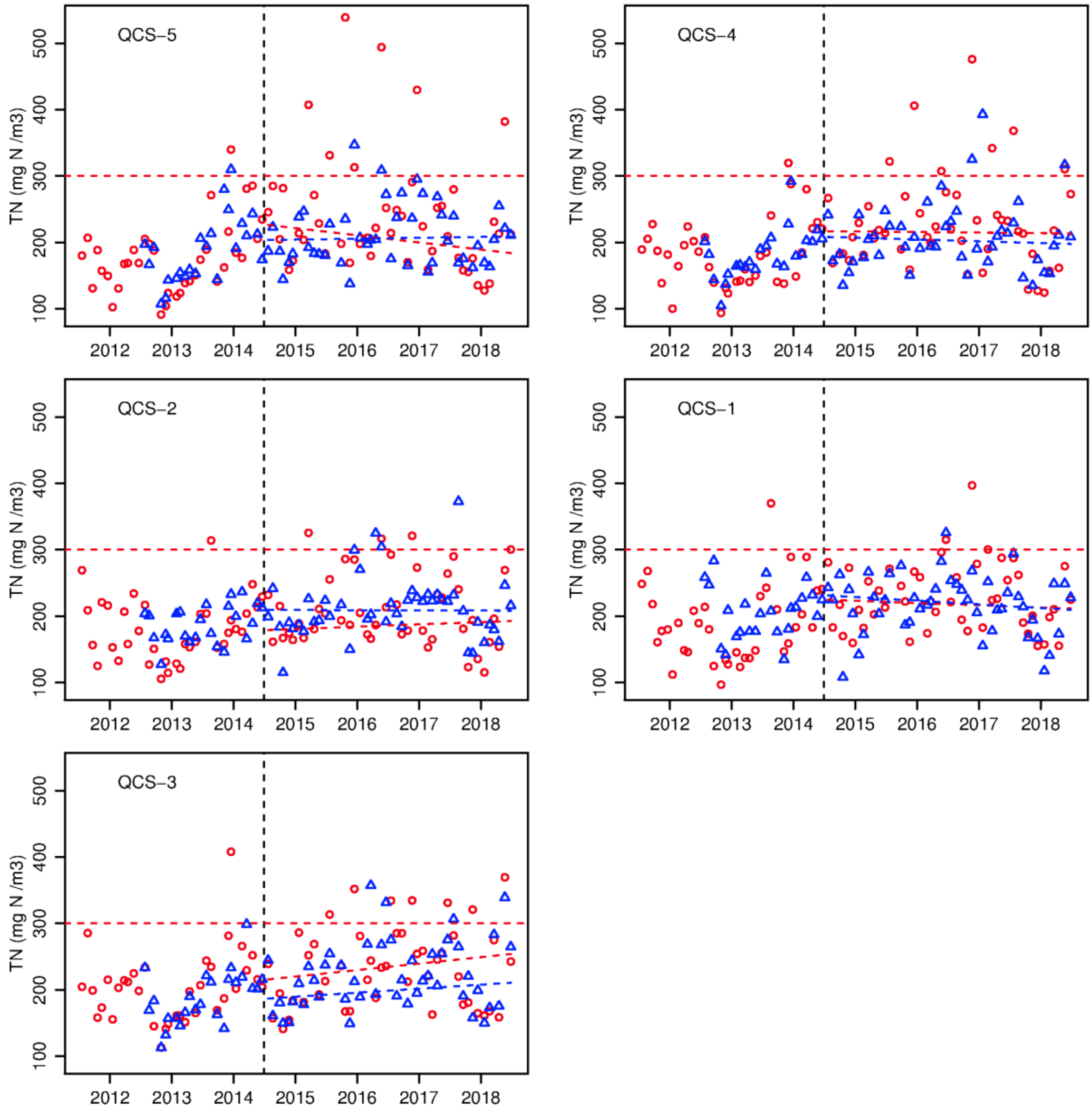


Figure 4-22: Total nitrogen in near-surface (red) and near-bed (blue) water measured at the five Marlborough District Council sampling sites in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue diagonal lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain. The dashed red horizontal line is a provisional threshold value used as part of the monitoring of some NZKS salmon farms.

4.19 Volatile Suspended Solids

Whilst both carbon and nitrogen are components of volatile suspended solids, VSS concentration is measured independently of P(O)C and P(O)N. Thus, VSS provide an alternative/independent (to POC and PC) measure of the abundance of particulate organic matter. It has been measured only in the surface waters (no near bed sampling). Like PC, VSS concentrations seem to have risen abruptly throughout the system during late 2013 to early 2014 (Figure 4-23). Indeed, prior to mid-2013, the majority of VSS records were scored as "less than detection limit (0.5 g m^{-3}). Since then, they have shown little trend at most sites, but the Sen slope at QCS-3 (Tory Channel) can confidently be said to be positive.

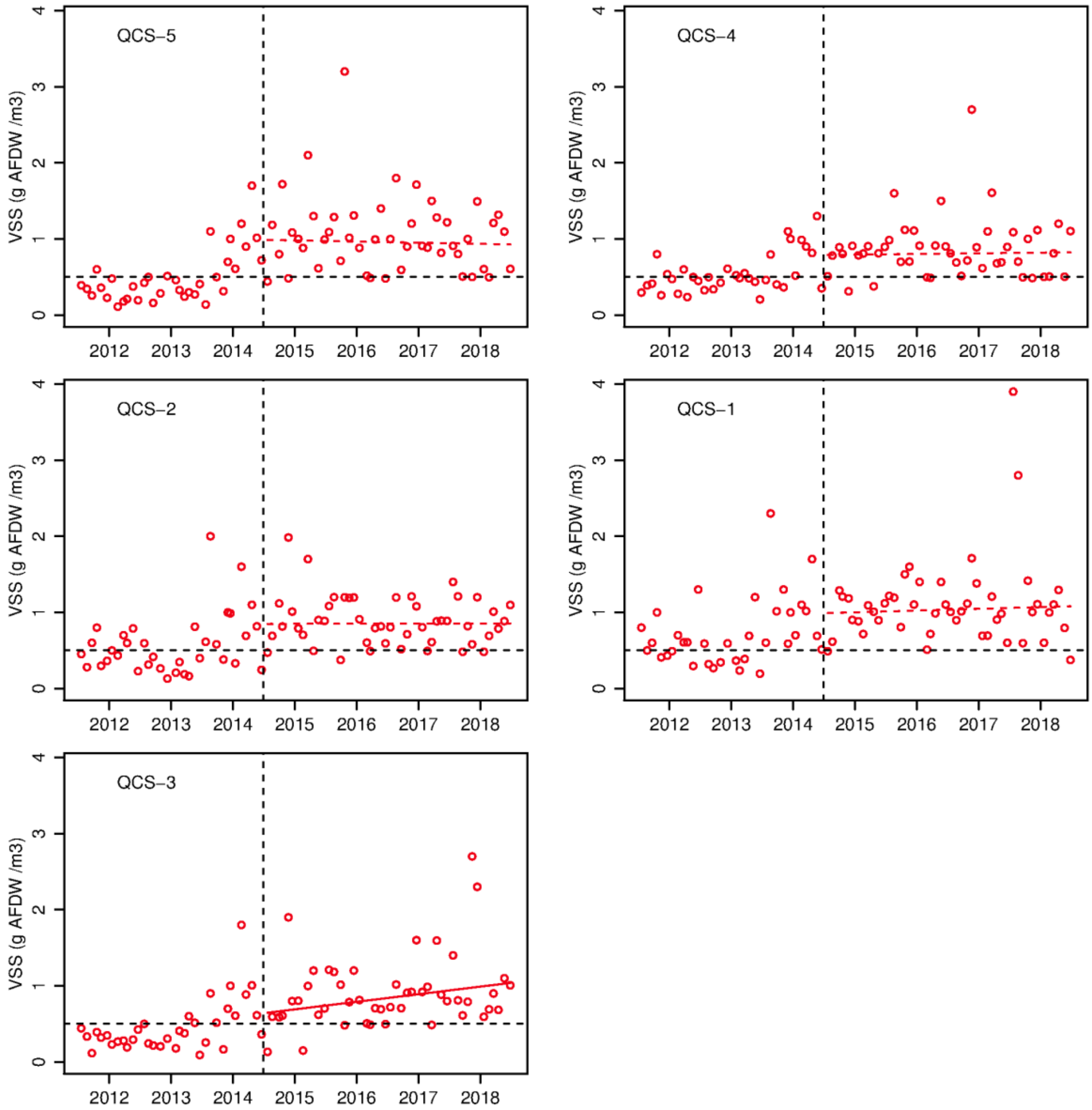


Figure 4-23: Volatile suspended solids concentrations measured in the near-surface waters at the five Marlborough District Council sites in Queen Charlotte Sound. The detection limit for VSS is 0.5 g Ash Free Dry Weight m^{-3} (horizontal black dashed line). Values that were recorded as "<detection" have been replaced with 'imputed values' based upon regression-on-order methods. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red line indicates the best-fit Sen-slope line fitted through the de-seasonalised data. If the line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.20 Chlorophyll

4.20.1 Hose & Van Dorn bottle samples

At all sites other than QCS-3, near-surface chlorophyll concentrations tend to exceed near-bed ones (Figure 4-24). In the surface waters, chlorophyll concentrations tend to be highest in late winter/spring and late summer/early autumn but there is little or no cycle in the near-bed waters (Table B-1). Chlorophyll concentrations are lower at QCS-3 (Tory Channel) than elsewhere. Whilst the highest recorded chlorophyll concentration is almost 15 mg m^{-3}, most have been much smaller. 3.5 mg m^{-3} (in the surface layer) is a threshold pertaining to regulation of NZKS fish-farms. It has been exceeded in only 25 (of 840) near-surface records. There has been only one sequence of three or more sequential sampling occasions (July – Sept 2017) where the chlorophyll concentration has exceeded 3.5 mg m^{-3} at one (or more) of the five full-water-quality stations in the sound.

The Sen slope signs is confidently determined only in the near-bed waters at QCS-2 (where it is negative). All Sen slopes are close to zero.

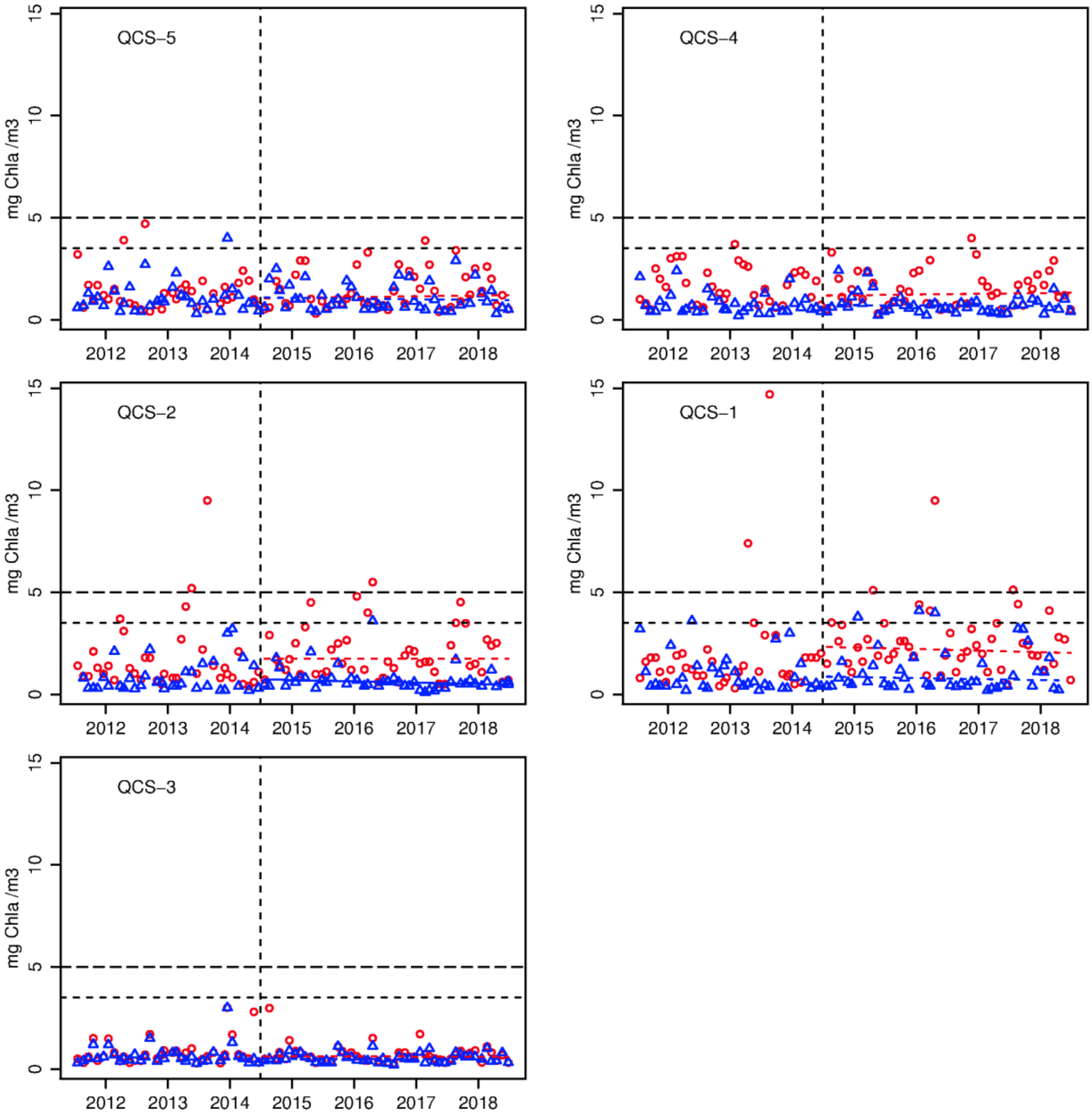
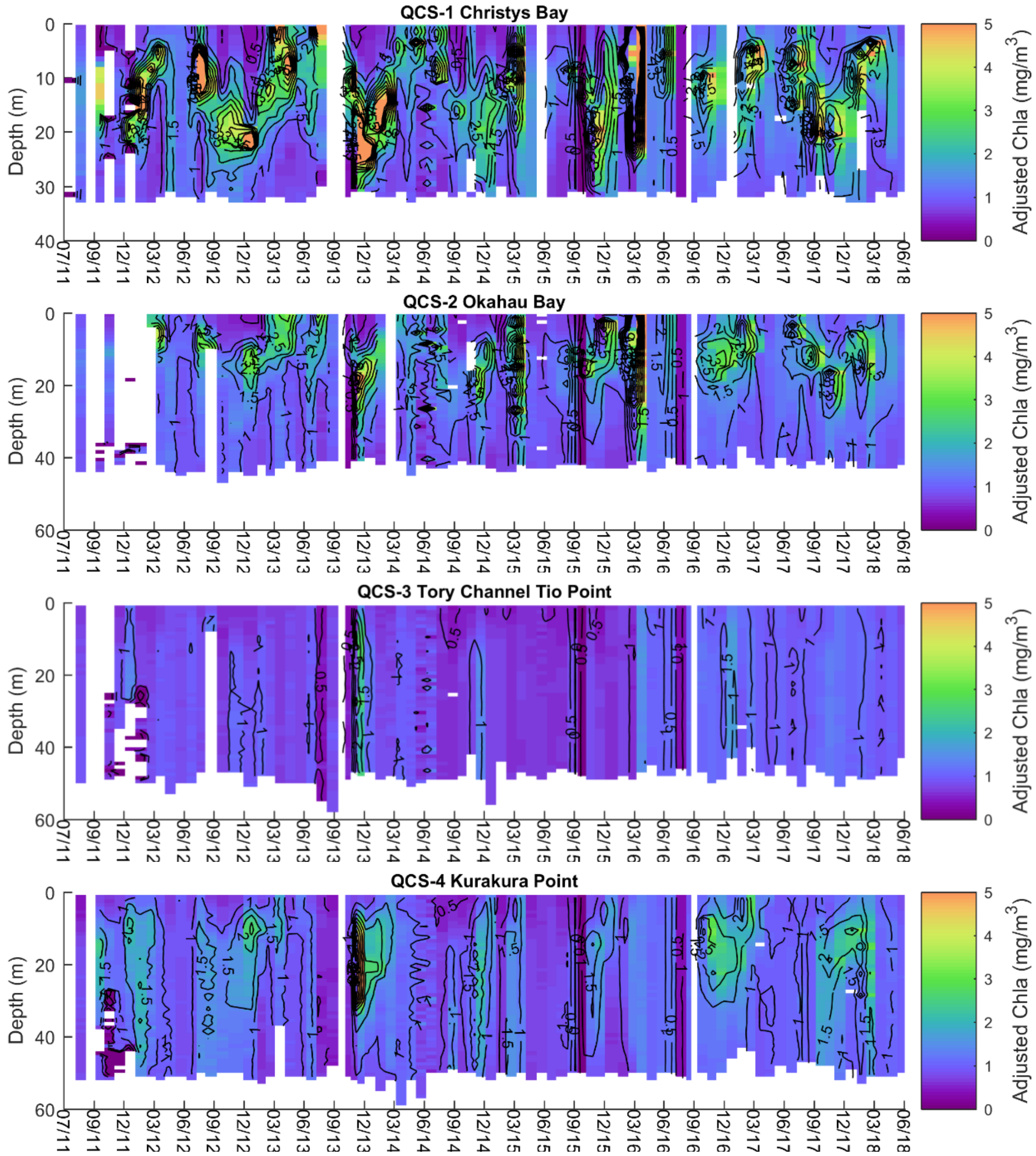


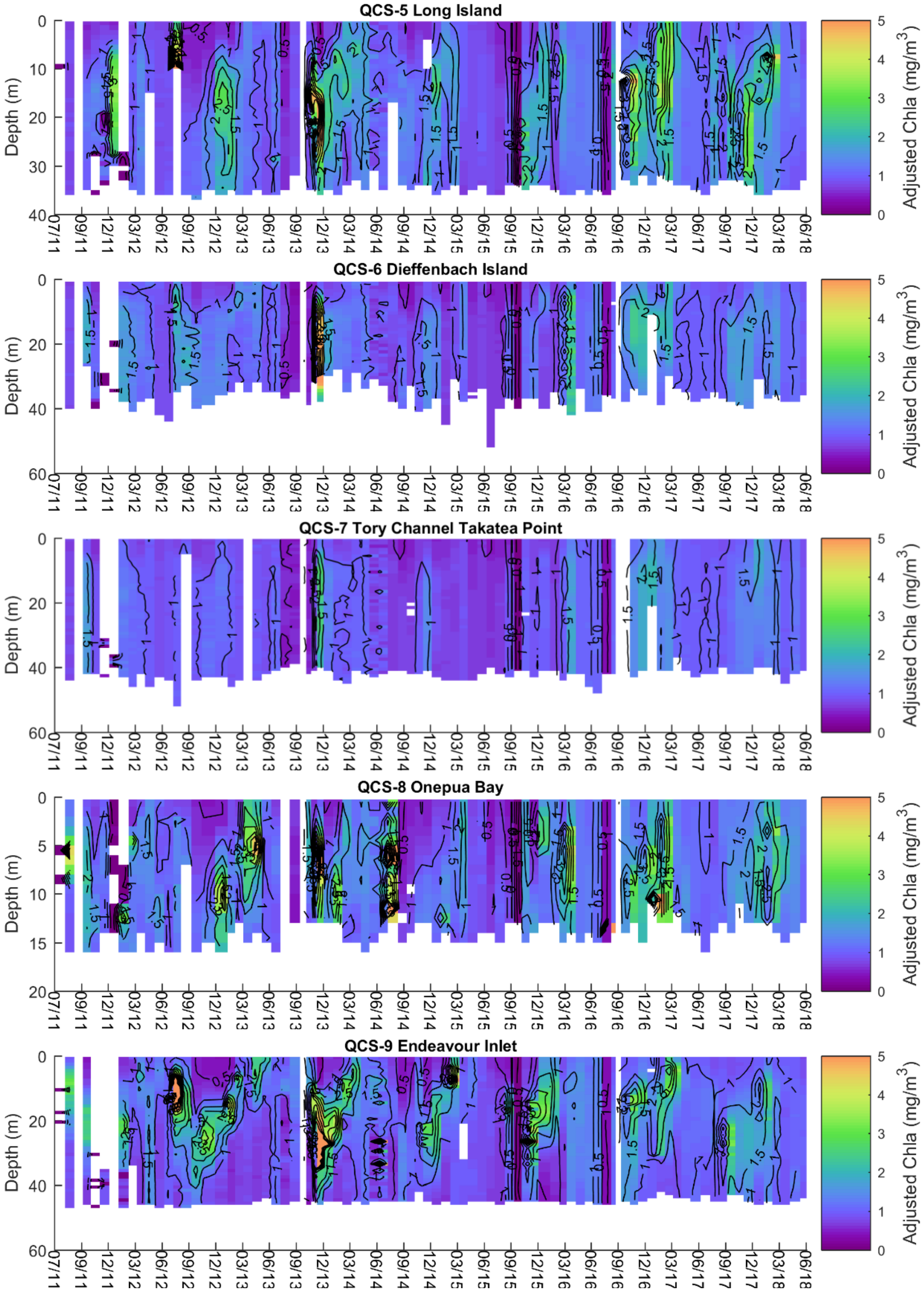
Figure 4-24: Chlorophyll concentrations measured near-surface (red) and near-bed (blue) at the five Marlborough District Council stations in Queen Charlotte Sound. Chlorophyll was measured on a GF-C filter (1.2 µm nominal pore size). The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain. The horizontal black dashed lines are provisional threshold-values used in monitoring of some NZKS salmon farms in the Sounds.

4.20.2 CTD fluorescence

Chlorophyll-a concentrations derived from CTD fluorometer measurements are shown in Figure 4-25. Different fluorometers have been used over the monitoring. These sensors have different characteristics and calibrations which results in differences in CHL-*a* estimates. To allow for better comparability over time, data from each CHL-a sensor have been compared to the water samples reported above, and regressions used to adjust fluorometer output to better match CHL-*a* determined from the water-samples that were returned to the laboratory. This re-calibration procedure is described in appendix E, and removes some, but not all, of the variability between sensors.

The fluorescence signal is usually greatest at mid-depths (usually, somewhere between about 5 m and 25 m). At some stations, the depth of the fluorescence maximum varies in a seasonal manner (being greater during the summer months).




QCS-5 Long Island
QCS-6 Dieffenbach Island
QCS-7 Tory Channel Takatea Point
QCS-8 Onepua Bay
QCS-9 Endeavour Inlet
Depth (m)
Adjusted Chla (mg/m3)
07/11 09/11 12/11 03/12 06/12 09/12 12/12 03/13 06/13 09/13 12/13 03/14 06/14 09/14 12/14 03/15 06/15 09/15 12/15 03/16 06/16 09/16 12/16 03/17 06/17 09/17 12/17 03/18 06/18

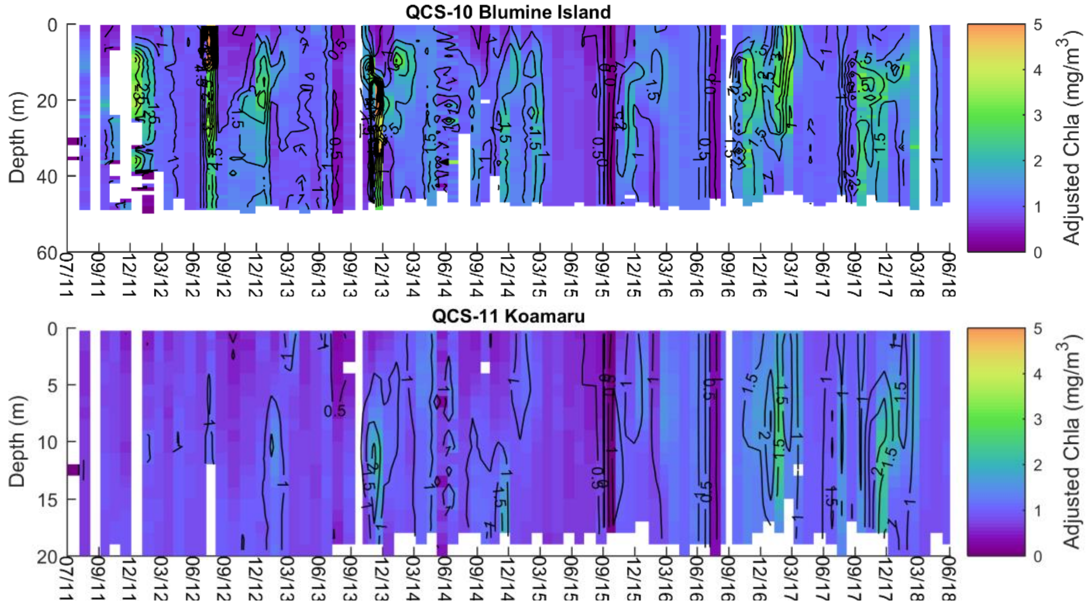


Figure 4-25: Contour plots of the evolving depth profiles of Chl-a through time at the Queen Charlotte and Tory stations. Data are from the monthly CTD casts, and have been re-calibrated using the water samples.

4.21 Algal carbon

Concentrations of algal carbon have been estimated from counts of taxon-specific cell numbers, estimates of cell-dimensions and published empirical relationships between cell volume and carbon biomass. The reader should recognise that there are numerous sources of imprecision associated with the biomass estimates. Whilst biomass estimates are available for each individual taxon, we have chosen to sum across taxa to yield biomass estimates at a higher taxonomic level (diatom family, dinoflagellate family and 'other' (mainly small phytoflagellates). Time-series for each group are illustrated in Figure 4-26 (note that the y-axes adopt a logarithmic scale).

Diatoms and dinoflagellates show greater seasonality than 'others' (Table B-1) but the biomass of all groups tends to be lowest around mid-winter. At that time, 'others' are often the most abundant by biomass, but at other times of the year diatoms are usually the most abundant. Dinoflagellates can also outweigh 'others' during the summer months (but only more rarely outweigh diatoms). Dinoflagellates tend to be most abundant at sites QCS-1 and QCS-2 and least abundant at QCS-3. This likely reflects the fact that they are motile – but fragile and slow-growing. Their motility gives them a competitive advantage in stratified waters (such as those that arise at QCS-1 and QCS-2). This advantage is lost in more turbulent waters. Indeed, their fragility puts them at a distinct disadvantage in such waters.

Algal abundance appears to have been at a minimum around the time that MDC switched from using a Van Dorn Sampler to using a hose-sampler (July 2014). The biomass concentration of all three taxonomic groups has risen at all sites since mid-2014 – but not to the extent that they now frequently exceed those measured during the first two years of sampling (July 2011-June 2014) [when sampling was by Van Dorn rather than by hose].

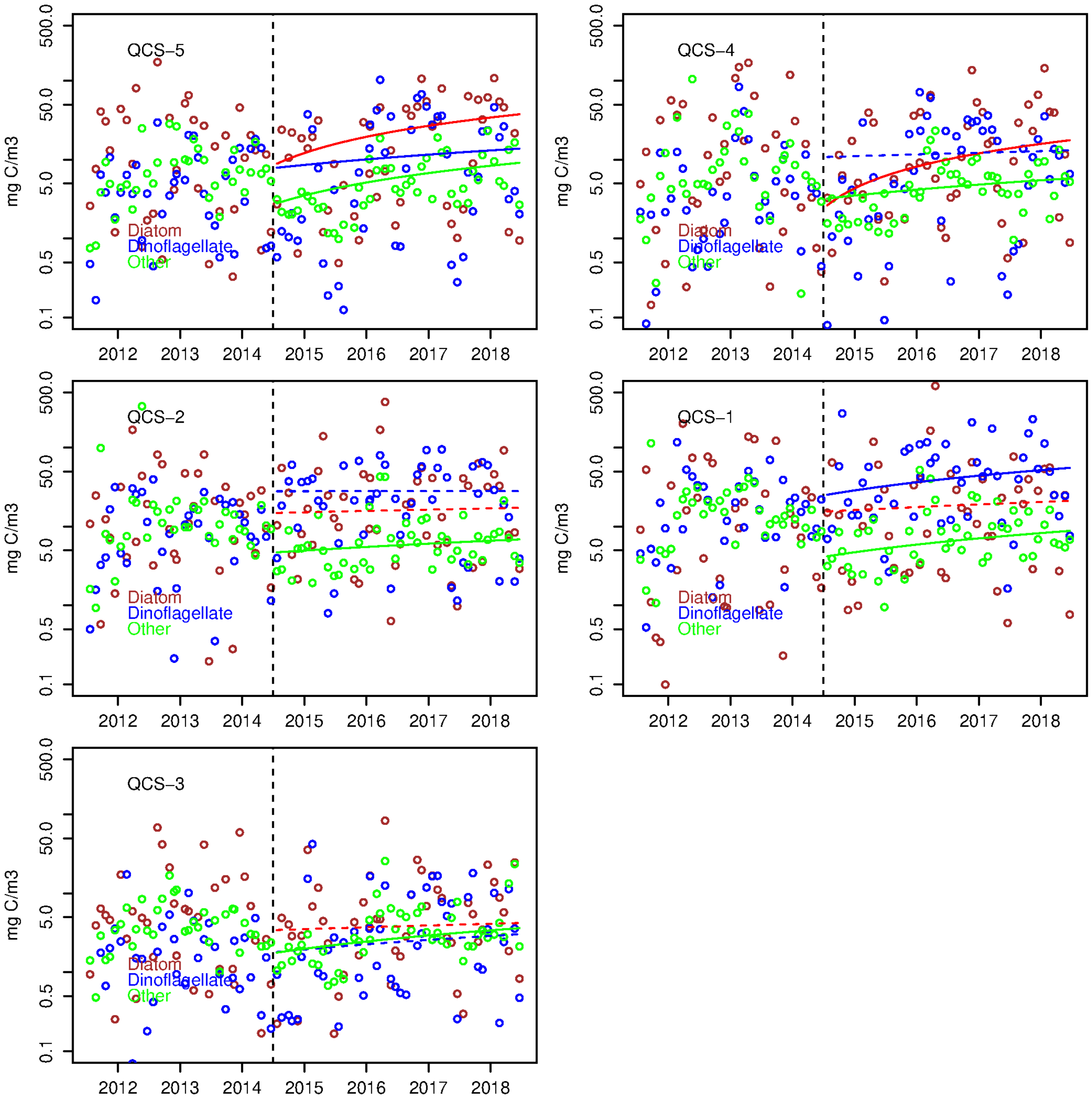


Figure 4-26: Phytoplankton carbon concentration from cell counts and cell dimensions at the Marlborough District Council stations (near surface water samples) in Queen Charlotte Sound. Red symbols: diatoms; blue symbols: dinoflagellates; green symbols: other taxa. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain. The lines appear curved (rather than straight) because of the logarithmic y-axis.

4.22 Zooplankton carbon

Zooplankton were counted only during the first two of the years of sampling. Biomass estimates are from counts, and measurements of the dimensions of a few, representative individuals. The size range spanned by different individuals of any given taxa can be very large (depending upon developmental stage). Furthermore, whilst the sampling devices (Van Dorn bottle and hose-sampler) are likely to sample protozoa reliably, they will not sample multi-cellular zooplankton reliably. Thus, the biomass estimates are extremely imprecise (qualitative).

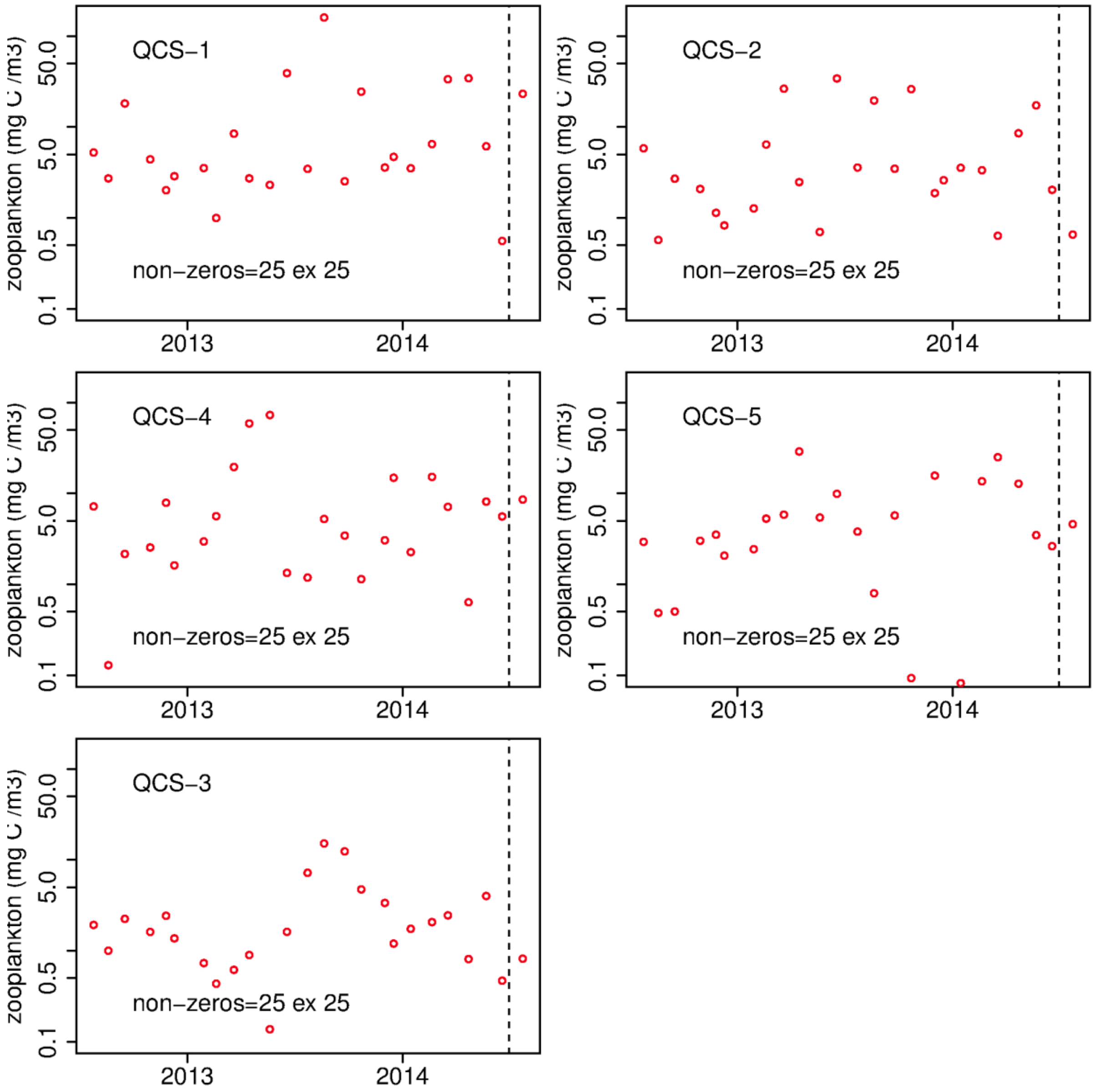


Figure 4-27: Zooplankton biomass inferred from counts and dimensions at the five Marlborough District Council sites (near surface water samples) in Queen Charlotte Sound. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. Note that the y-axis is logarithmic. This makes it impossible to display zero-concentrations. The inset text (e.g., non-zeros=25 ex 25) allows the reader to determine how many zeros may have been 'hidden' by the logarithmic axis.

4.23 Elemental ratios

Figure 4-28 presents time-series of the rations of DIN/DRP, DRSi/DRP and DRSi/DIN. The figures also present the Redfield-ratios for these elements. Loosely speaking, if the realised ratio is less than the Redfield ratio then the element that is represented in the numerator of the realised ratio is the more likely of the two to be (or become) limiting to phytoplankton growth. Note, that in the context of these plots, the limiting element is the one which would first become exhausted if growth were allowed to continue for sufficiently long (i.e., the elemental resource that will become exhausted first). This long-term limiting element may not be the resource (or even the element) which most limiting to the instantaneous growth of the algae at the sampling instant. DIN and DRSi are invariably more limiting than DRP at all sites. At sites QCS-1 and QCS-2, DIN is usually more limiting than DRSi (especially in surface waters). At sites QCS-3, DRSi is usually more limiting than DIN. Sites QCS-4 and QCS-5 are sometimes N-limited and sometimes Si-limited.

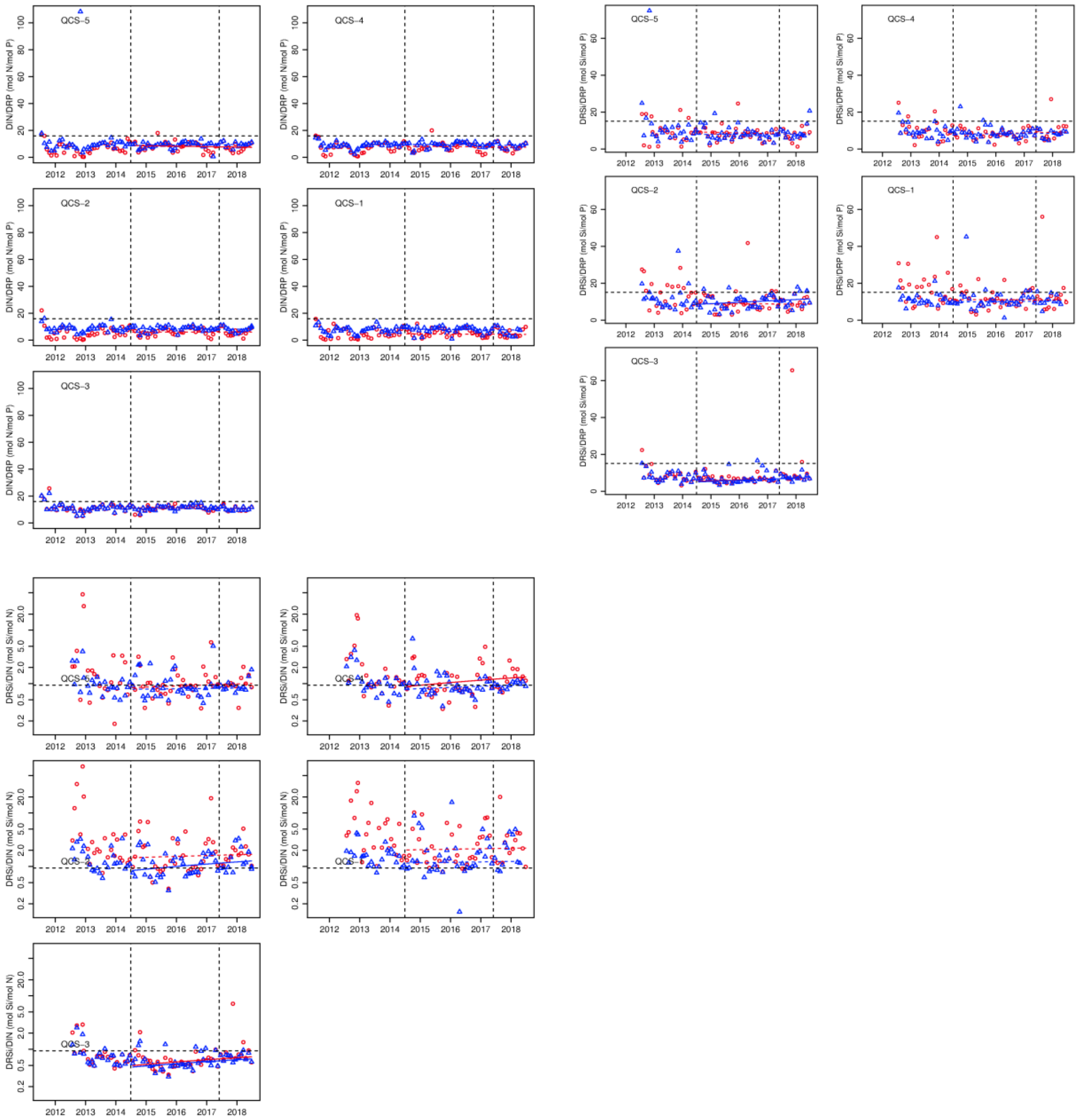


Figure 4-28: Ratios of dissolved inorganic nutrients measured near-surface (red) and near-bed (blue) at the five Marlborough District Council sites in Queen Charlotte Sound. The horizontal dashed line indicates the Redfield ratio for the pair of elements in question. When the symbols lie below the line, the element in the numerator of the quotient expressed in the y-axis is the more limiting of the two. If the symbols lie above the line, the element in the denominator of the quotient is the more limiting. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The dashed vertical line in mid-217 denotes the time at which a replacement nutrient-analyser was brought into use. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

4.24 Secchi disk depth

Secchi disk measurements provide a crude measurement of water clarity and the amount of light available for photosynthesis by algae. Clarity is influenced by two factors: (a) the probability (per unit straight-line travel distance) that a photon will encounter a reflective object (i.e., the scattering properties of the water), (b) the absorbance properties of the water. Secchi disk depth is influenced by these two facts but, unfortunately, it is also influenced by several other confounding factors. These include: the visual acuity of the observer, the surface state (smooth, choppy etc.,) of the water, degree of cloud-cover, elevation of the sun, ship-shadow effects etc.). Despite the poor precision of Secchi disk measurements, they are a common part of many water-quality monitoring programmes. They do not require expensive/difficult to maintain equipment and they are quick/easy to make. Perhaps more importantly, the Secchi Disk depth has greater intuitive meaning to a lay-person than a measure such as concentration of suspended solids, or chlorophyll, or light attenuation.

Secchi disk depths have ranged from a little more than 2 m to about 12 m with most values being in the range 4-8 m (Figure 4-29). Site QCS-5 tends to have the greatest Secchi disk depths. World-wide, Secchi disk depths range from a few cm in very turbid waters to (exceptionally) several tens of metres (Antarctic waters) but Secchi disk depths in the range 2-10 m are the norm in coastal waters. The majority of Secchi disk depths in Queen Charlotte/Tory Channel fall within that range (and none are < 2 m). The signs of the Sen-slope trend lines cannot be confidently determined.

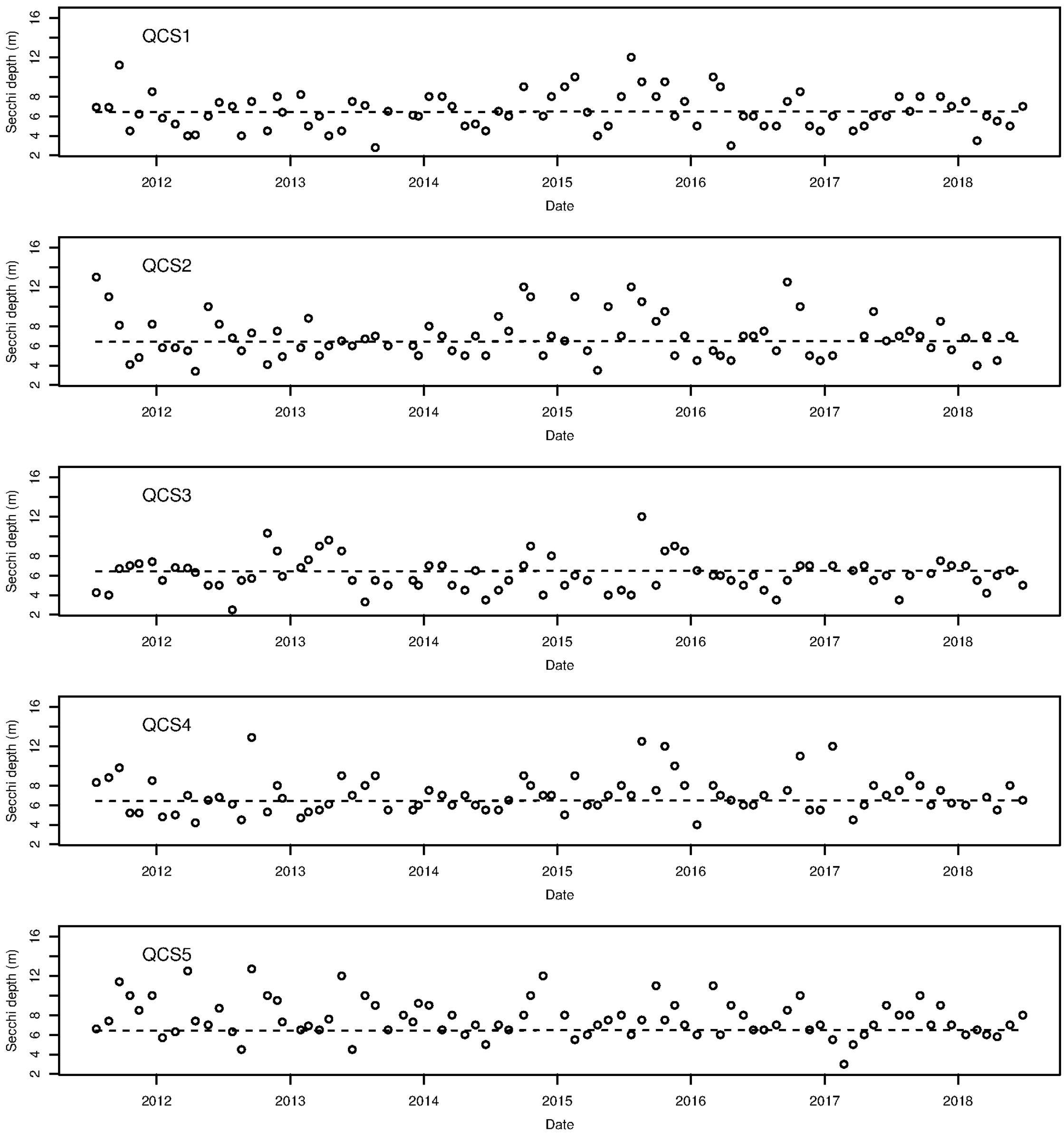


Figure 4-29: Secchi disk depth measured at the five sites in Queen Charlotte Sound and Tory Channel. The dashed line is a best-fit Sen line for the data calculated after removing seasonal effects.

5 Results (Pelorus Sound)

5.1 Temperature

5.1.1 Hand-held surface temperature

The phase of the annual temperature cycle is similar at all sites and in all years (Figure 5-1). The winter minimum occurs around August and the summer maximum around February. The winter minima are around 10-11 °C at the inner Sound sites and around 12 °C at the outer sites. During the summer, the inner Sound sites are warmer (circa 21 °C) than the outer Sound sites (circa 18 °C). Over the comparatively short period spanned by the data, temperatures have trended down very slightly.

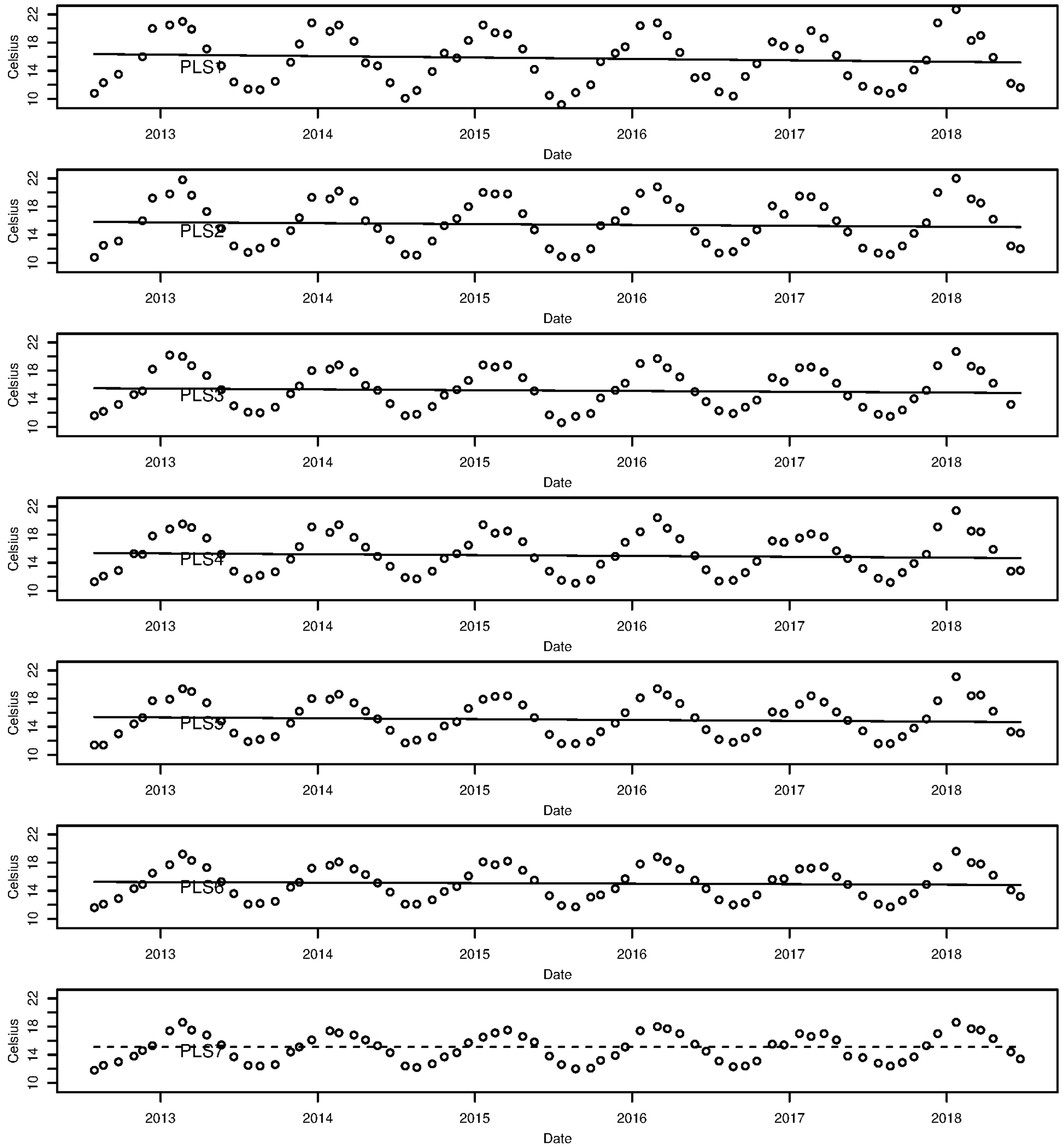
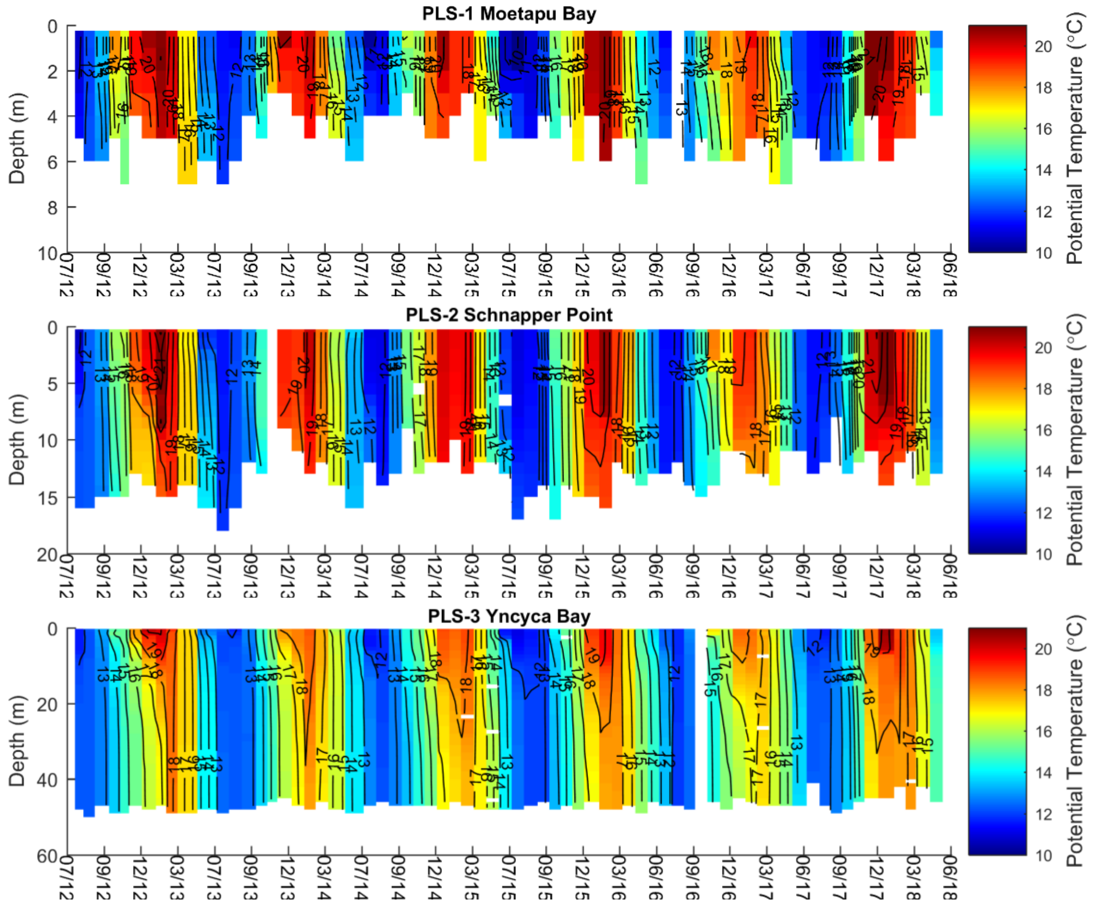


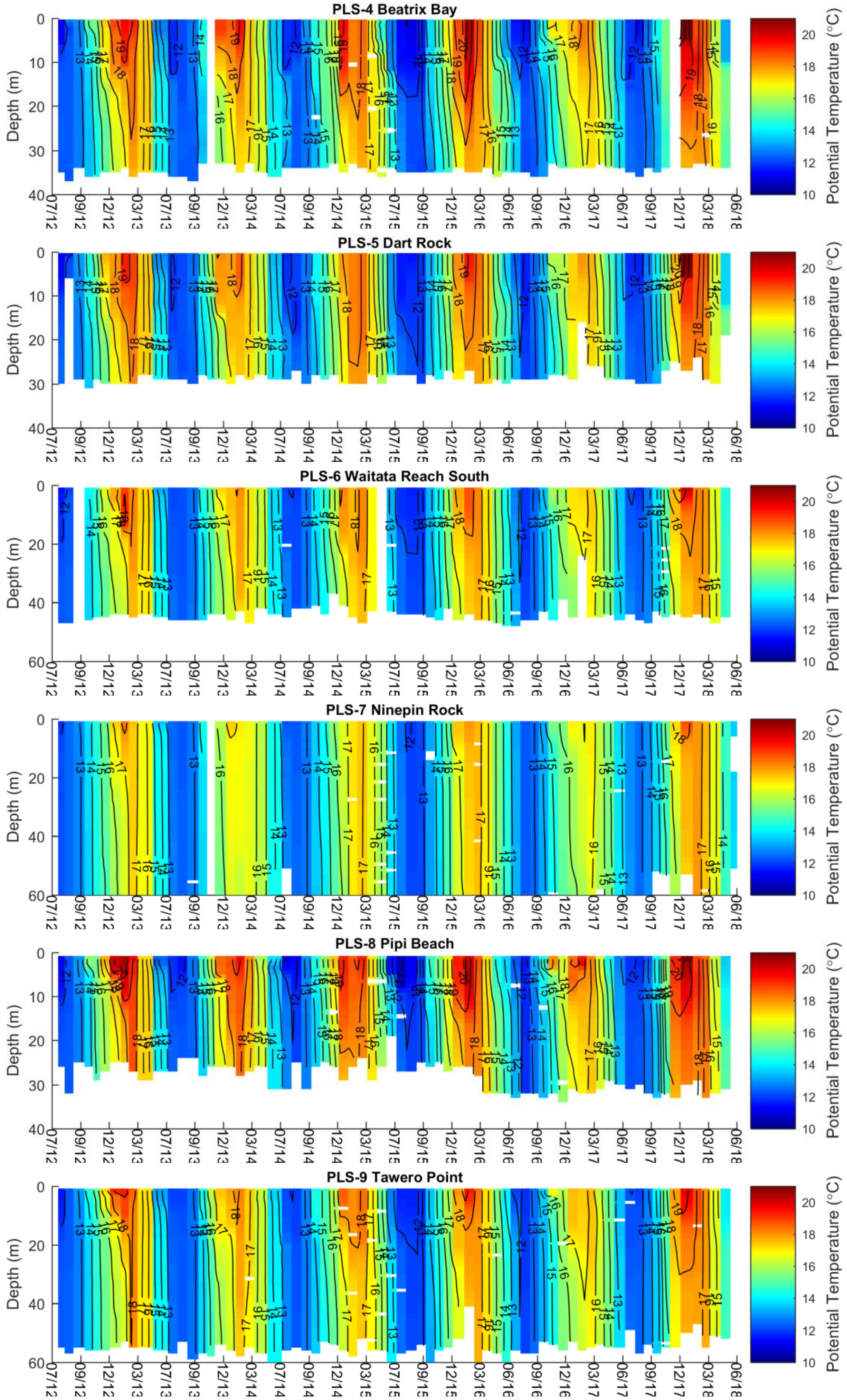
Figure 5-1: Near surface water temperature measured with a hand-held probe at each of the seven Marlborough District Council Pelorus water quality sampling stations. The black lines denote the best-fit Sen-lines calculated after removing seasonal effects.

5.1.2 CTD temperature profiles

The seasonal variations in temperature throughout the sounds are evident in the temperature-by-depth-and-time colour plots (Figure 5-2). Temperatures are coolest (around 12°C) between July and September, and warmest February-March. The warmest sites in summer are usually those furthest into the sound (PLS-1, 2 and 8), but over the 2017/18 summer, temperatures over 20°C were observed over most of the inner (PLS-1, 2, 3 and 8) and mid-sound (PLS-4, 5 and 6) sites. Water temperatures exceed 22°C at PLS-2 in January 2018.

Summer thermal stratification occurs at many sites, particularly PLS-3, 4, 5, and 8. The innermost sites PLS 1 and 2 are sufficiently shallow that the surface mixed layer extends to the full depth of the water column in summer so thermal stratification is not evident. The intermediate sites PLS-6 and 9 show weaker stratification, which is reduced further at the outer sites 7, 10 and 11 (which remain mixed most of the year). Most sites are well mixed during the winter period, although surface cooling can be seen at some of the inner and mid-sound sites. Cooler waters are normally denser than warmer water and sink, however the lower salinity of surface waters during winter (see below) has a stronger influence on density.




PLS-4 Beatrix Bay
PLS-5 Dart Rock
PLS-6 Waitata Reach South
PLS-7 Ninepin Rock
PLS-8 Pipi Beach
PLS-9 Tawero Point
Depth (m)
Potential Temperature (°C)
07/12
09/12
12/12
03/13
07/13
09/13
12/13
03/14
07/14
09/14
12/14
03/15
07/15
09/15
12/15
03/16
06/16
09/16
12/16
03/17
06/17
09/17
12/17
03/18
06/18

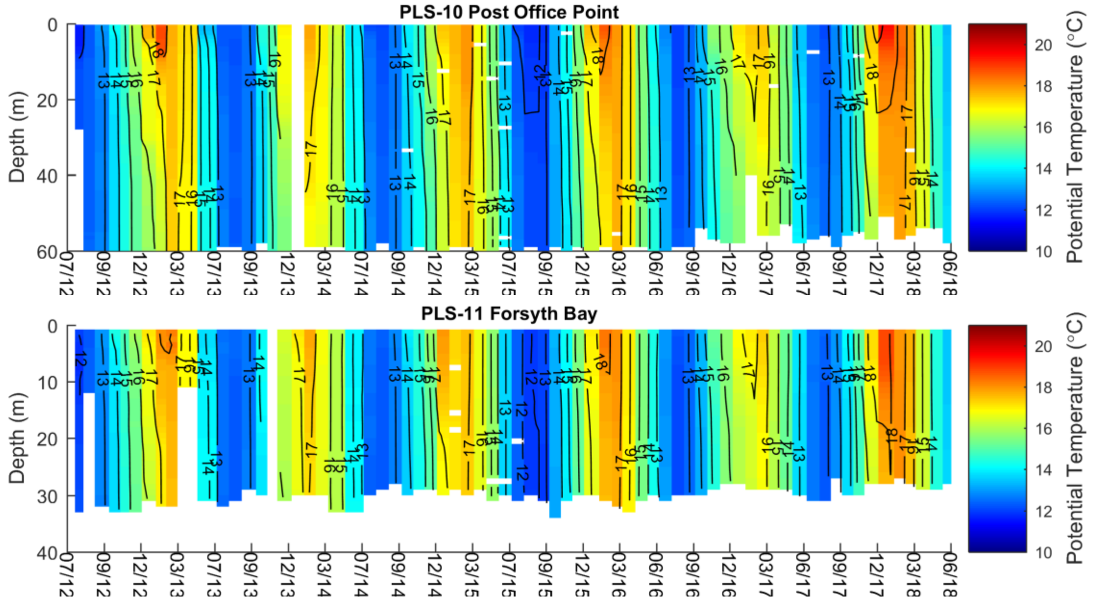


Figure 5-2: Contour plots of evolving depth profiles of temperature through time at the Pelorus stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended).

5.2 Salinity

5.2.1 Hand-held surface salinity & laboratory determinations

As one might expect, near surface salinities tend to be a little lower than near-bed ones (Figure 5-3). Near surface salinities measured at sea are very similar to those subsequently recorded in the lab. Near surface salinities have dropped below 20 PSU in inner Pelorus from time-to-time (presumably, following high rainfall events in the catchment) but they have remained above 30 PSU at central and outer sites.

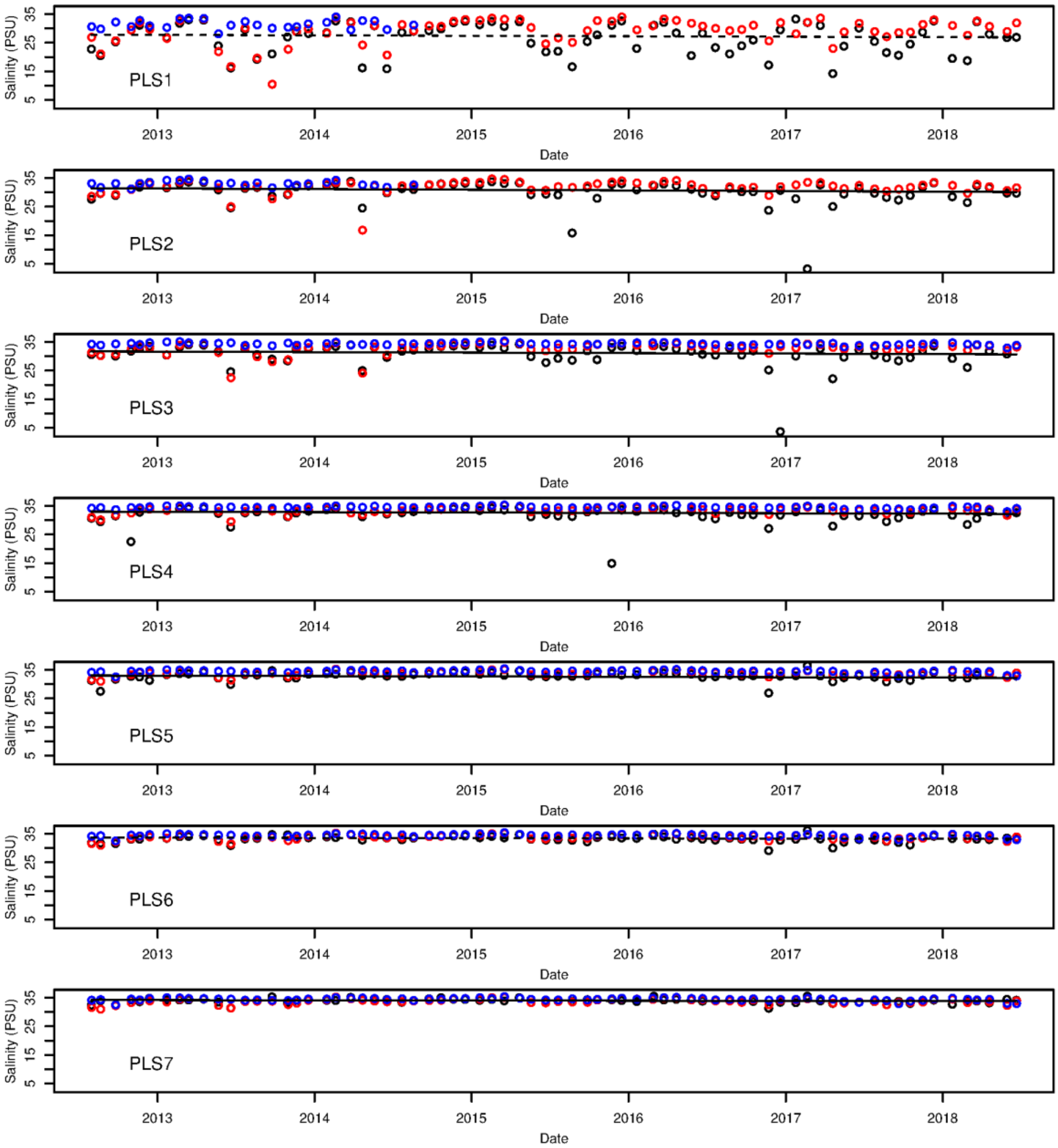
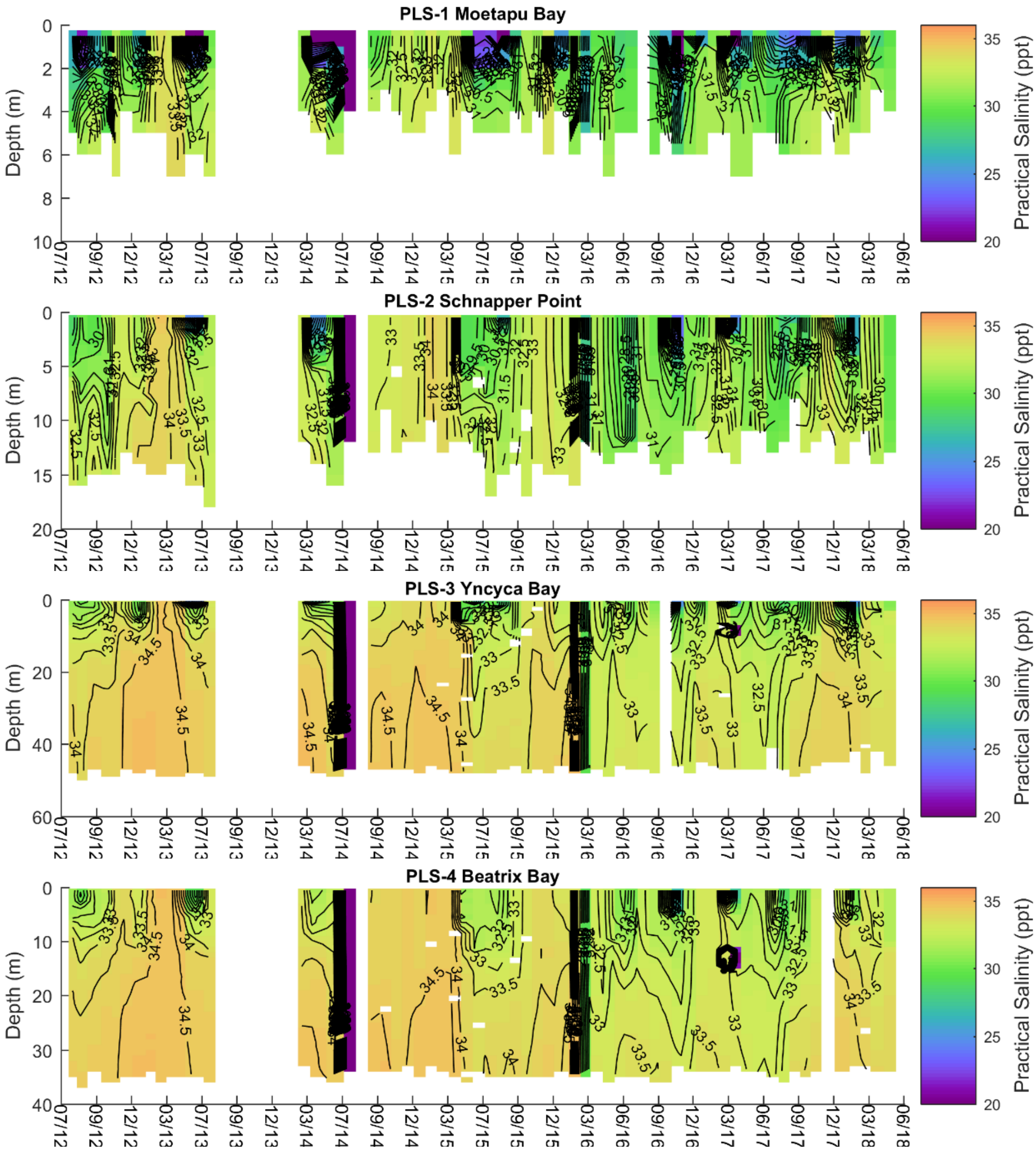


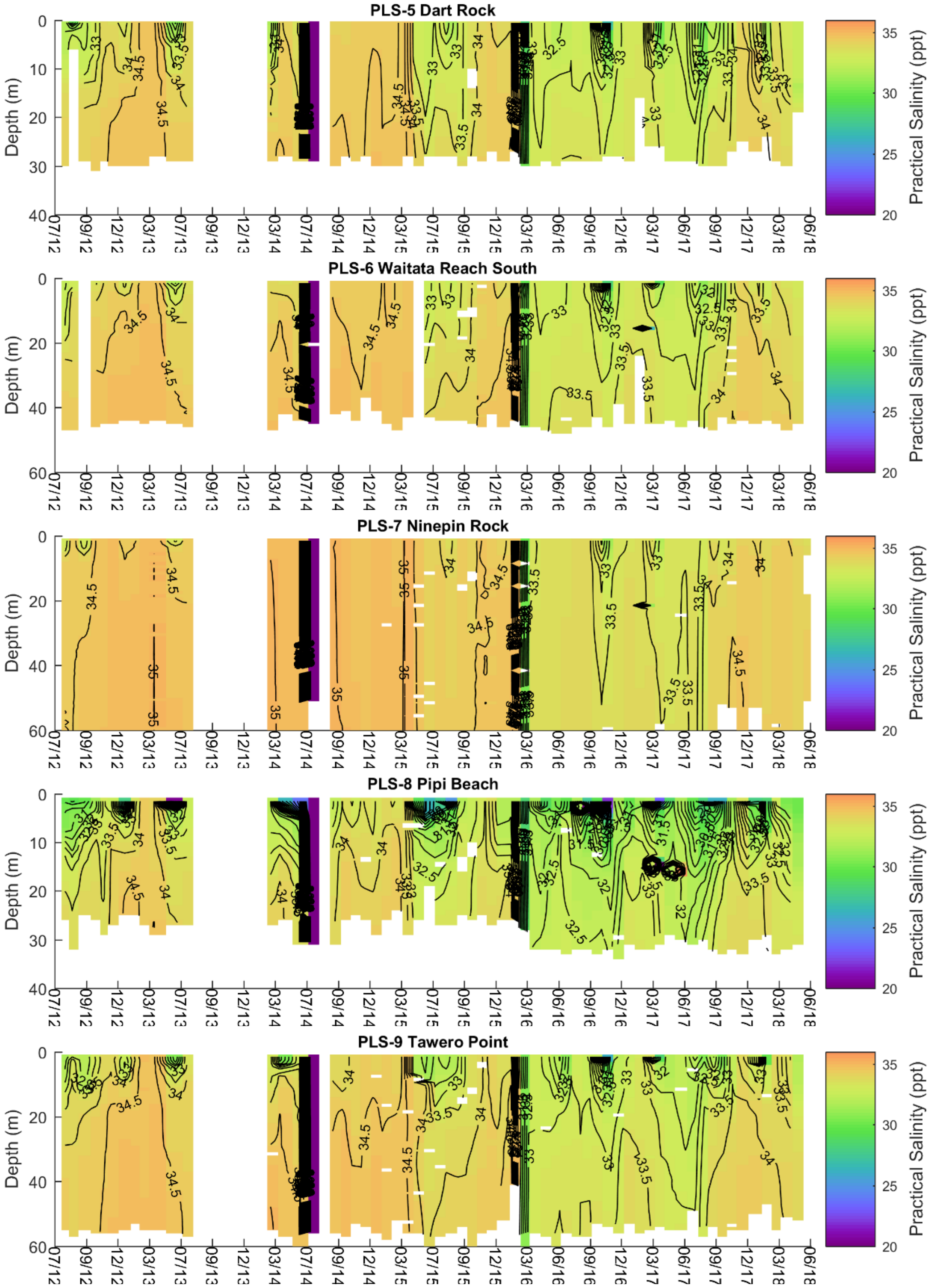
Figure 5-3: Salinity measured at the seven Marlborough District Council sites within Pelorus Sound. A hand-held probe was used at 1 m depth (black circles) and in water-samples were returned to the laboratory (red circles: near surface (1m or depth averaged to 15 m); blue circles: near-bed). Different instruments were used to measure salinity at sea and in the laboratory. The black lines denote the best-fit Sen-lines calculated after removing seasonal effects.

5.2.2 CTD salinity profiles

Contour plots of evolving depth profiles of salinity through time at the Pelorus stations are shown in Figure 5-4. Salinities in the Pelorus Sound vary over a larger range than in the Queen Charlotte Sound due to the influence of the Pelorus River. There is no clear seasonal trend; rather low salinity occurs in pulses throughout the monitoring period. Salinity generally has a stronger effect on density than temperature. Periods of high river discharge cause low salinity plumes that spread throughout the sound. This can be seen by the low salinity surface waters particularly at the inner sites. The salinity increases with distance through the sound as the plume mixes.

Some of the changes of salinity over time are due to use of different salinity sensors or changes in calibration. This is less evident in the plots for Pelorus Sound than Queen Charlotte because of the wider colour range used to show to salinities (required to capture the greater variations in salinity caused by the Pelorus River).




PLS-5 Dart Rock
PLS-6 Waitata Reach South
PLS-7 Ninepin Rock
PLS-8 Pipi Beach
PLS-9 Tawero Point
Depth (m)
Practical Salinity (ppt)
07/12
09/12
12/12
03/13
07/13
09/13
12/13
03/14
07/14
09/14
12/14
03/15
07/15
09/15
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12/17
03/18
06/18

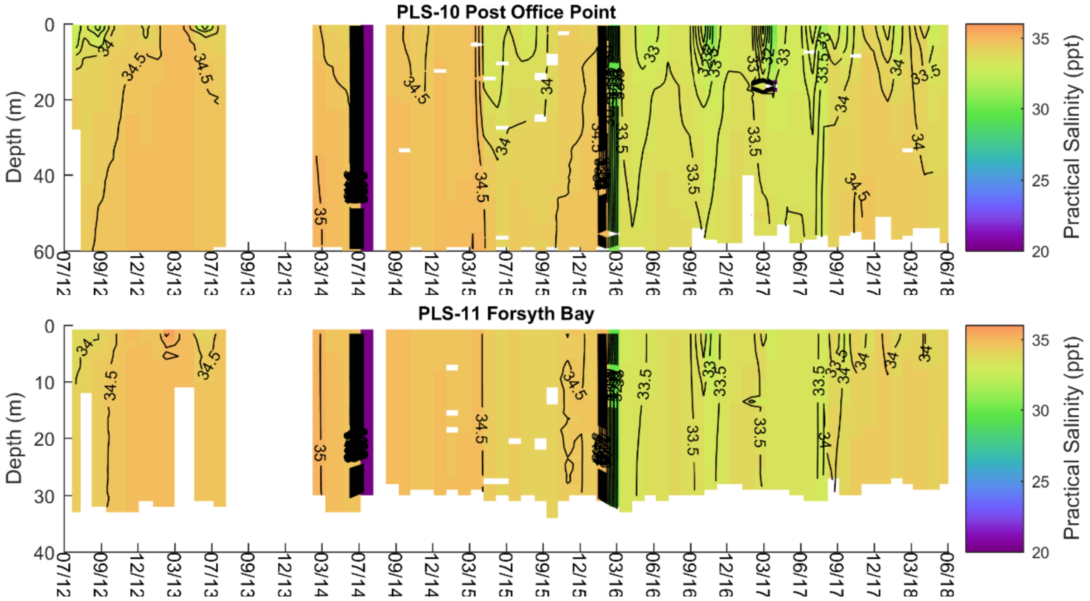


Figure 5-4: Contour plots of evolving depth profiles of salinity through time at the Pelorus stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended). Regions which appear black are time-regions during which salinity changed dramatically between sequential months – such that the black contour lines are very closely spaced.

5.3 Dissolved oxygen

5.3.1 Hand-held surface oxygen saturation

Near surface dissolved oxygen concentrations have been high (>90% saturation) at all stations throughout the sampling period (Figure 5-5). Concentrations and saturation levels tend to be highest in late-winter/early spring and lowest during the summer months.

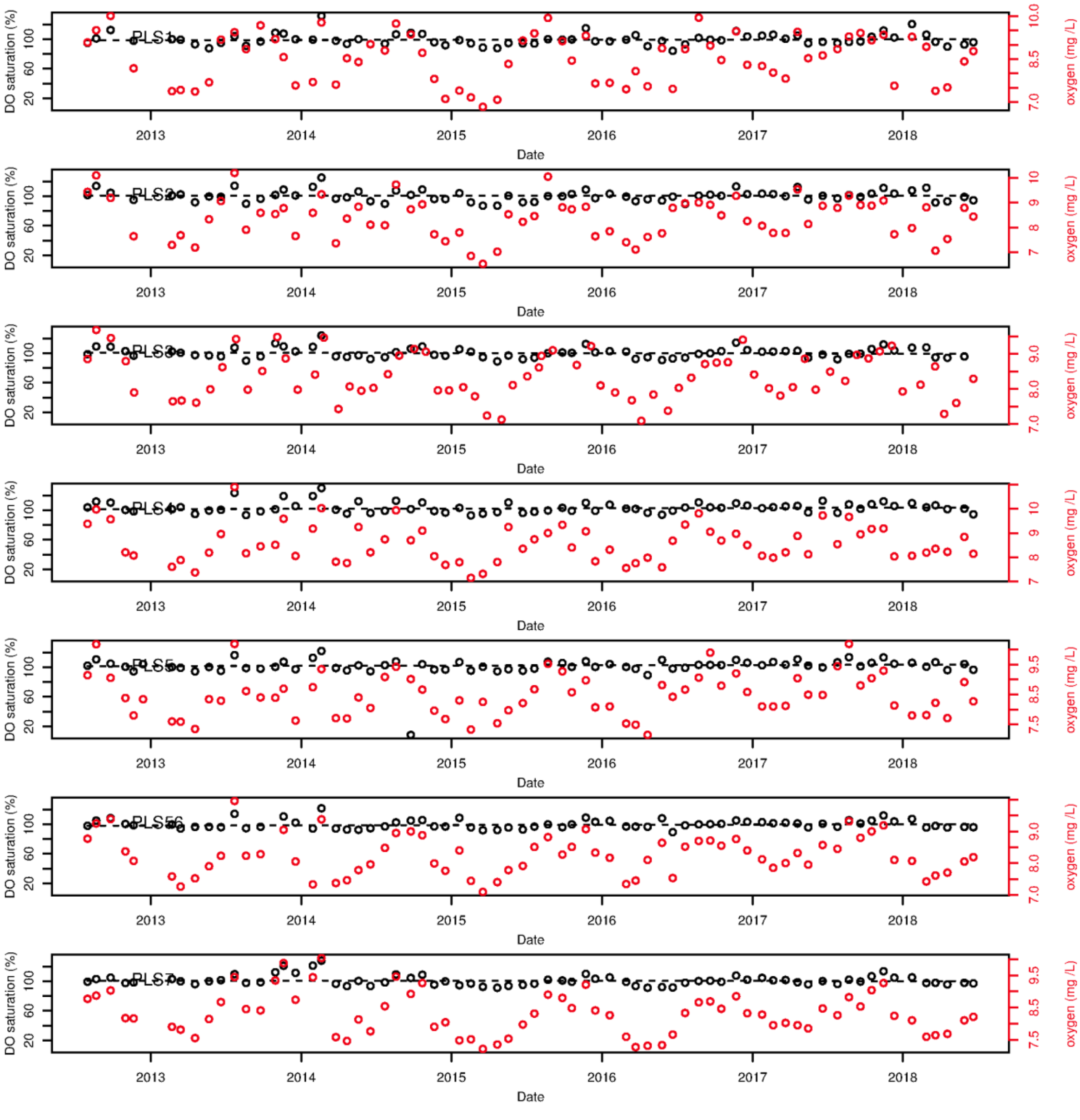
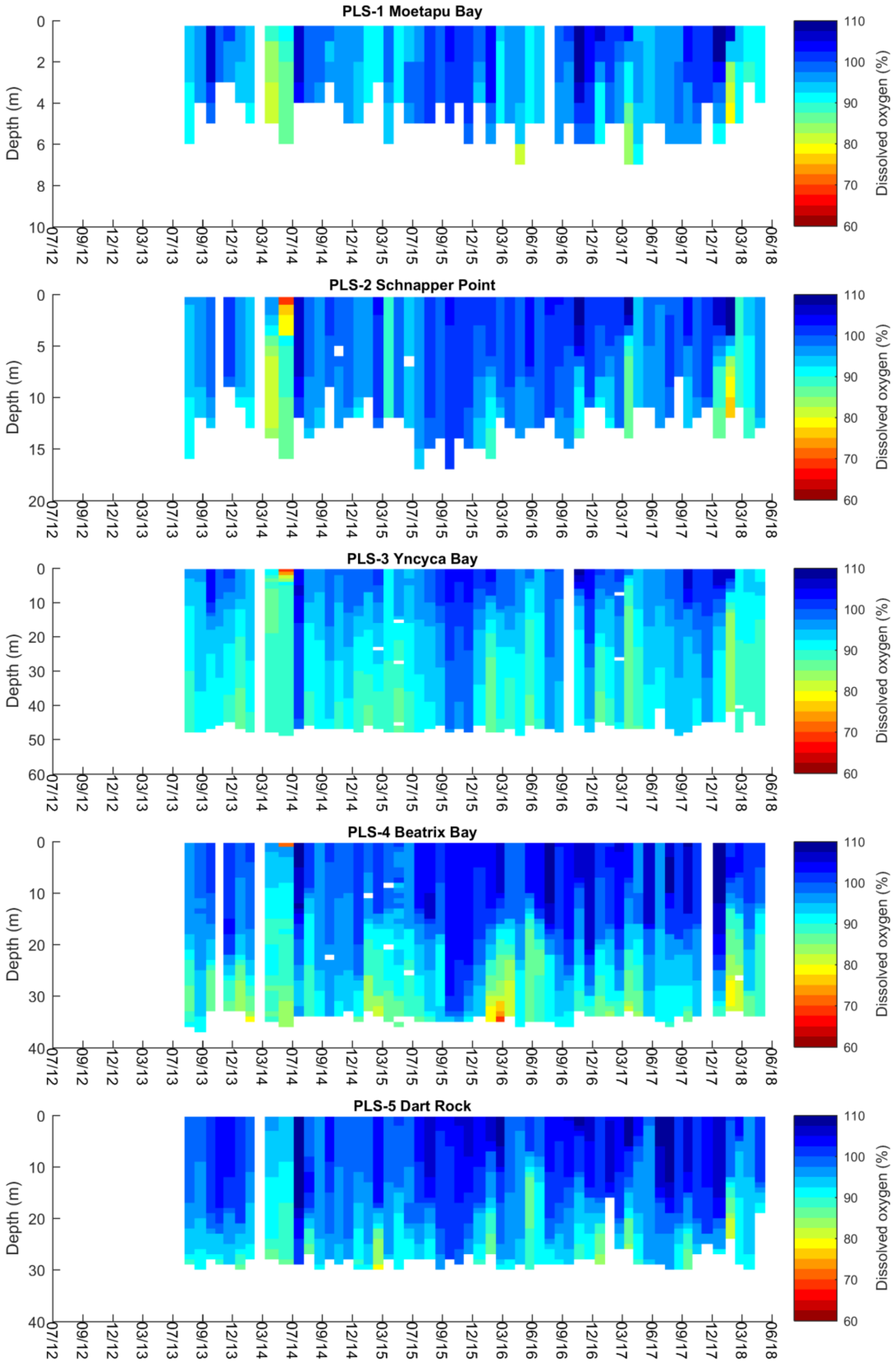
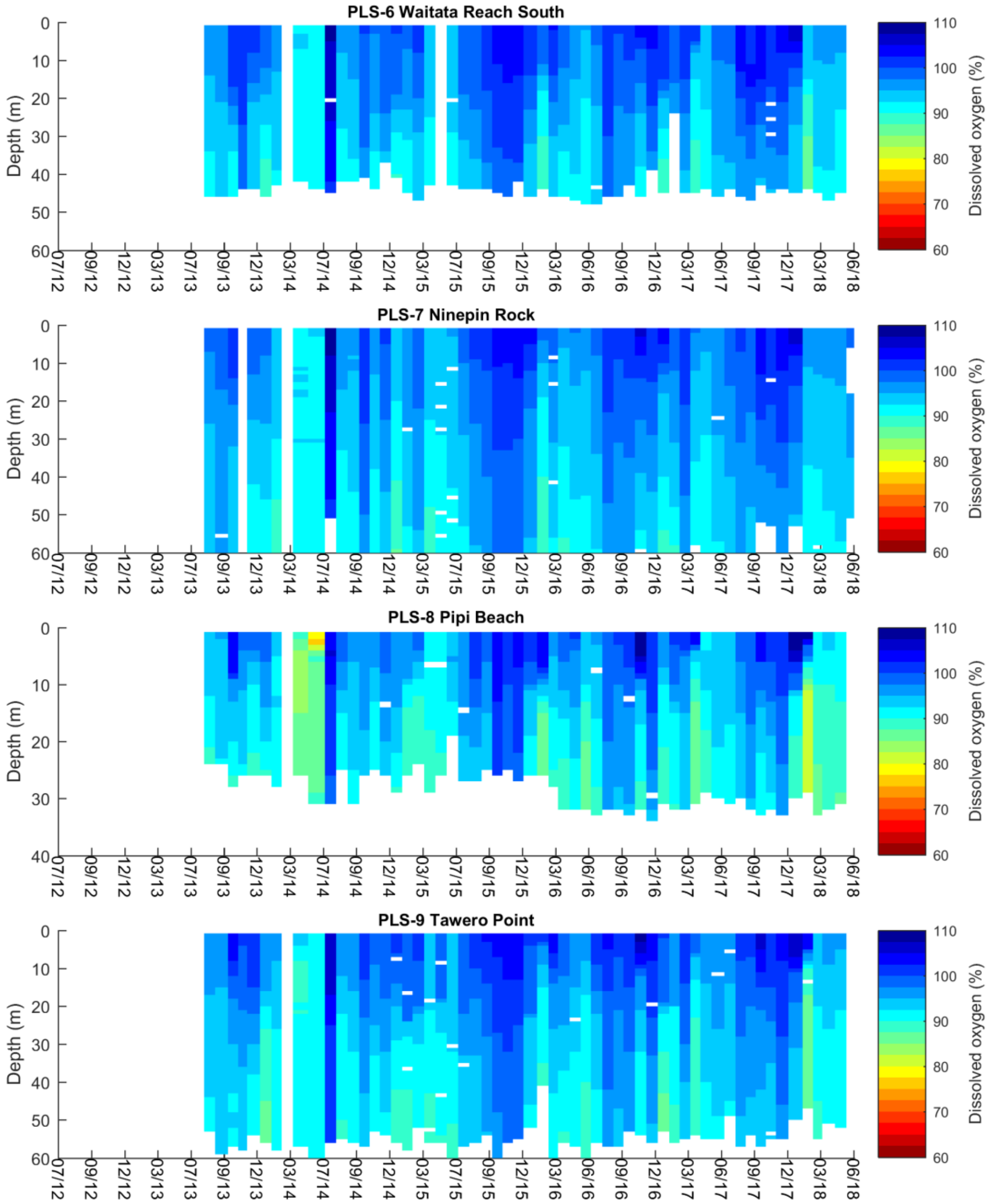


Figure 5-5: Dissolved oxygen measured at one metre below the sea-surface at the seven Marlborough District Council Pelorus water-quality monitoring stations. The black lines denote the best-fit Sen-lines for DO saturation calculated after removing seasonal effects. A small number of records from the hand-held sensor have been rejected as being implausibly high saturation (>140%) and concentration. Where possible, those records were replaced with near-surface readings from the CTD casts. Black symbols are oxygen saturation (left axis). Red symbols are concentration (right axis). The saturation concentration for dissolved oxygen is a function of salinity, temperature (and air pressure). Thus, the correlation between realized saturation and absolute oxygen concentration is strong, but imperfect.

5.3.2 CTD oxygen profiles

Depth-resolved oxygen profiles are presented in Figure 5-6. Oxygen saturation levels tend to be lower in the near-bed waters. Nonetheless, even there, they rarely fall much below 80%. The lowest recorded value has been 68%. As with Queen Charlotte, the lowest values tend to arise in late summer/early autumn.




PLS-6 Waitata Reach South
PLS-7 Ninepin Rock
PLS-8 Pipi Beach
PLS-9 Tawero Point
Depth (m)
Dissolved oxygen (%)
07/12 09/12 12/12 03/13 07/13 09/13 12/13 03/14 07/14 09/14 12/14 03/15 07/15 09/15 12/15 03/16 06/16 09/16 12/16 03/17 06/17 09/17 12/17 03/18 06/18

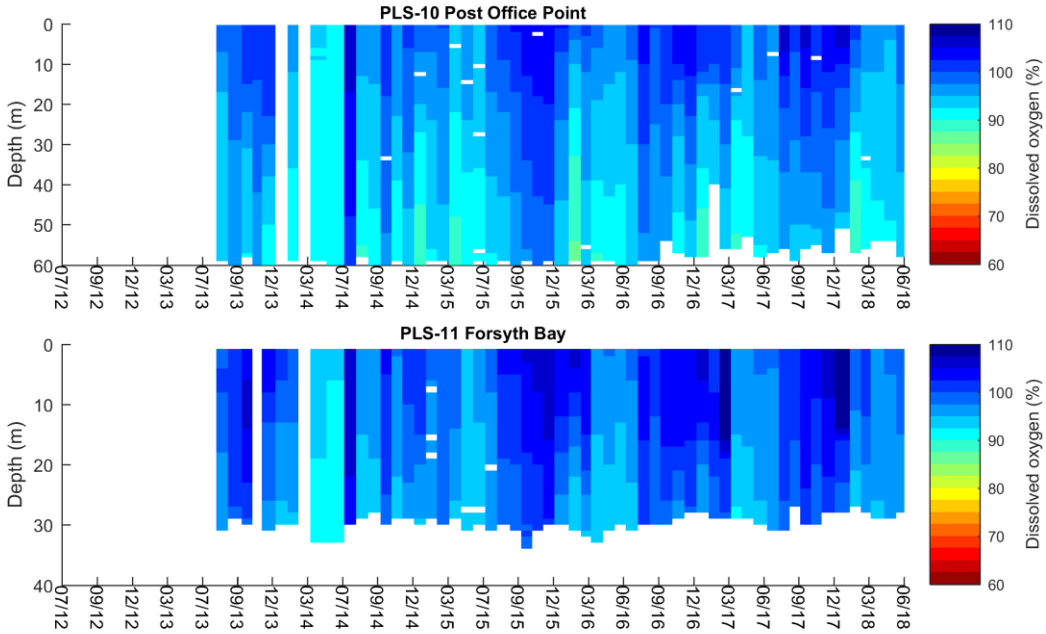


Figure 5-6: Contour plots of evolving depth profiles of oxygen saturation through time at the Pelorus stations. Data are from the monthly CTD casts. White space indicates missing/rejected data (or the maximum depth to which the cast extended). The CTD instrument package did not include a DO sensor until July 2013.

5.4 Suspended inorganic solids

Concentrations of suspended inorganic solids fluctuate widely (Figure 5-7) (note log-scale on plots). The largest concentrations are associated with lower salinities and probably derive from sediment washing from the land. Concentrations tend to decline within increasing distance from the river-mouths (increasing proximity to Cook Strait). The Sen-slopes are positive at all sites, but the 95% confidence intervals on these slopes span 0 at five of the seven sites.

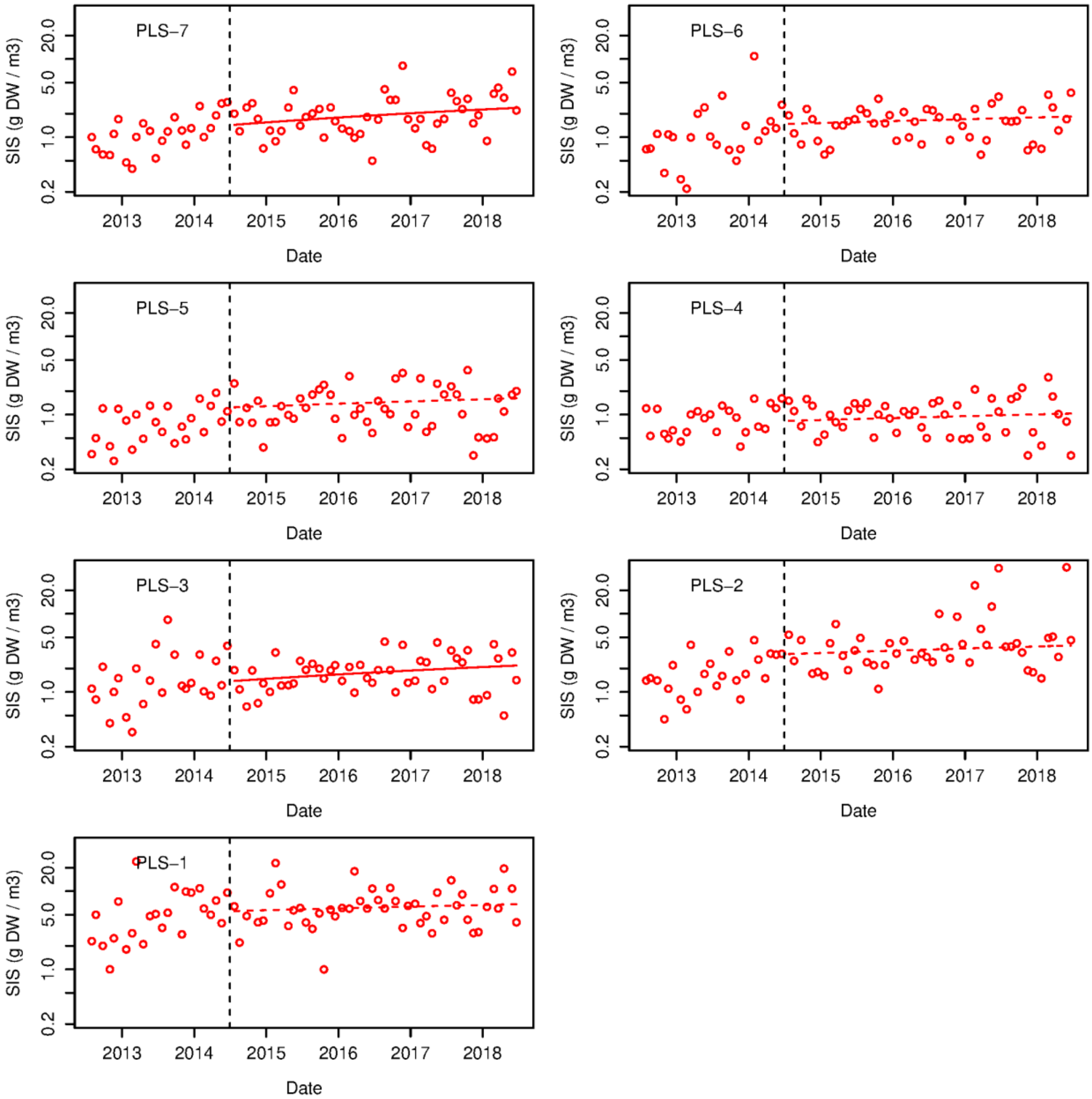


Figure 5-7: Concentrations of suspended inorganic solids measured in the near-surface water-samples of the seven Marlborough District Council Pelorus stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red line indicates the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.5 Turbidity

5.5.1 Hose & Van Dorn bottle samples

Turbidity is a manifestation of scattering in the water. The scattering is induced by photons reflecting off particles suspended in the water. Thus, fluctuations in turbidity have tended to correlate with those of suspended particulates (particularly, suspended inorganic ones - section 5.4). Like the concentrations of suspended inorganic particulates, turbidity tends to be greater at the inner Sound sites (Figure 5-8).

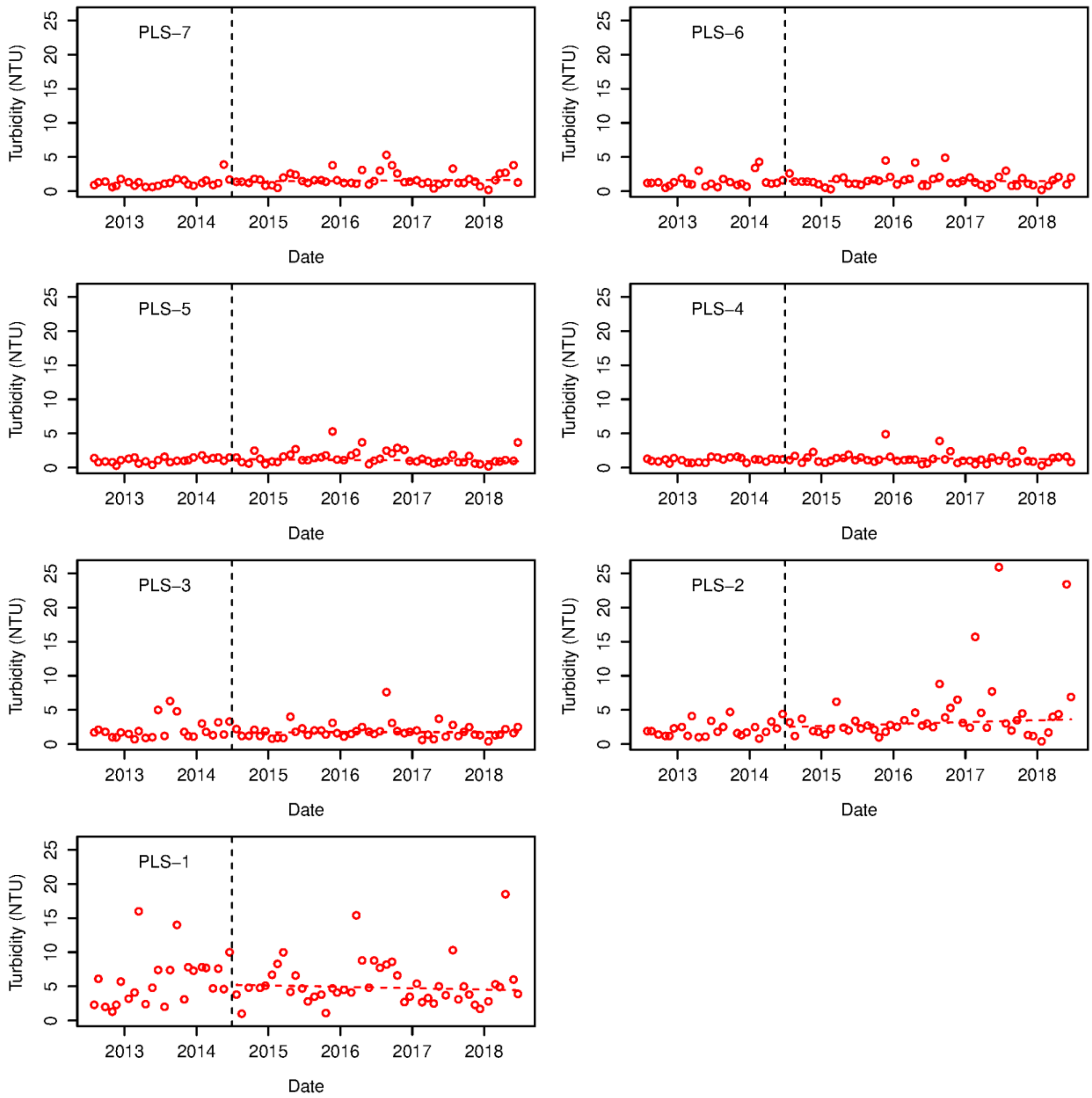
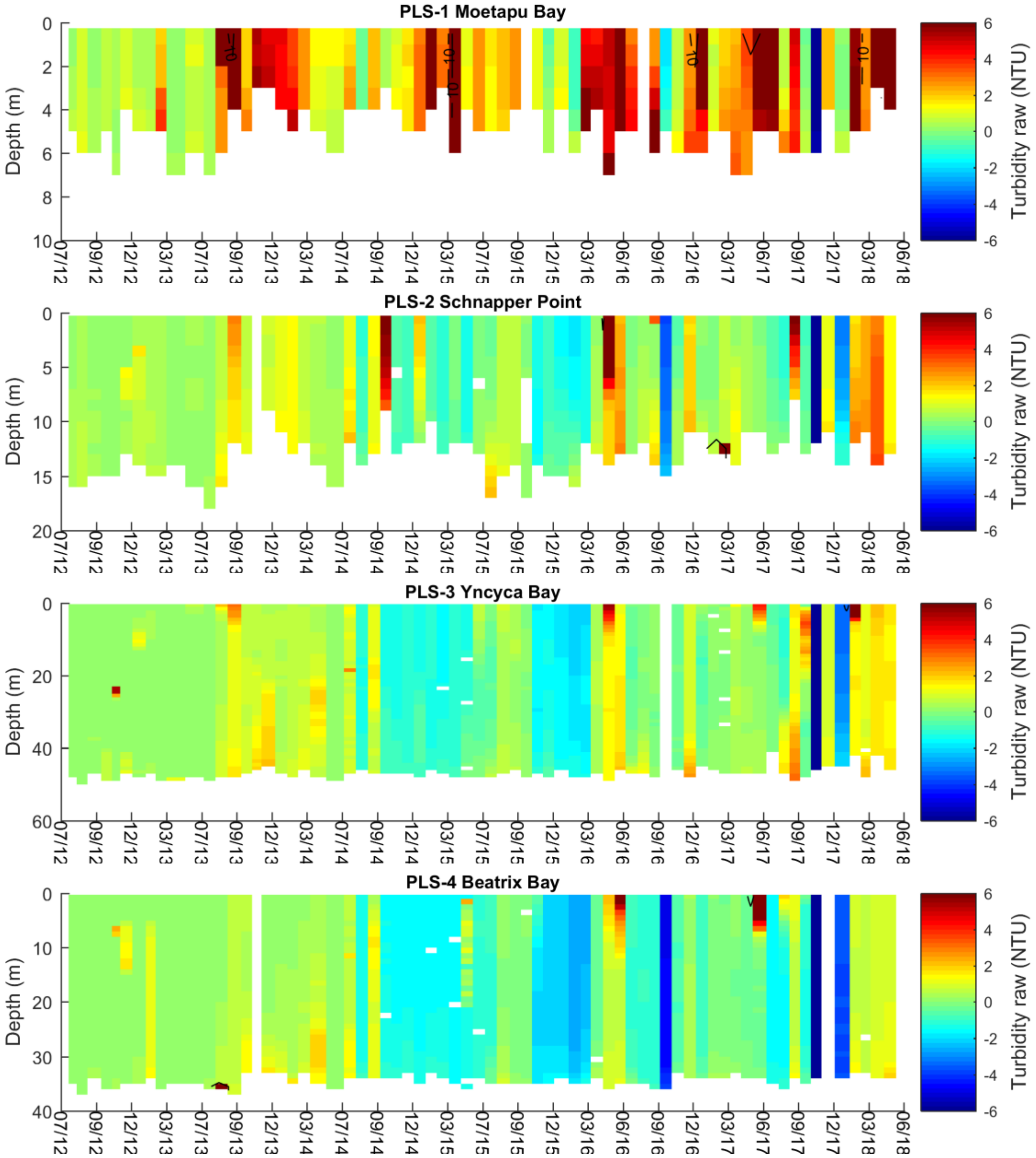


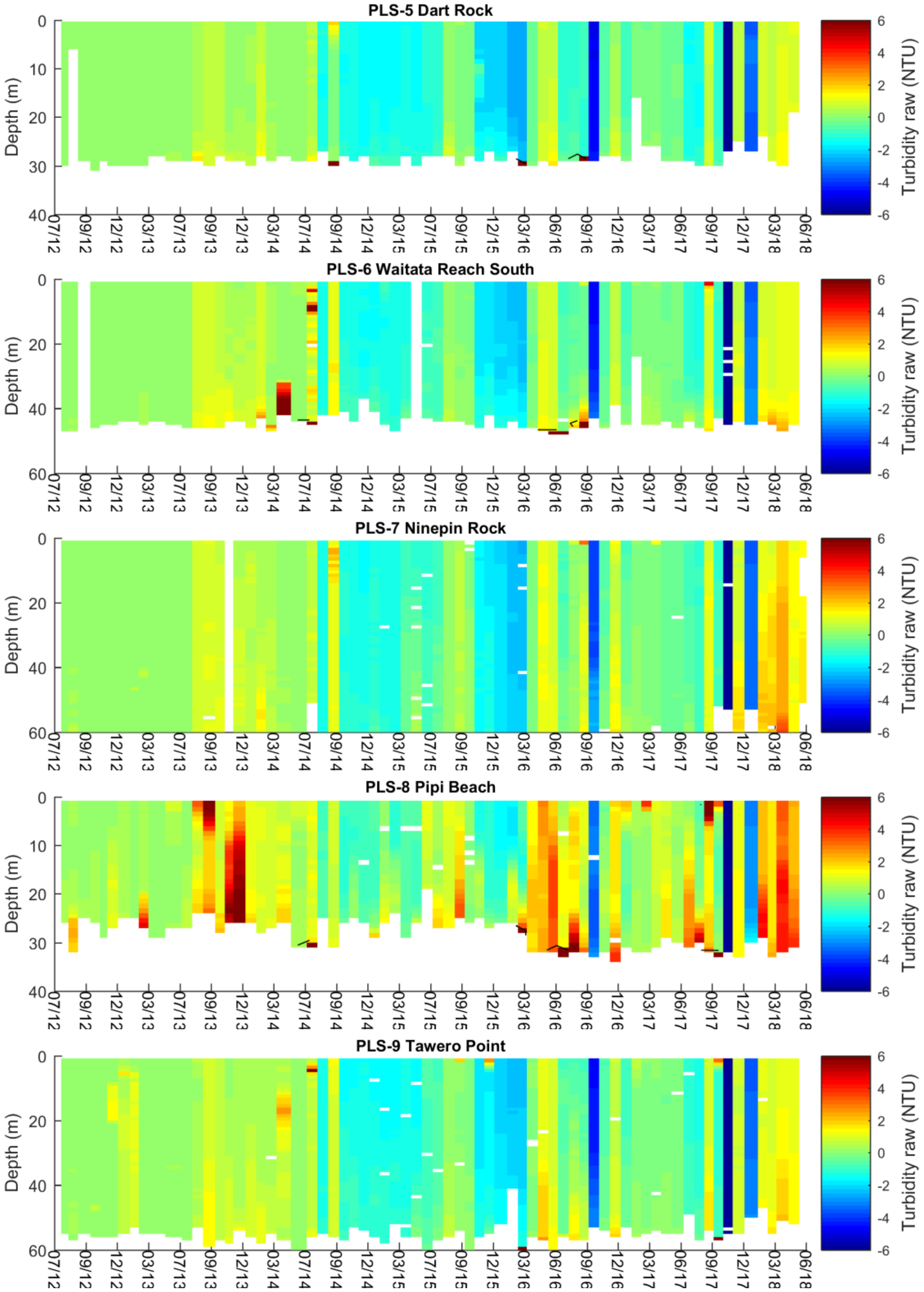
Figure 5-8: Near-surface turbidity measured at the seven Marlborough District Council water quality monitoring sites in Pelorus. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.5.2 CTD-turbidity

Contour plots of turbidity through time and depth from the CTD profiles are shown in Figure 5-9. Like the Queen Charlotte data, these data are of dubious quality with frequent unrealistic negative turbidity values. The CTD turbidity observations may be useful for comparing between sites at any instant, and over depth at a site on a given day, but not for comparing changes over time. CTD turbidity data may be improved by comparing to the water sample reported above, but a preliminary inspection showed that the relationship between CTD turbidity and water sample turbidity changes significantly over time, and a thorough analysis was beyond the scope of the present work. Turbidity monitoring may be improved by more frequent sensor calibration, and/or use of a calibration standard to reference data from each period.

In general, turbidity is highest at PLS-1, which is the site closest to the Pelorus River. High turbidity events originating from the Pelorus River can be seen extending, mostly in the upper water column, to more distance sites, particularly PLS-2, 8 and 3.




PLS-5 Dart Rock
PLS-6 Waitata Reach South
PLS-7 Ninepin Rock
PLS-8 Pipi Beach
PLS-9 Tawero Point
Depth (m)
Turbidity raw (NTU)
07/12 09/12 12/12 03/13 07/13 09/13 12/13 03/14 07/14 09/14 12/14 03/15 07/15 09/15 12/15 03/16 06/16 09/16 12/16 03/17 06/17 09/17 12/17 03/18 06/18

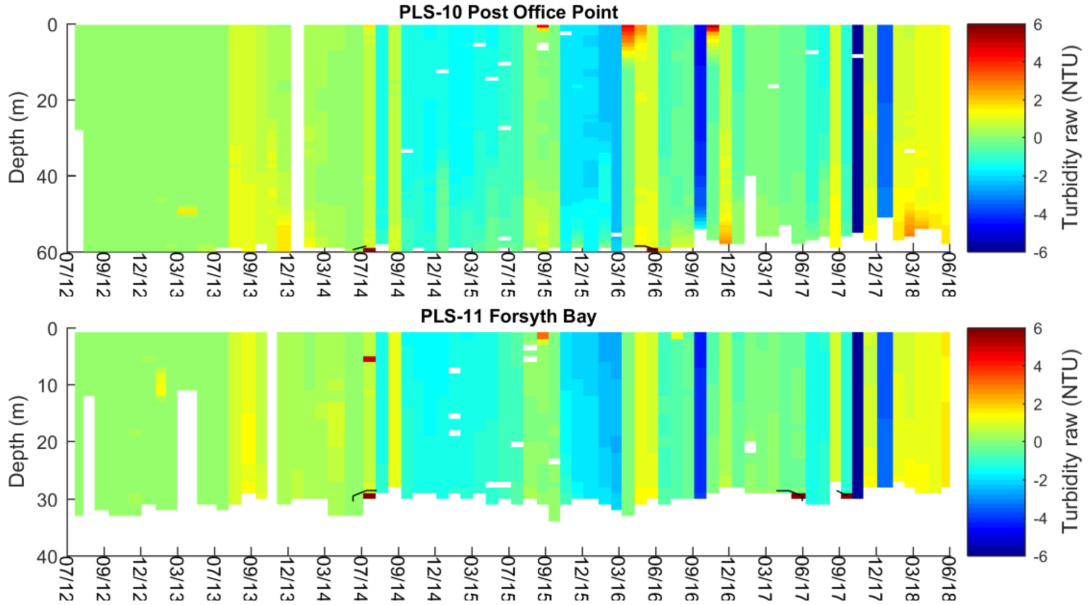


Figure 5-9: Raw turbidity from Pelorus Sound as recorded by the turbidity sensor on the CTD probe. These data are of dubious quality. Negative turbidity values are physically unrealistic; furthermore, the turbidities measured using the sensor that accompanied the CTD are often inconsistent with those measured in the water-samples that were returned to the laboratory.

5.6 Dissolved reactive phosphorus

DRP concentrations show a weak annual cycle (Figure 5-10). They tend to be higher near-bed than near-surface and higher inshore than close to Pelorus Sound. Sen slopes are positive at some stations and negative at others. The signs are confidently determined at only a minority of locations.

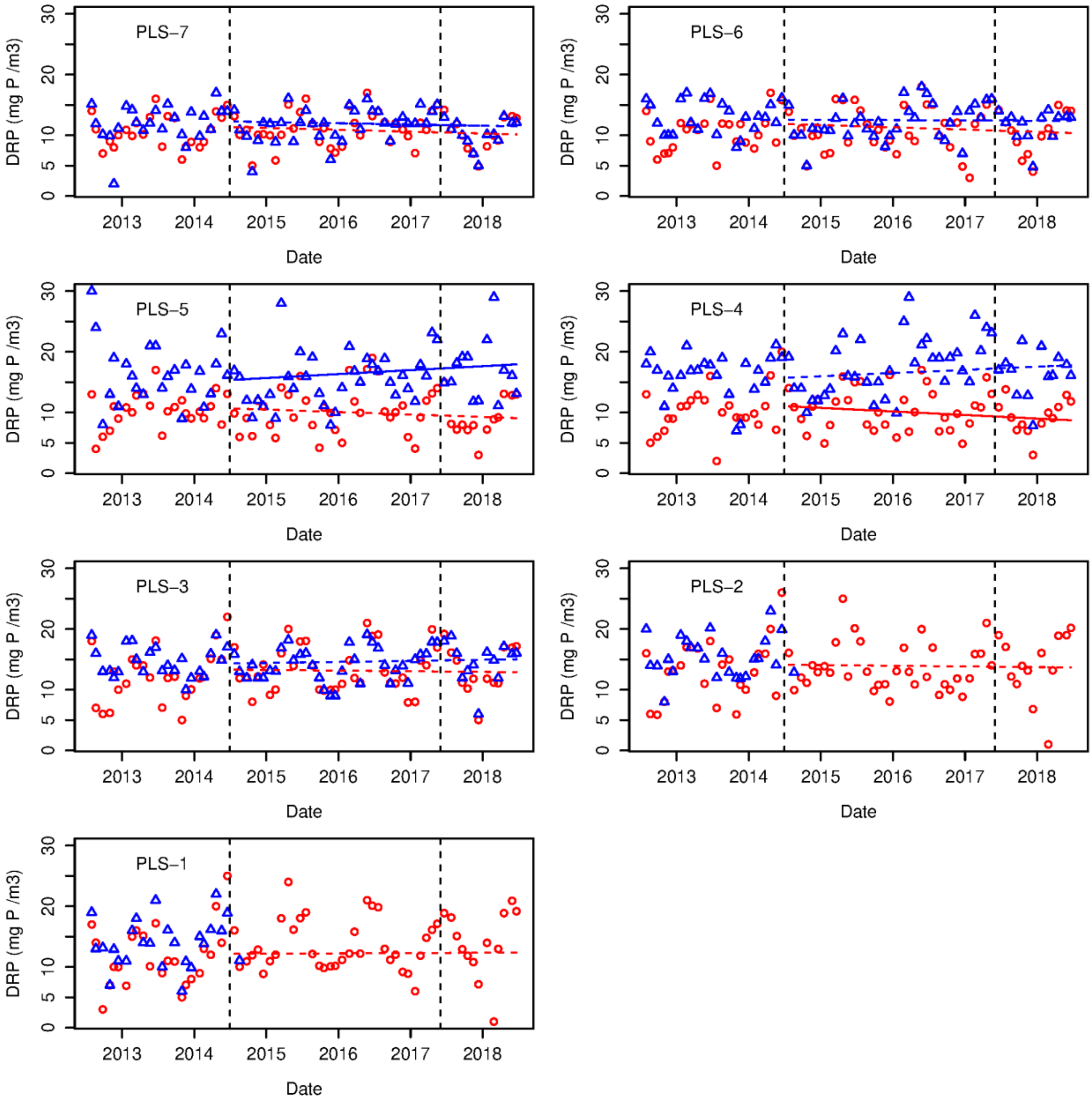


Figure 5-10: Time-series of dissolved reactive phosphorus measured near surface (red) and near bed (blue) at the seven Marlborough District Council Pelorus sampling sites. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-217 denotes the date on which the replacement nutrient analyser came into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.7 Total dissolved phosphorus

Total dissolved phosphorus concentration also shows a weak annual cycle Figure 5-11. The signs of the Sen-slopes vary across locations, but most have been negative.

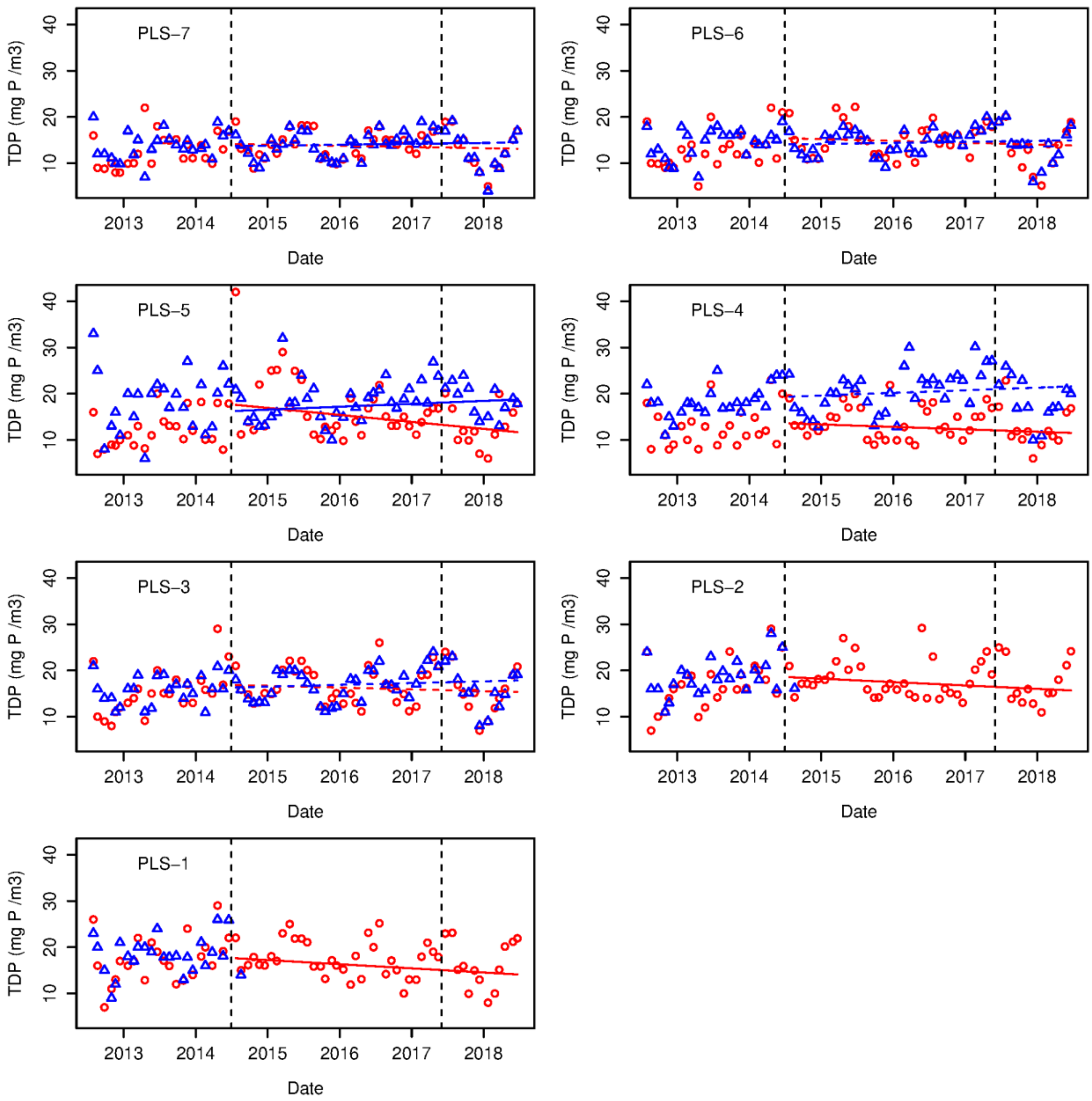


Figure 5-11: Total dissolved near-surface (red) and near-bed (blue) phosphorus measured at the seven Marlborough District Council Pelorus stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-217 denotes the date on which the replacement nutrient analyser came into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.8 Dissolved organic phosphorus

Dissolved organic phosphorus has been calculated by subtracting measured DRP concentrations from measured TDP concentrations. The inferred concentrations of dissolved organic phosphorus are usually low (Figure 5-12). Indeed, they are sometimes negative. In the real-world, negative concentrations are impossible. The negatives arise because of unavoidable sampling/measurement error (imprecision) associated with the measurements of DRP and TDP. A majority of the Sen-slope signs appear negative, but few are confidently determined.

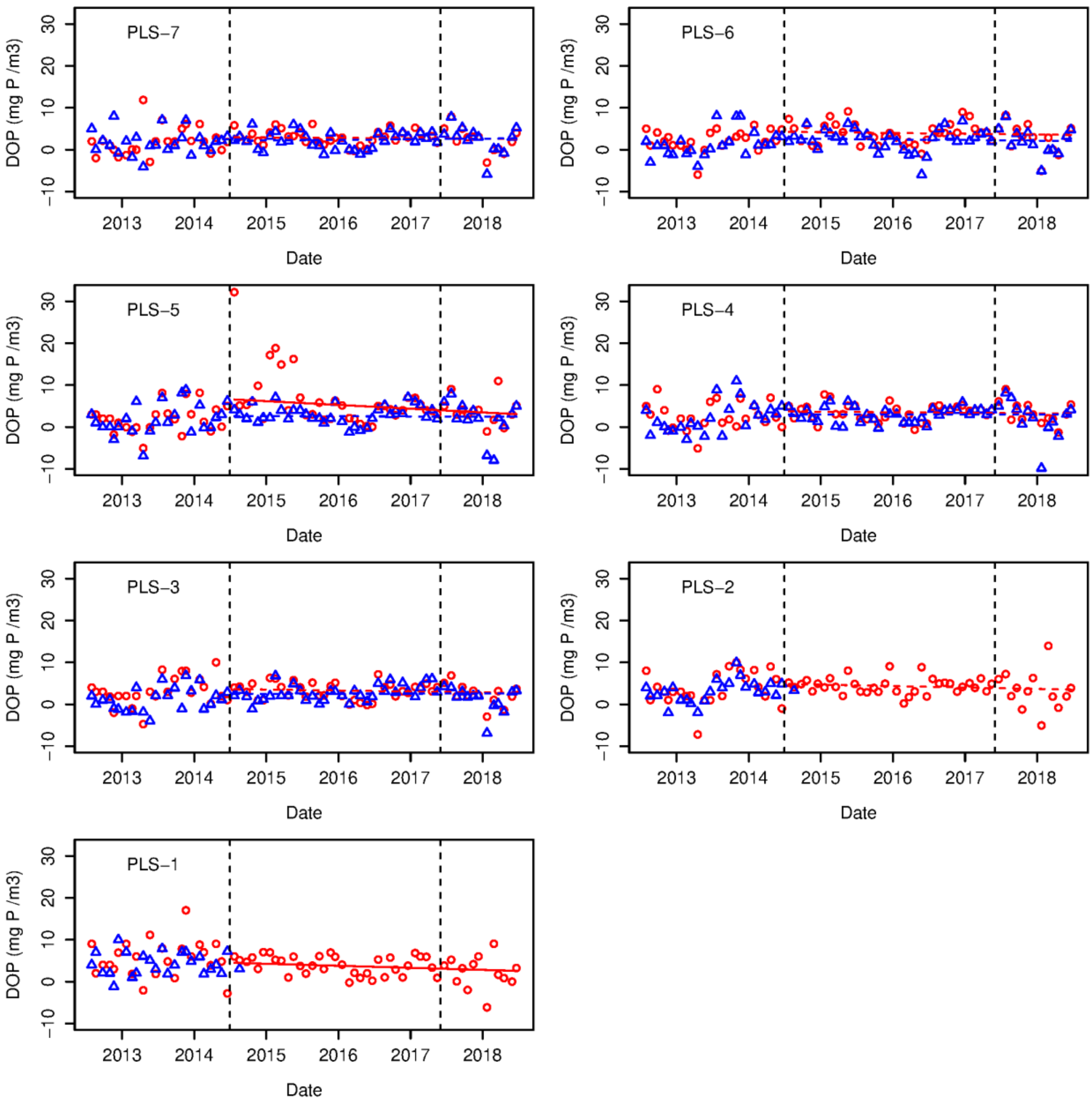


Figure 5-12: Inferred near-surface (red) and near-bed (blue) dissolved organic phosphorus (TDP-DRP) at the seven Marlborough District Council Pelorus water quality sites. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.9 Dissolved reactive silicon

Dissolved reactive silicon tends to be more abundant at the inner-most stations (Figure 5-13) (because its origin is largely terrestrial rock weathering, and subsequent Pelorus River input). Like other inorganic nutrients, it is more abundant during the winter months (Table B-1). The majority of Sen-slopes appear to be positive, but direction of trend can be confidently determined in only four cases.

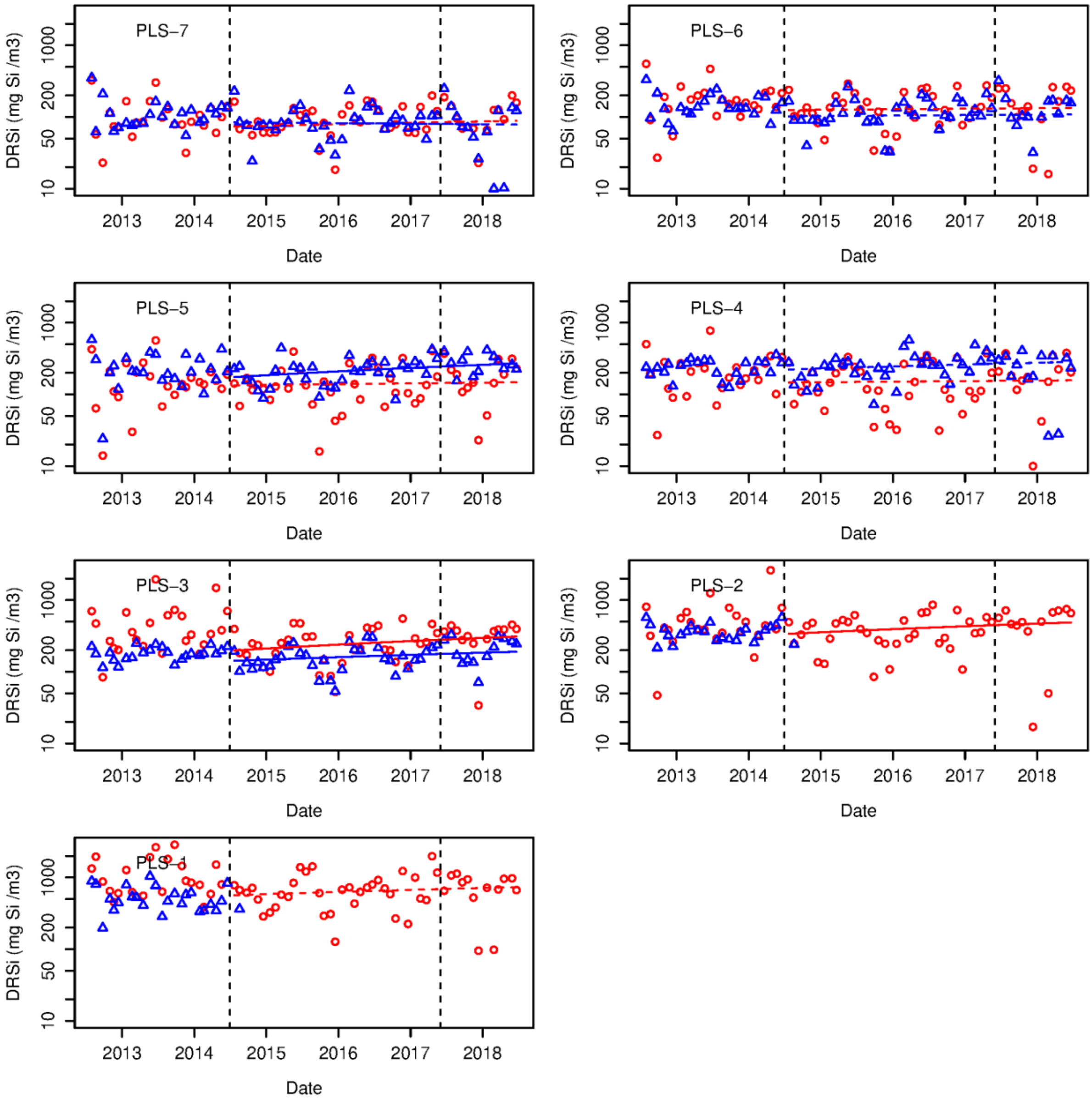


Figure 5-13: Dissolved reactive silicon concentrations near-surface (red) and near-bed (blue) at the seven Marlborough District Council Pelorus water quality stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.10 Total dissolved nitrogen

TDN concentrations tend to be higher in the inner Pelorus and central Pelorus (Figure 5-14) and a little greater in near-bed waters than near-surface ones. The annual cycles vary somewhat across stations (Table B-1). At the inner-most sites, TDN is most abundant during the winter months. At the central sites, peak abundances arise during autumn and spring. TDN concentrations appear to have trended upwards more strongly at the three inner-most sites (PLS-1 – PLS-3) than elsewhere but the trend signs are confidently determined only at two sites (PLS-2 near-surface & PLS-3 near-bed).

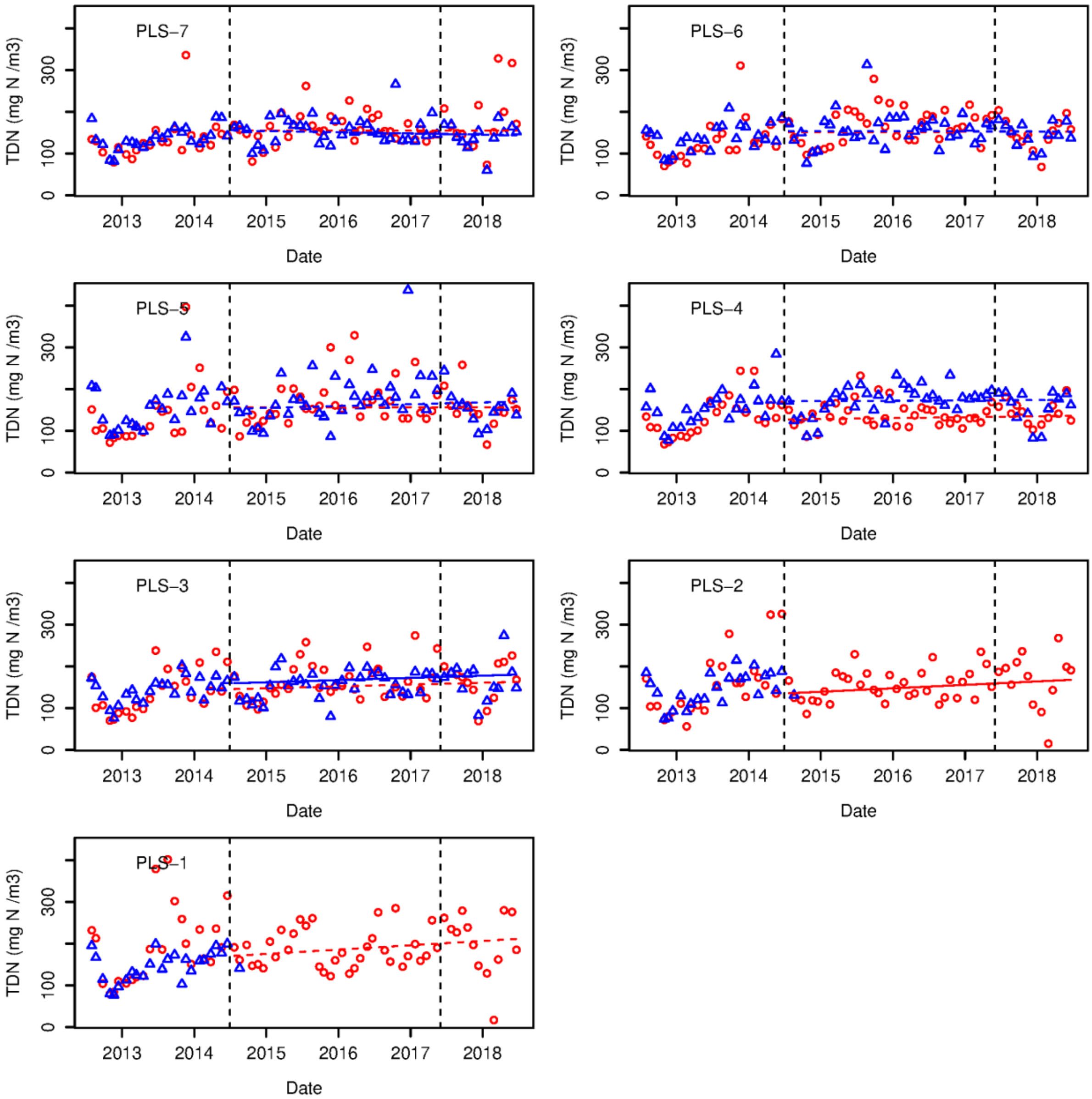


Figure 5-14: Total dissolved nitrogen near-surface (red) and near-bed (blue) measured at the seven Marlborough District Council Pelorus water-quality stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.11 Nitrate

Nitrate concentrations show a clear annual cycle (Figure 5-15, Table B-1). Winter maxima are greatest at the inner-most sites and smallest at the outer-most sites – but summer minima are similar everywhere (close to or below the detection limit). The Sen slopes are positive at all locations and the signs of these slopes can be confidently determined at most sites.

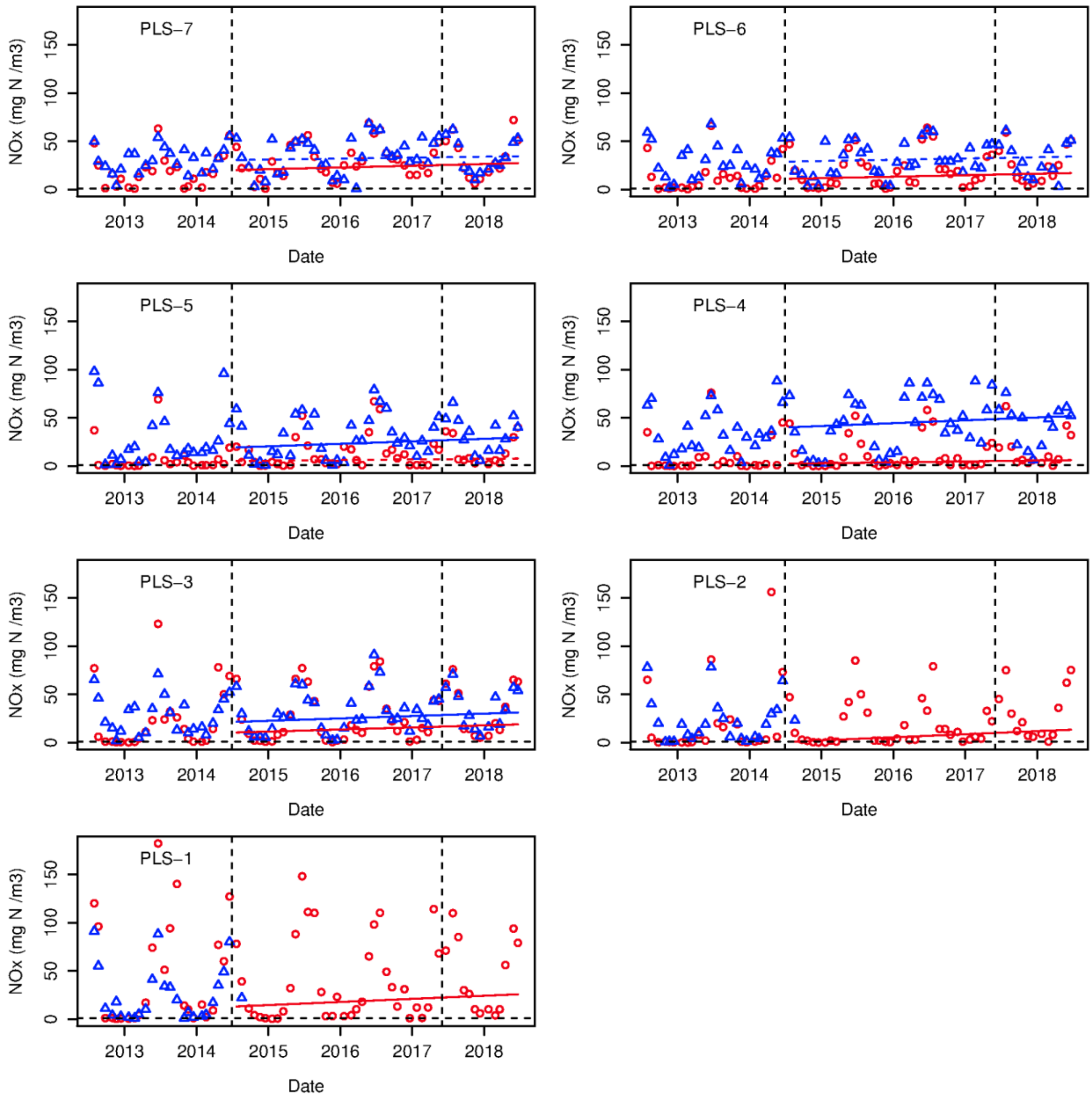


Figure 5-15: Nitrate concentrations near-surface (red) and near-bed (blue) measured at the seven Marlborough District Council Pelorus water-quality stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The horizontal black line denotes the detection limit (1 mg N m^{-3}). Values recorded as “<detection” have been replaced with imputed values calculated using regression-on-order methods. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.12 Ammoniacal nitrogen

Ammoniacal nitrogen concentrations tend to be highest during the summer at all sites (Table B-1) and tend to be higher near-bed than near-surface (Figure 5-16). They appear to have trended upward during 2012-2013, but the Sen slopes have been negative since mid-2014 (though only a minority of the slopes are confidently determined).

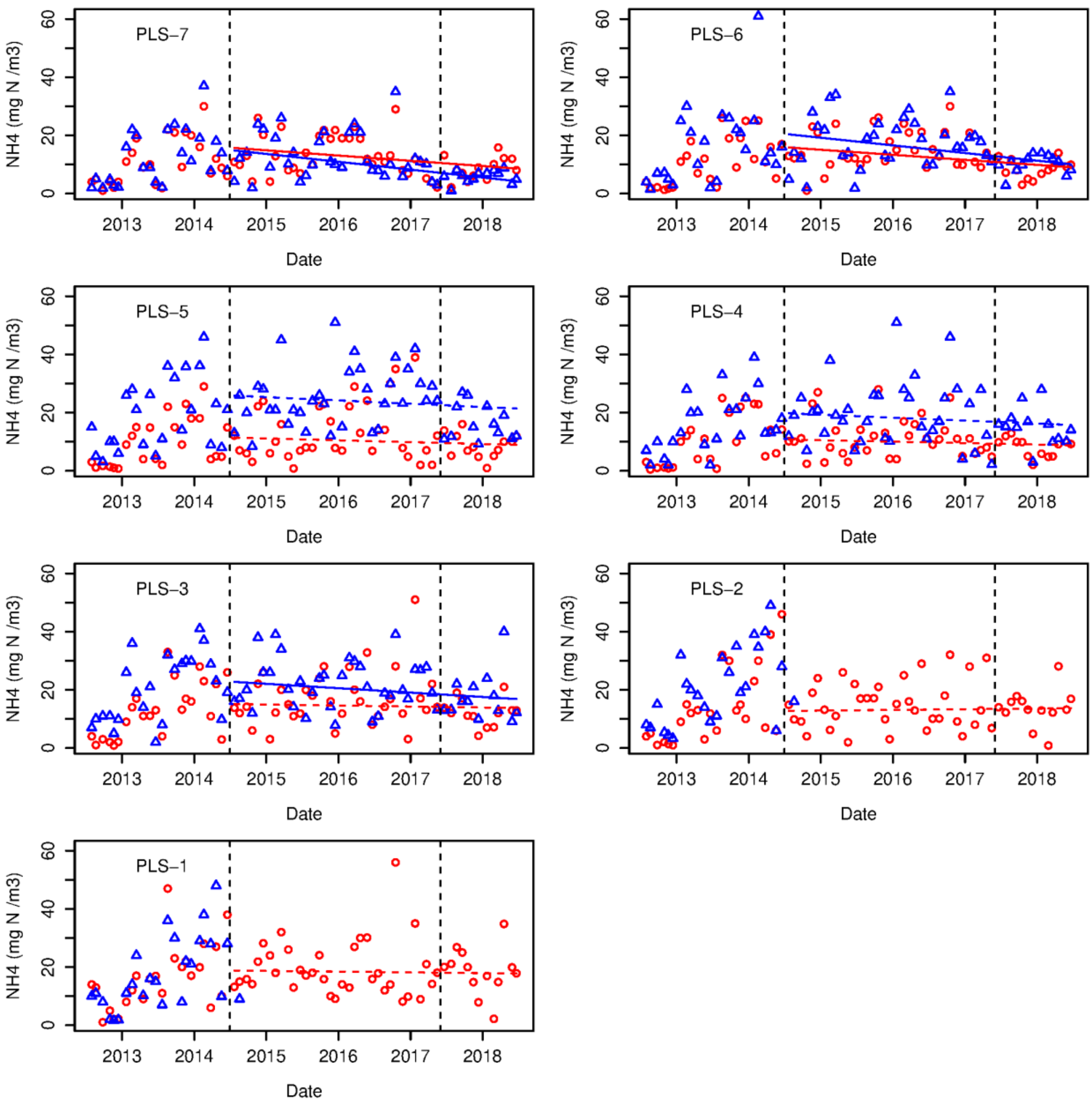


Figure 5-16: Ammoniacal nitrogen near-surface (red) and near-bed (blue) measured at the seven Marlborough District Council Pelorus water-quality stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.13 Dissolved inorganic nitrogen

Dissolved inorganic nitrogen is the sum of oxidized nitrogen (section 5.11) and ammoniacal nitrogen (section 5.12). These have tended to exhibit opposing trends such that DIN trends have almost invariably been close to zero. Indeed, the direction of trend can confidently be determined (upward) only at site PLS-2.

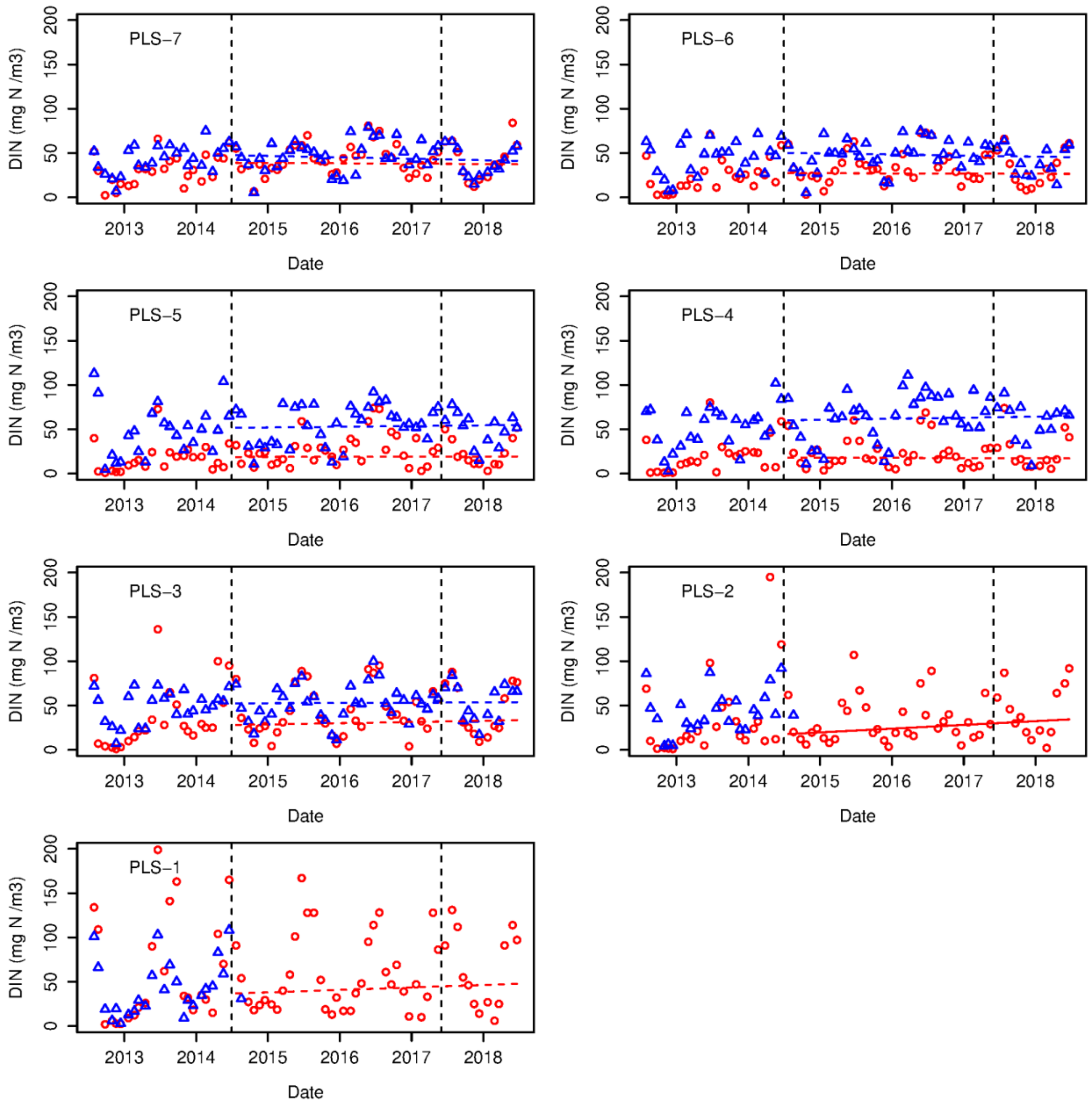


Figure 5-17: Dissolved inorganic nitrogen near-surface (red) and near-bed (blue) measured at the seven Marlborough District Council Pelorus water-quality stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-July 2017 denotes the date on which the replacement nutrient-analyser was brought into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.14 Dissolved organic nitrogen

Dissolved organic nitrogen concentrations do not show a strong annual cycle and are similar throughout the Sound (Figure 5-18). The signs of most Sen-slopes are not confidently determined.

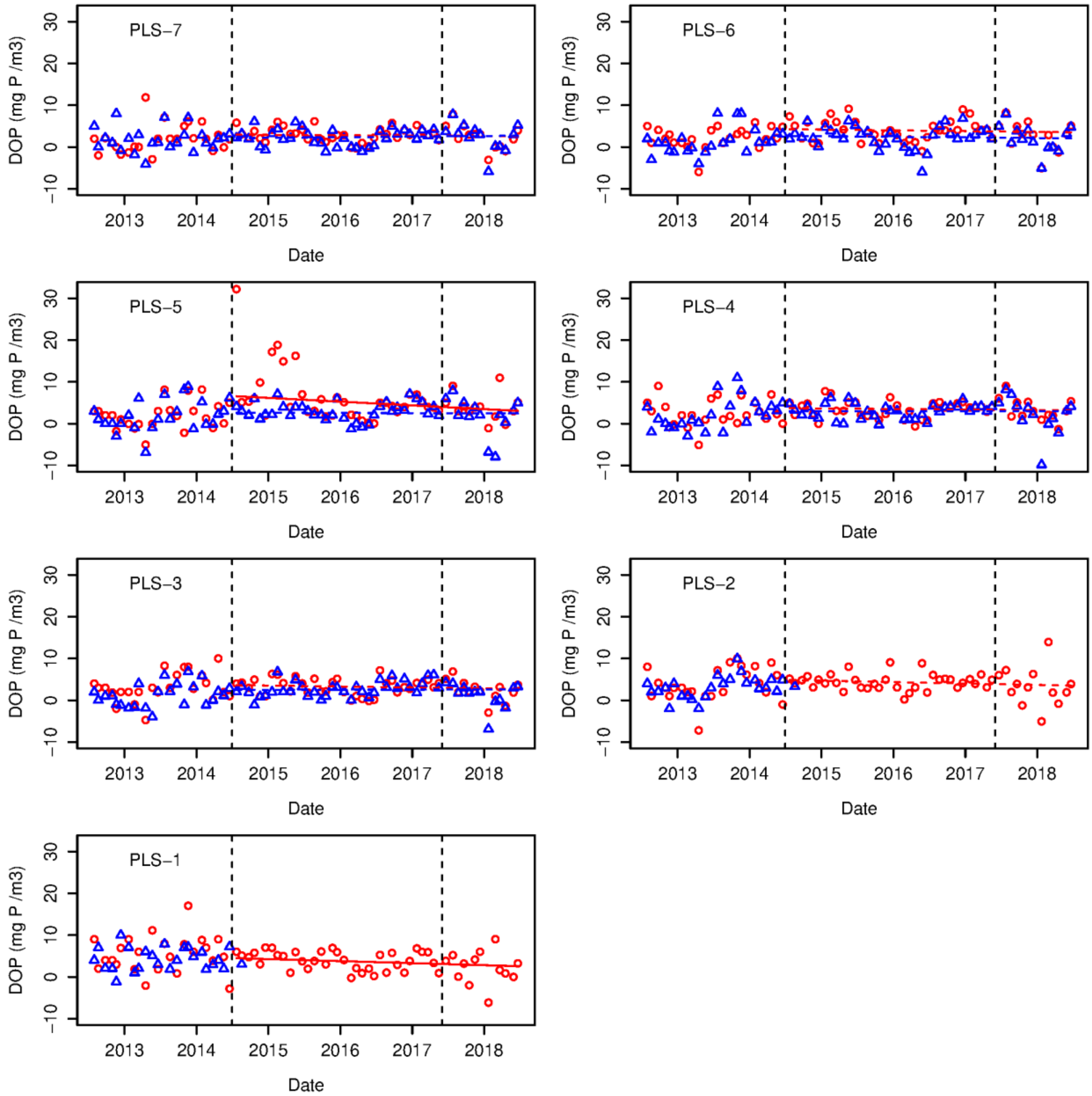


Figure 5-18: Inferred dissolved organic nitrogen concentrations near-surface (red) and near-bed (blue) at the seven Marlborough District Council Pelorus stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The vertical line in mid-217 denotes the date on which the replacement nutrient analyser came into operation. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.15 Particulate nitrogen

Particulate nitrogen concentrations show only a weak annual cycle – tending to be slightly lower during winter (Figure 5-19, Table B-1). They tend to be higher near-surface than near-bed. They trended upward during the period 2012-2014 but the trends have been shallower since then (and, in some cases downward). The signs of the Sen-slopes are confidently determined in only two of 12 cases.

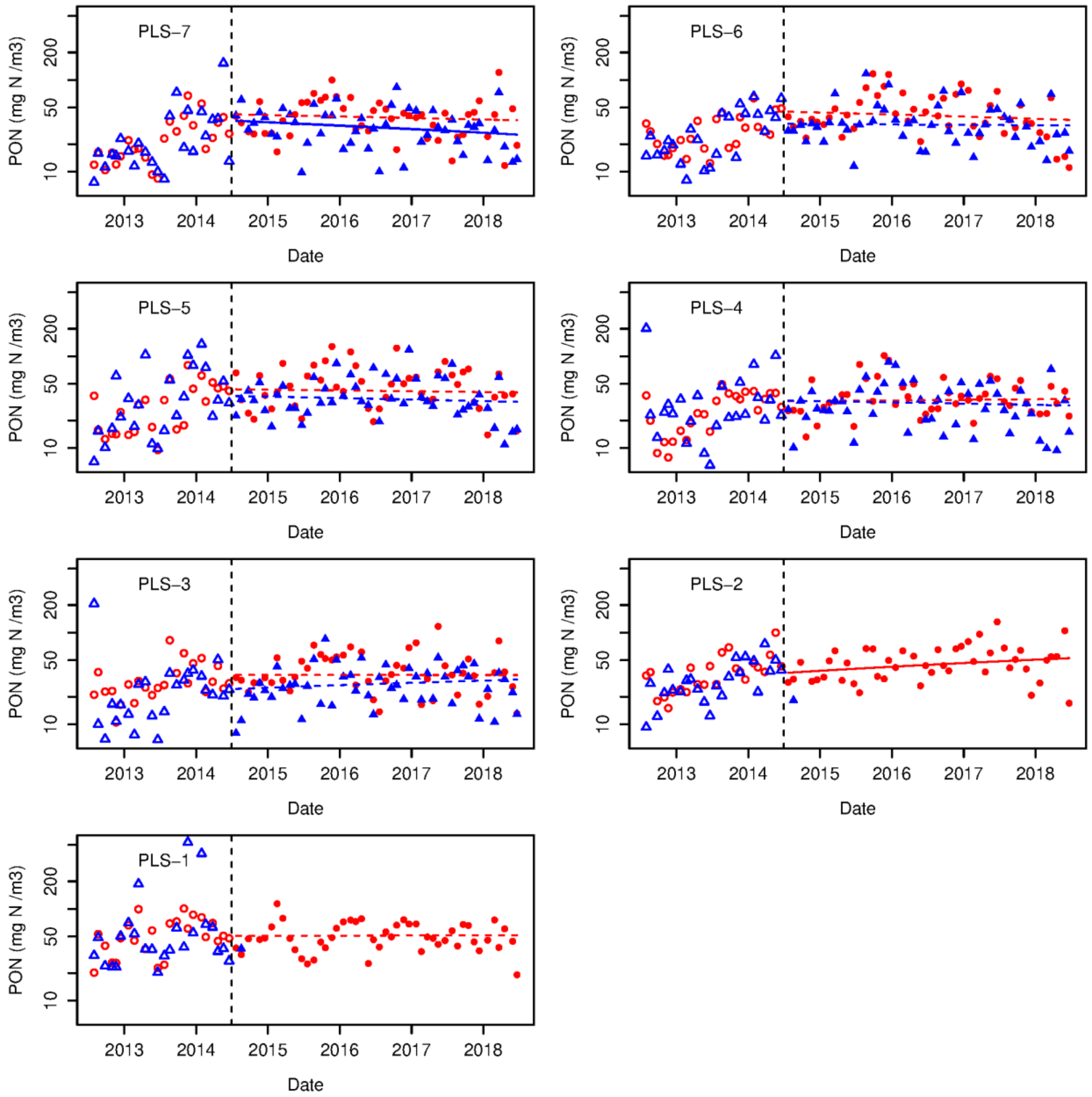


Figure 5-19: Particulate nitrogen near-surface (red) and near-bed (blue) at the seven Marlborough District Council Pelorus monitoring stations. The dashed vertical line (July 1, 2014) and switch from open to closed symbols separates measurements of Particulate Organic Nitrogen sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Nitrogen measured sampled from the upper 15 using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.16 Particulate carbon

The dynamics of particulate carbon have been similar to those of particulate nitrogen. Concentrations rose during the first two years of sampling but have been more stable since then (in some cases falling, in other cases rising more slowly). The sign of only one of the Sen-slopes is confidently determined.

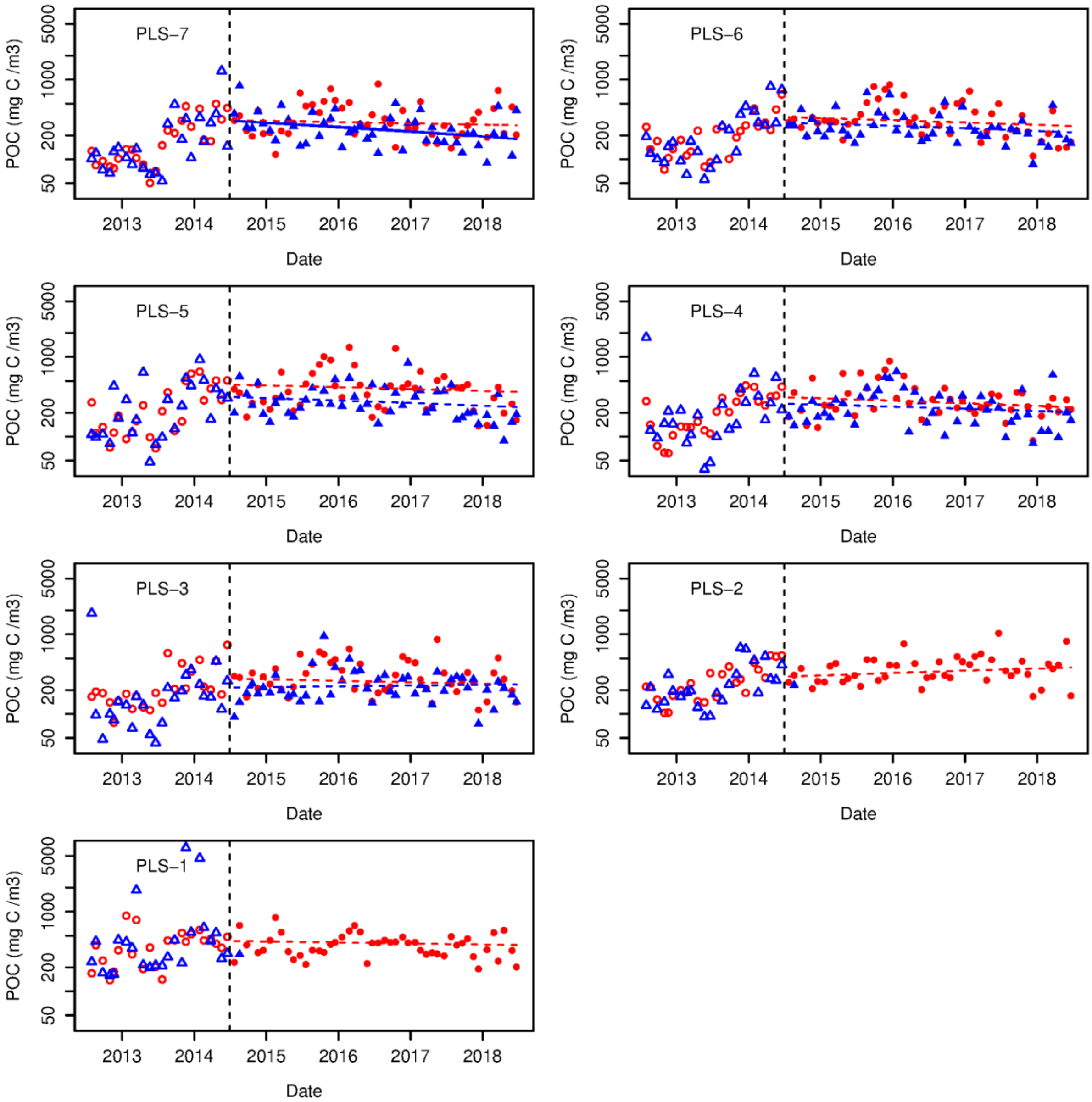


Figure 5-20: Particulate carbon near-surface (red) and near-bed (blue) at the seven Marlborough District Council Pelorus monitoring stations. The dashed vertical line (July 1, 2014) and switch from open to closed symbols separates measurements of Particulate Organic Carbon sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Carbon measured sampled from the upper 15 using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.17 PN:PC

PN:PC ratios tended to decline during the first two years of sampling but have recovered since then (Figure 5-21). The majority of PN:PC ratios are usually a little below the Redfield ratio, but ratios are well above those that would be associated with woody terrestrial litter. This suggests that the majority of suspended fine particulate organic matter may stem from phytoplankton (or other protein rich material) rather than woody plant material imported from the catchment.

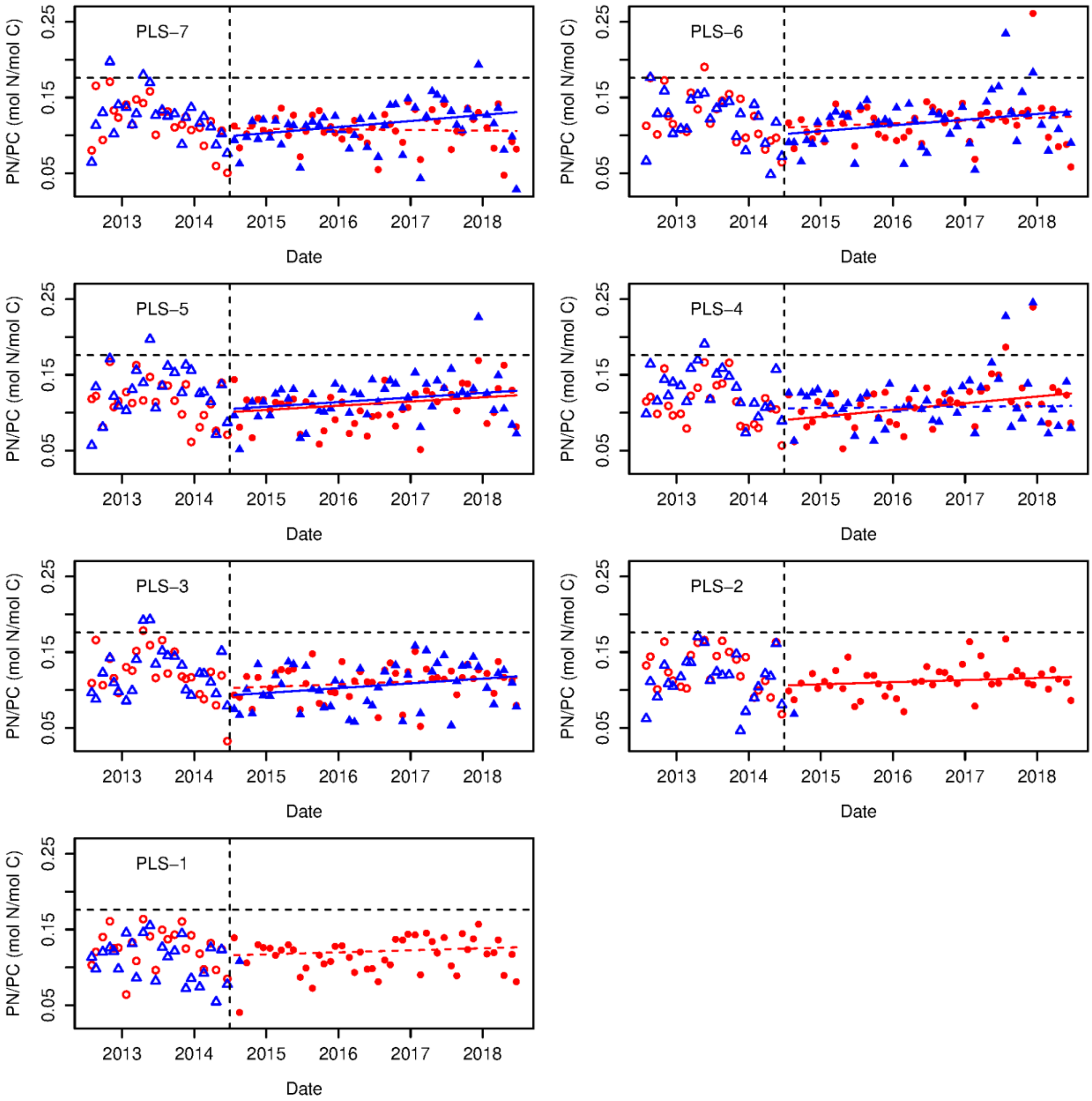


Figure 5-21: PN:PC ratios in near-surface (red) and near-bed (blue) samples at the seven Marlborough District Council Pelorus sampling sites. The vertical dashed line (1 July, 2014) and switch from open to closed symbols separates measurements of Particulate Organic Carbon sampled at one metre depth using a Van Dorn bottle from measurements of Particulate Carbon measured sampled from the upper 15 m using a hose-sampler. The horizontal dashed line represents the so-called 'Redfield ratio' (empirically determined N:C ratio for particulate material in oceanic waters). The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.18 Total nitrogen

Total nitrogen is the sum of particulate and dissolved nitrogen components. The majority of TN concentrations have been between about 100 and 300 mg N m^{-3} (Figure 5-22). Nonetheless, there have been three periods during which TN concentrations >300 at least one station in three sequential sampling campaigns. At most sites, the Sen slopes appear to be positive, but the signs are confidently determined at only one site (PLS-2).

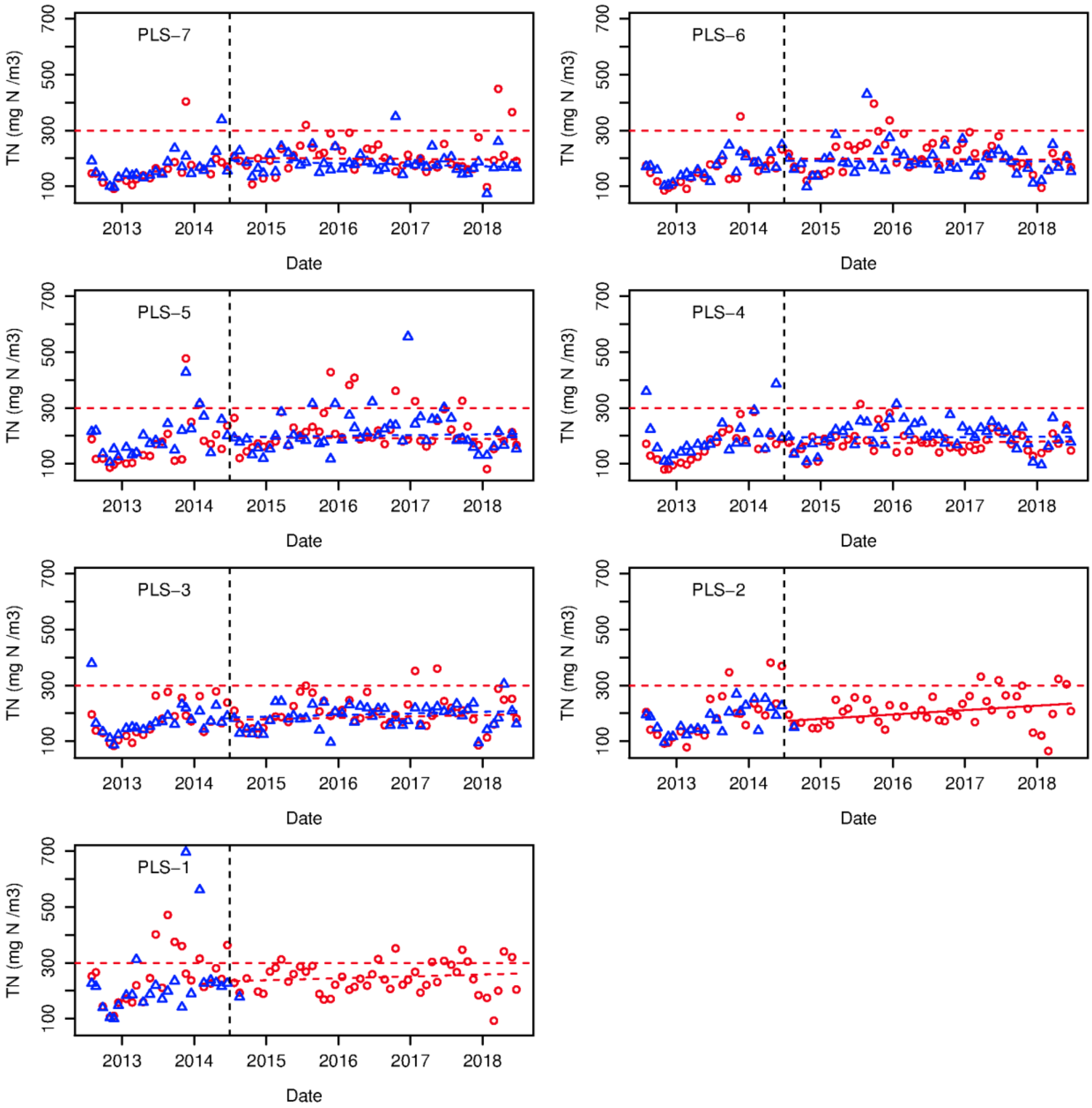


Figure 5-22: Total nitrogen in near-surface (red) and near-bed (blue) water measured at the seven Marlborough District Council Pelorus sampling sites. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The horizontal dashed line represents a trigger-value that has been proposed in relation to operation of New Zealand King Salmon Ltd salmon farms. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.19 Volatile Suspended Solids

Whilst both carbon and nitrogen are components of volatile suspended solids, VSS concentration is measured independently of P(O)C and P(O)N. Thus, VSS provide an alternative/independent (to POC and PC) measure of the abundance of particulate organic matter. VSS concentrations appear to have risen over the course of the sampling period at all stations (albeit that the sign of the Sen slope is confidently determined at only three sites, Figure 5-23). The annual cycle is weak, with all stations showing a small maximum in late summer/early autumn and some exhibit a second (perhaps larger) one in spring (Table B-1).

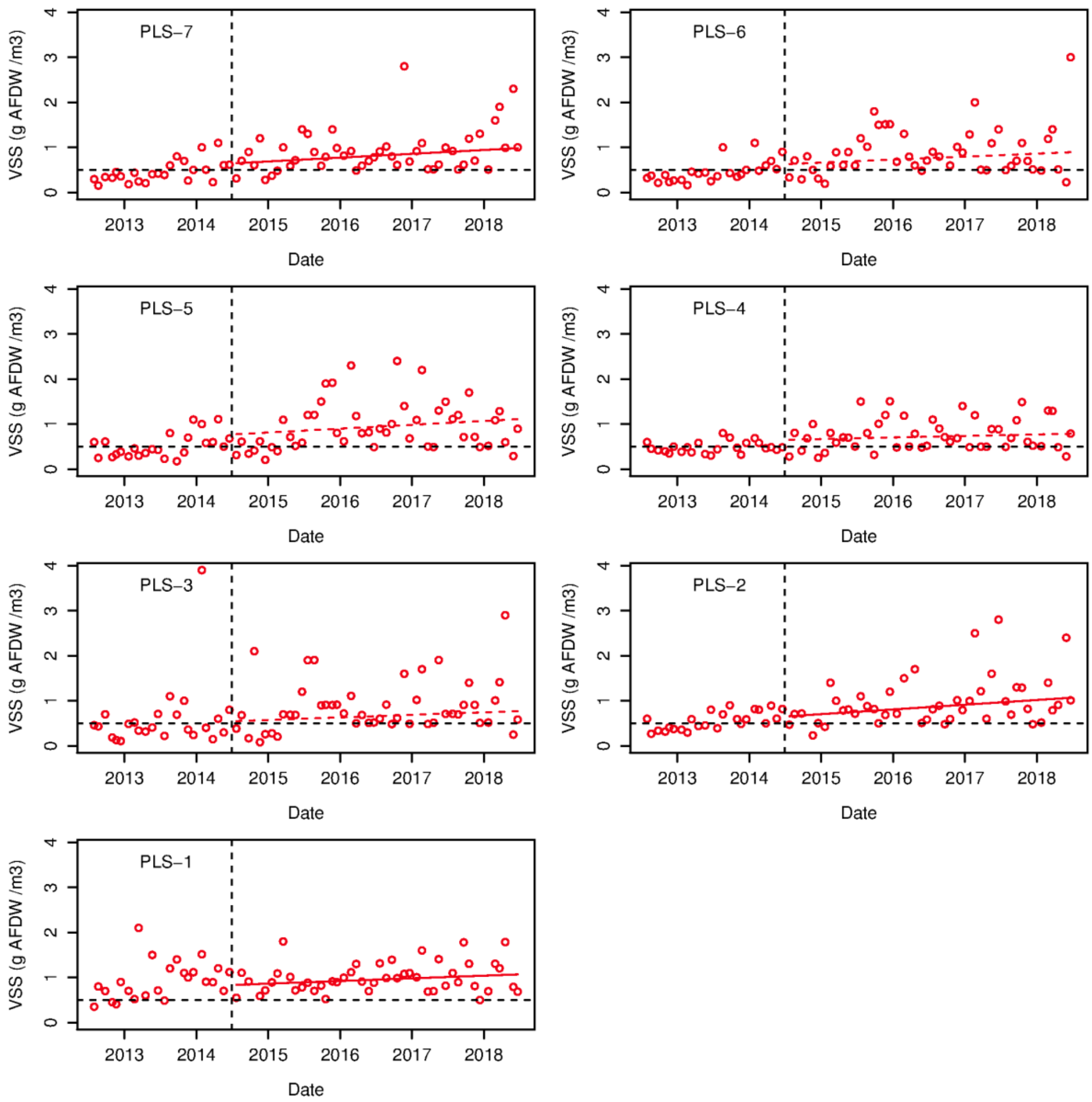


Figure 5-23: Volatile suspended solids concentrations measured in the near-surface waters at the seven Marlborough District Council Pelorus sites. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The horizontal dashed line denotes the detection limit (0.5 g m^{-3}). Values recorded as “<detection” have been replaced with imputed values calculated using regression-on-order methods. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.20 Chlorophyll

5.20.1 Hose & Van Dorn bottle samples

Chlorophyll concentrations tend to be highest in the inner parts of Pelorus Sound – and the amplitude of the annual cycle also tends to be greater there (Figure 5-24, Table B-1). The majority of concentrations have been below 2 mg m^{-3} (even in the inner Sound), but the highest record has been close to 5 mg m^{-3} and there have been two periods where a concentration >3.5 mg m^{-3} has been recorded somewhere within the surface waters of the Sound on three or more successive occasions.

Near surface chlorophyll concentrations tend to be highest during the winter at sites PLS-4 (Beatrix Bay) and PLs-5 (Tawhitinui Reach). Elsewhere, they peak during spring summer or autumn. The signs of the Sen-slopes vary across geographic locations, and in some cases across depth at a given geographic location. In the majority of cases the sign of the slope has not been confidently determined.

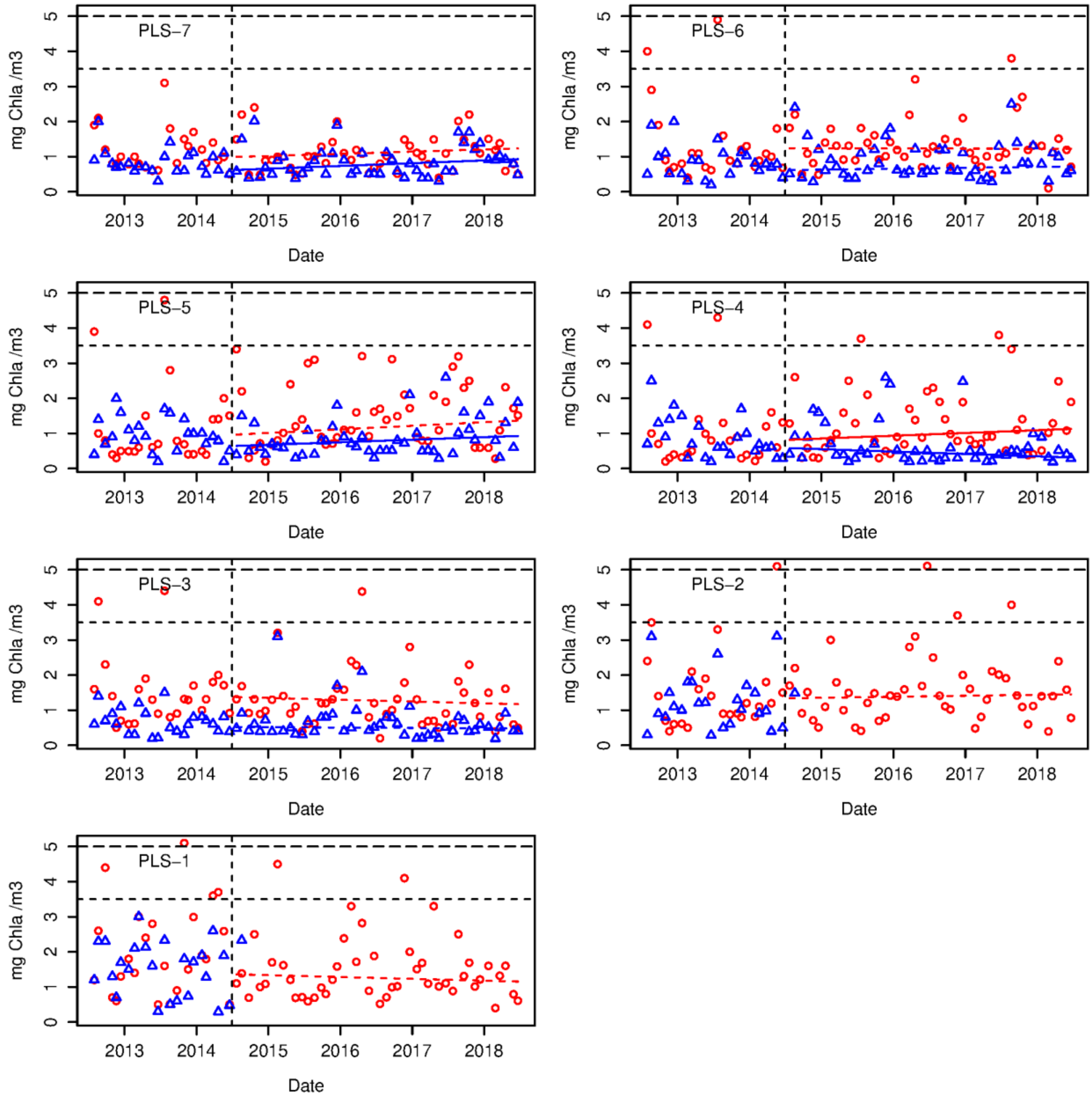
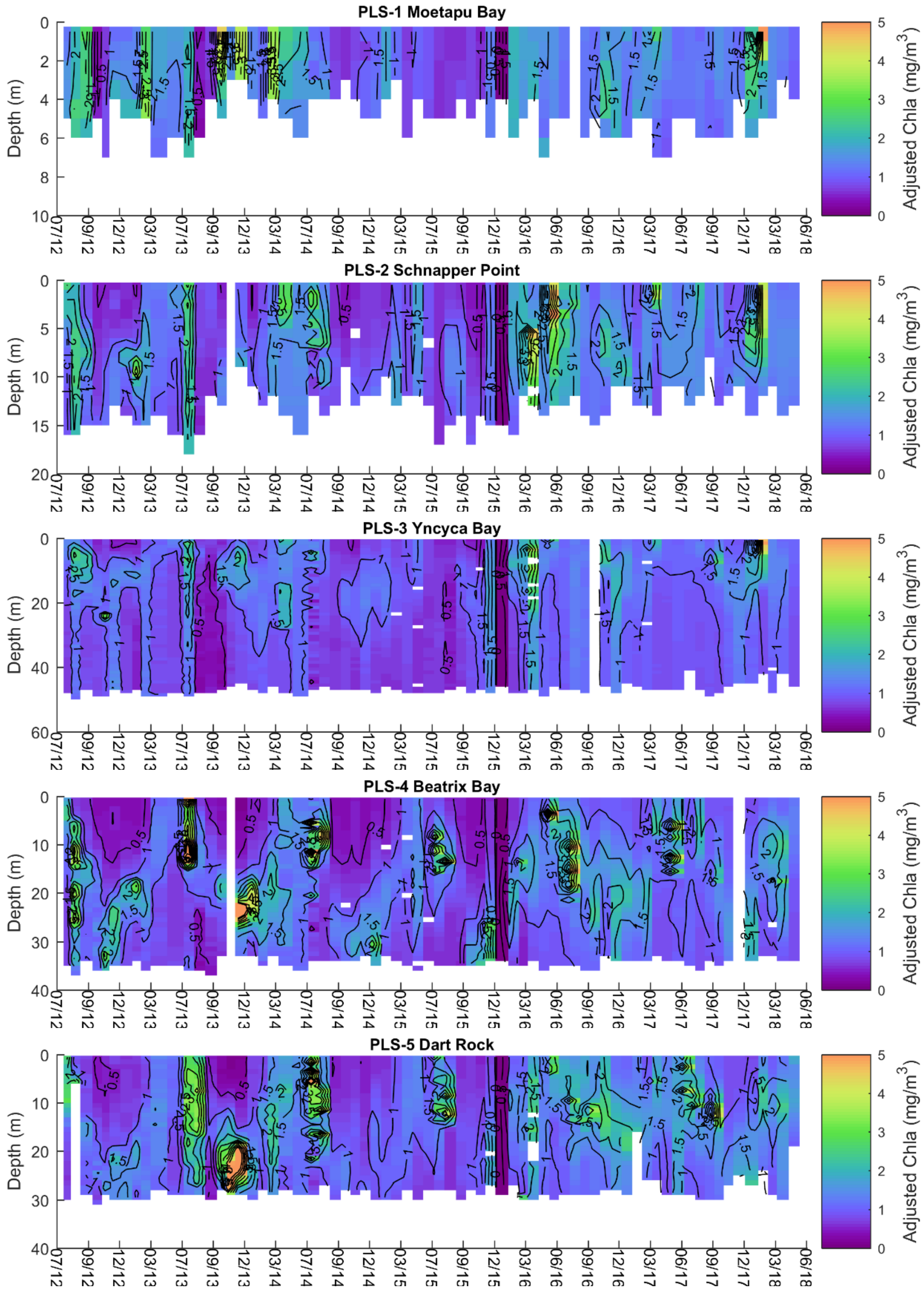
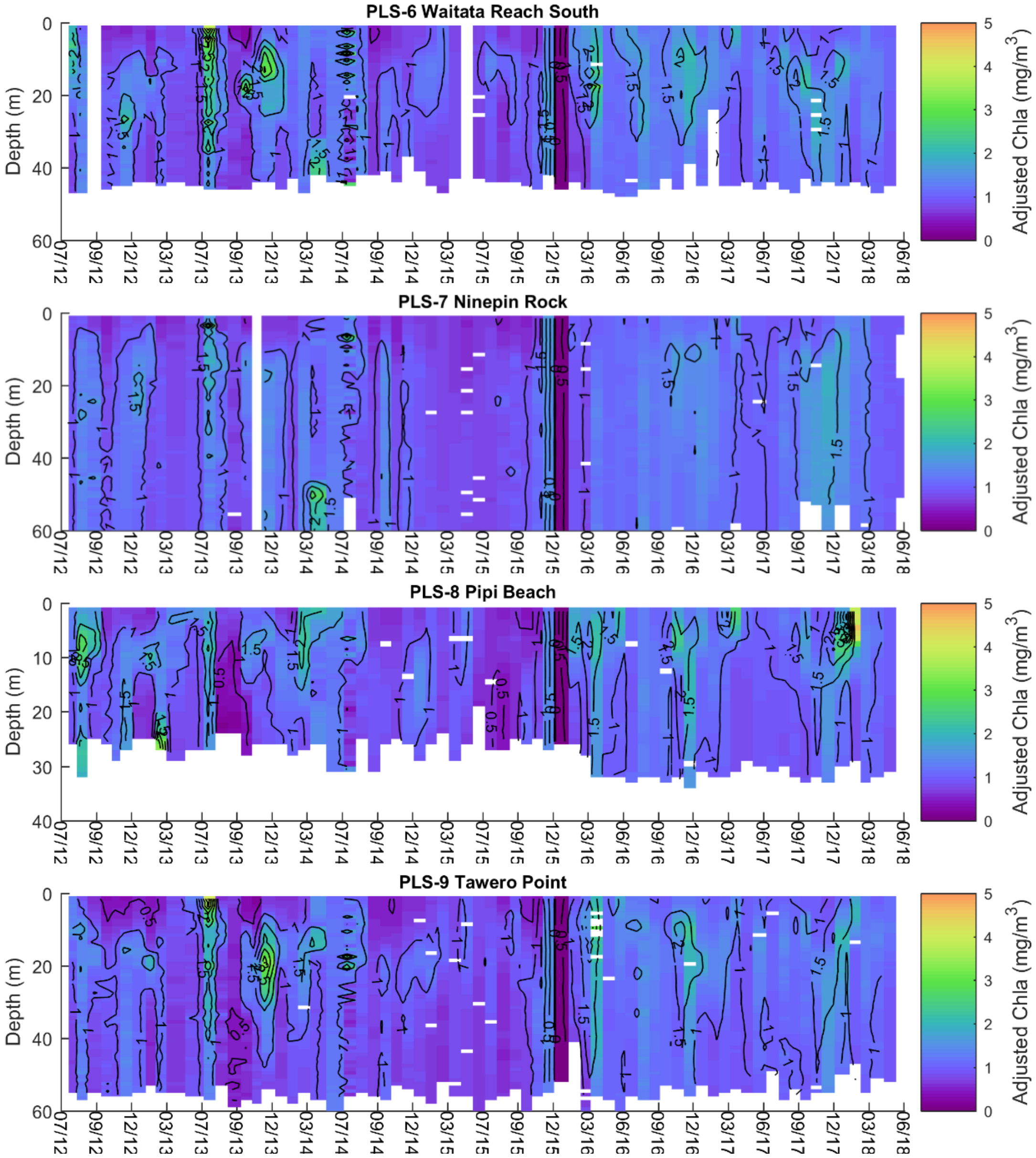


Figure 5-24: Chlorophyll concentrations measured near-surface (red) and near-bed (blue) at the seven Marlborough District Council Pelorus stations. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The horizontal black lines denote trigger values that have been proposed in relation to regulation of New Zealand King Salmon Ltd. Salmon farming operations. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.20.2 CTD-fluorescence

Figure 5-25 illustrates the time-and-depth evolution of chlorophyll concentration inferred from fluorescence. The fluorescence data suggest that, with the possible exceptions of the two innermost locations (PLS-1, Mahau Sound and PLS-2, Kenepuru Sound) chlorophyll is often most abundant some way below the sea-surface. During the period mid-2014 – mid-2015, none of the casts yielded ‘high’ chlorophyll concentrations. Since the data have only monthly resolution, it is not clear whether they simply did not coincide with times of high chlorophyll, or whether there were no such events.




PLS-6 Waitata Reach South
PLS-7 Ninepin Rock
PLS-8 Pipi Beach
PLS-9 Tawero Point
Depth (m)
Adjusted Chla (mg/m3)
07/12
09/12
12/12
03/13
07/13
09/13
12/13
03/14
07/14
09/14
12/14
03/15
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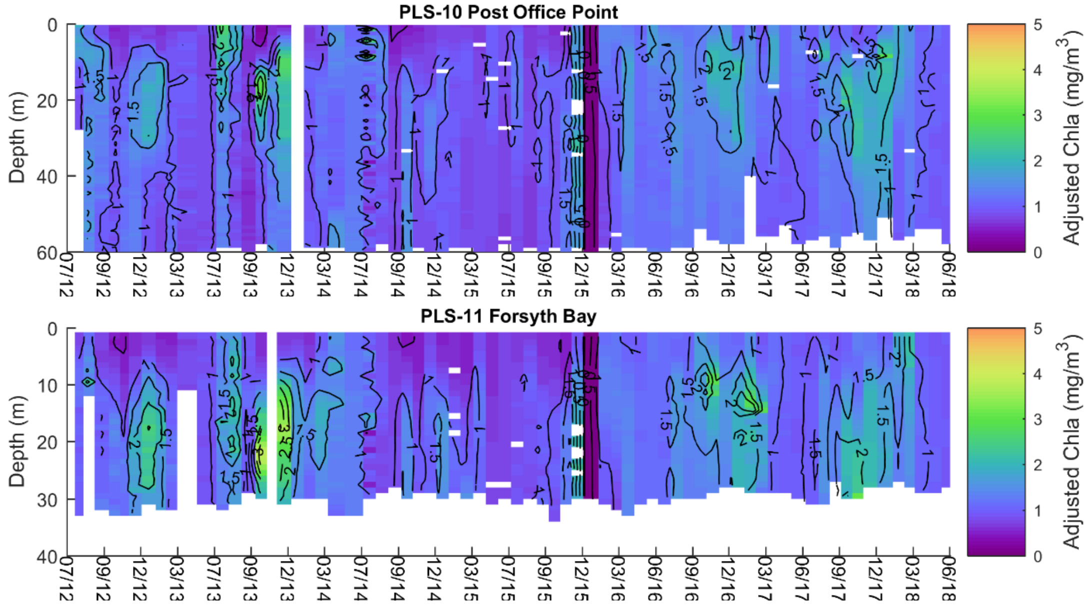

Figure 5-25: Contour plots of the evolving depth profiles of Chl-a through time at the Pelorus stations. Data are from the monthly CTD casts and have been re-calibrated using the water samples.

5.21 Algal carbon

Time-series of estimated phytoplankton carbon concentration (by taxonomic families) are illustrated in Figure 5-26. The abundance of all taxa appeared to decline during the 2013/2014 period, but they have recovered since then. The 'other' group exhibits only small amplitude seasonal fluctuations in comparison with diatoms and dinoflagellates. Except during the depths of winter, diatoms are usually the most abundant group by carbon mass. Dinoflagellates are scarce during the winter but abundant (rarely, dominant) in the summer months.

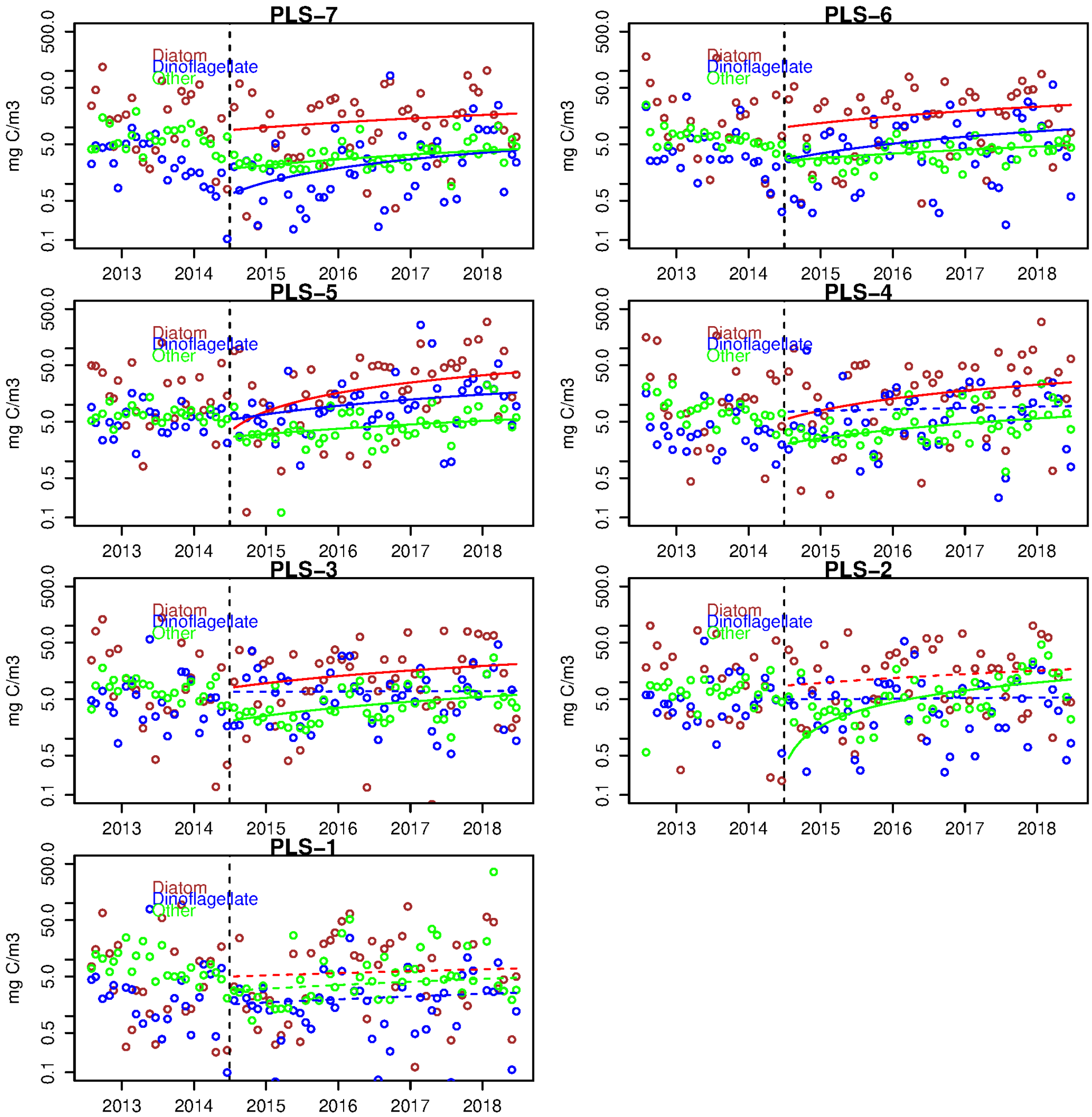

Figure 5-26: Phytoplankton carbon concentration from cell counts and cell dimensions at the seven Marlborough District Council Pelorus stations (near surface water samples). Red symbols: diatoms; blue symbols: dinoflagellates; green symbols: other taxa. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain. The lines appear curved (rather than straight) because the y-axis is logarithmic.

5.22 Zooplankton carbon

Zooplankton were counted only during the first two of the years of sampling. Biomass estimates are from counts, and measurements of the dimensions of a few, representative individuals. The size range spanned by different individuals of any given taxa can be very large (dep. upon developmental stage). Furthermore, whilst the sampling devices (Van Dorn bottle and hose-sampler) probably sample protozoa well, they will not sample multi-cellular zooplankton reliably. Thus, the biomass estimates are extremely imprecise (qualitative). Nonetheless, the time-series of zooplankton biomass are presented in Figure 5-27. Biomass concentrations have proven to be moderately stable at all sites (though most show one or two extremely high outlying values). Concentrations tend to be highest at PLS-1 and lowest at sites PLS-5 – PLS-7. Whilst no formal statistical tests have been undertaken, we note that zooplankton biomass concentrations are not markedly lower in two regions which have high densities of mussel farms (Kenepuru and Beatrix Bay) than in other regions.

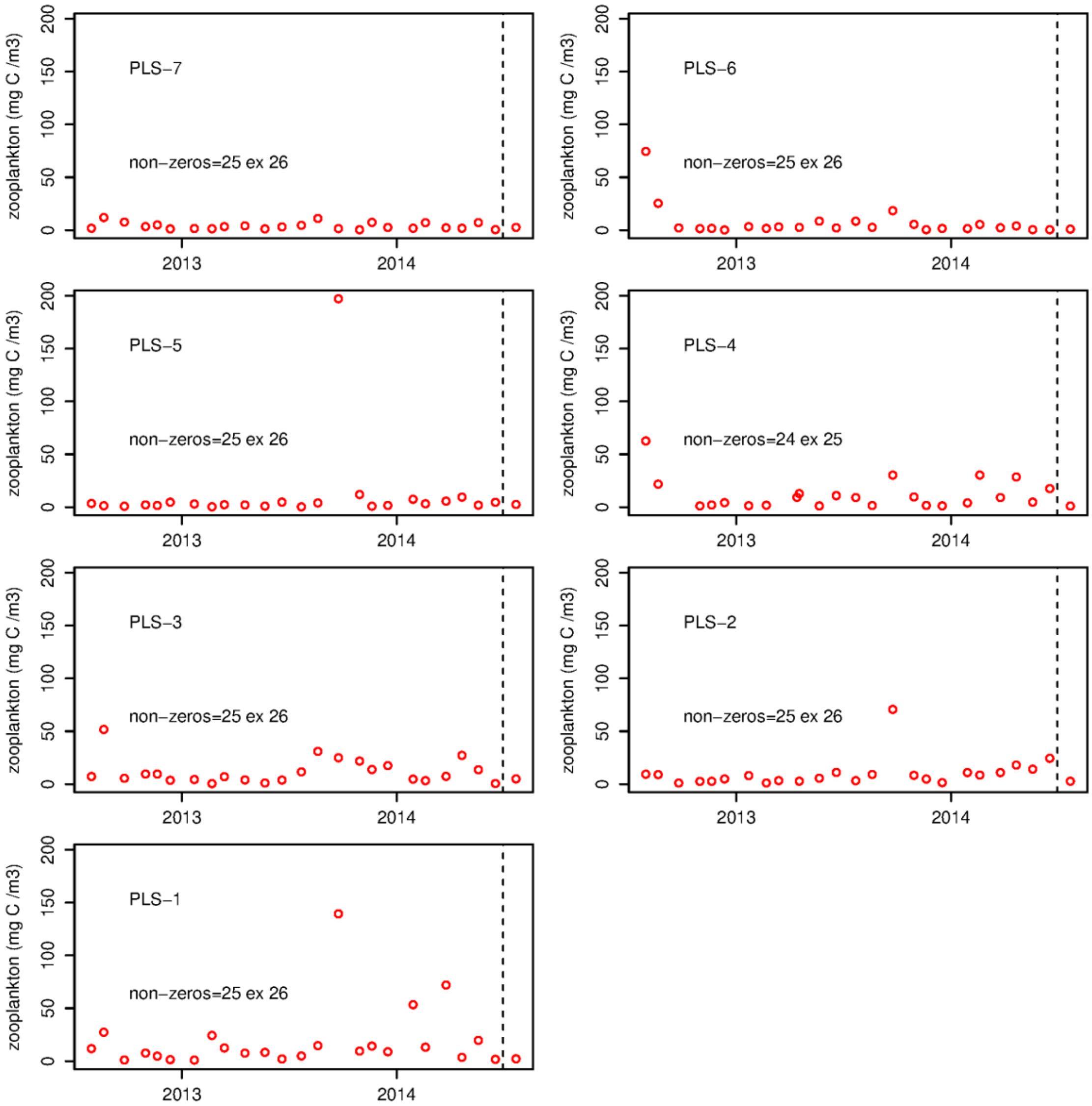

Figure 5-27: Zooplankton biomass inferred from counts and dimensions at the seven Marlborough District Council Pelorus sites (near surface water samples). The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler.

5.23 Elemental ratios

Ratios amongst the dissolved inorganic elements indicate that, in the inner and central Sound, nitrogen is invariably the nutrient that is most likely to be (or become) limiting to phytoplankton growth (Figure 5-28). In the outer-most Sound (PLS-7), nitrogen will often be the limiting element, but the system may sometimes become co-limited by silicon.

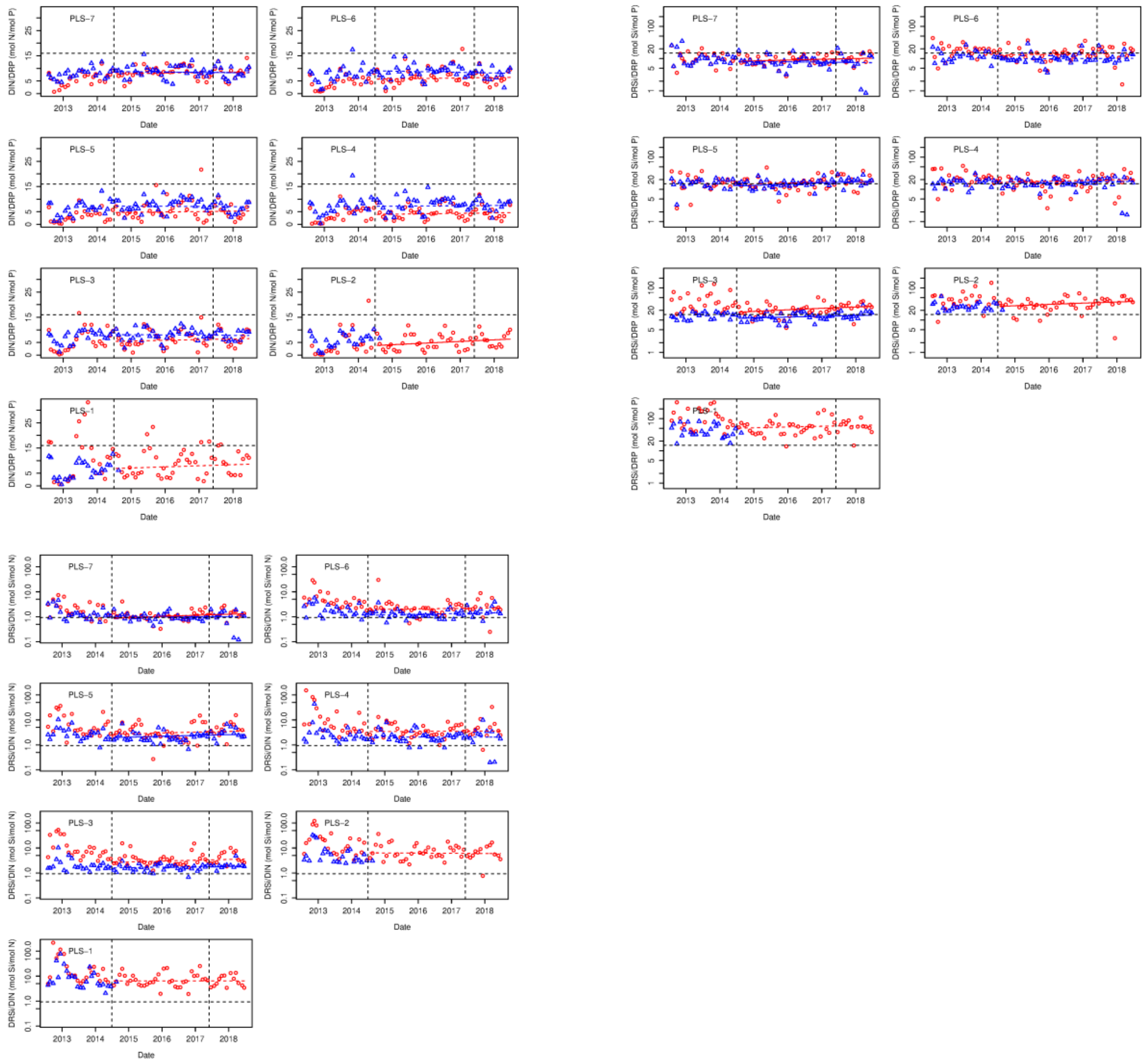

Figure 5-28: Ratios of dissolved inorganic nutrients measured near-surface (red) and near-bed (blue) at each MDC Pelorus site. The dashed vertical line (1 July 2014) separates data collected with a Van Dorn bottle at 1 m depth (to left of line) from data collected from the upper 15 m of the water column using a hose-sampler. The horizontal dashed line indicates the Redfield ratio for the pair of elements in question. When the symbols lie below the line, the element in the numerator of the quotient expressed in the y-variate is the more limiting of the two. If the symbols lie above the line, the element in the denominator of the quotient is the more limiting. Thus, DIN and DRSi are both almost invariably more limiting than DRP at all sites. DIN is almost invariably the most limiting nutrient. Note, that in the context of these plots, the limiting element is the one which would first become exhausted if growth were allowed to continue for sufficiently long (i.e., the elemental resource that will become exhausted first). This long-term limiting element may not be the resource (or even the element) which most limited/constrained the instantaneous growth of the algae at the sampling instant. The red- and blue lines indicate the best-fit Sen-slopes line fitted through the de-seasonalised data. If a line is solid, then the sign of its slope can be ascertained with probability >=95%. If the line is dashed, the sign of the slope is less certain.

5.24 Secchi disk depth

Secchi disk depths range from circa 2-5 m (at the inner-most Pelorus sites) up to circa 5-15 m at central and outer sites (Figure 5-29). The Sen-slopes appear negative at all sites but the signs of those at sites PLS-1 – PLS-3 are not confidently determined.

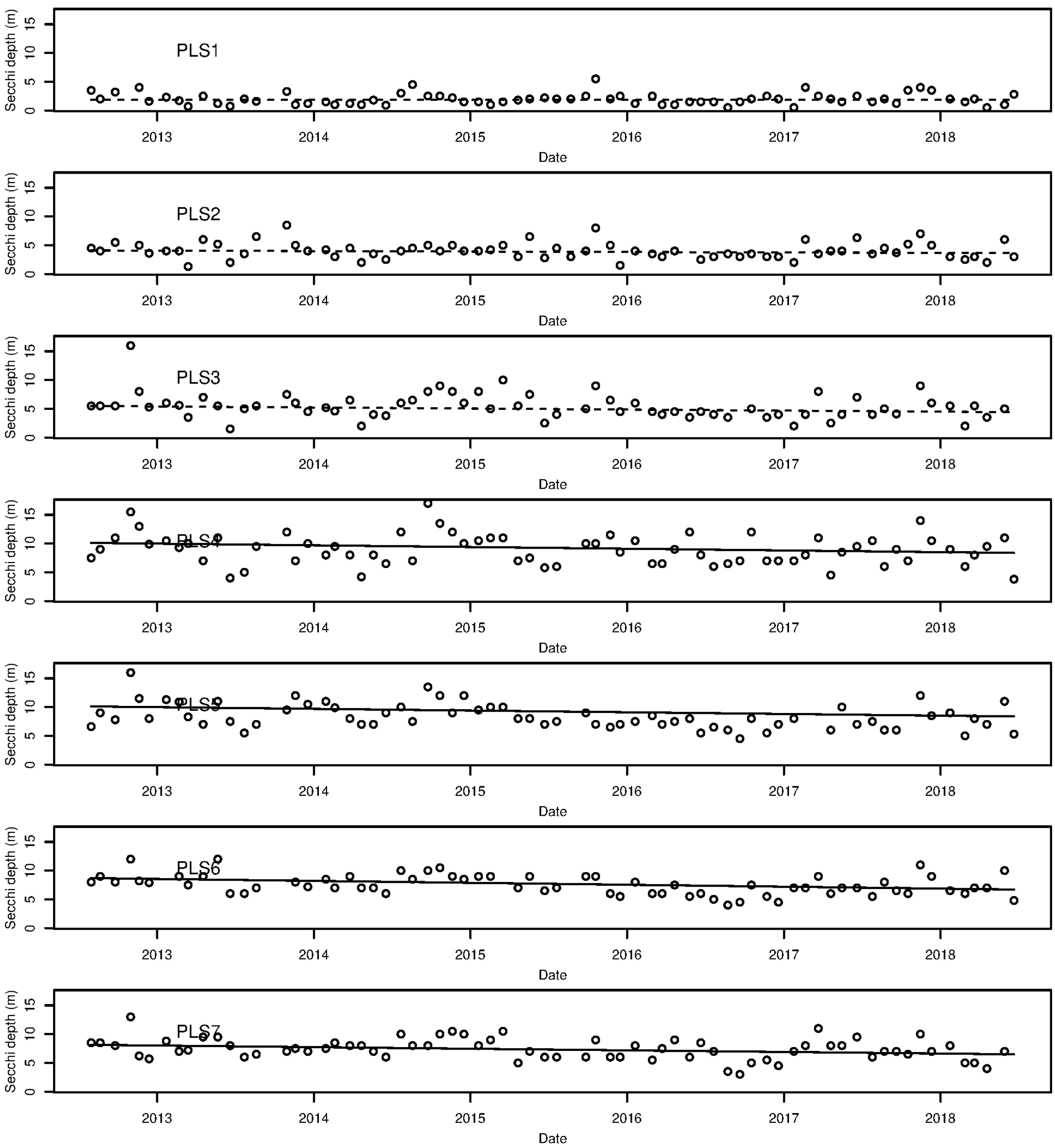

Figure 5-29: Secchi disk depth measured in Pelorus Sound at the seven Marlborough District Council stations. The black lines denote the best-fit Sen-lines for DO saturation calculated after removing seasonal effects.

6 Assessment relative to provisional water quality standards for NZKS farms

6.1 Dissolved oxygen

New Zealand King Salmon Ltd and Marlborough District Council have agreed to a set of provisional standards to govern farm operations (Morrisey, Anderson et al. 2015). These include rules which state "… *at sampling sites within 250 m of the net pens (i.e., Site 1 at Richmond, Site 8 at Waitata and Site 18 at Ngamahau), DO levels should not drop below 70% and at all remaining sampling sites, levels at all depths should not drop below 90% for any consecutive 3 months"*.

The MDC sites all lie beyond 250 m from any NZKS farm. Inspection of the oxygen saturation profiles from the CTD casts (Figure 4-6, Figure 5-6) suggest that the oxygen saturations below 90% threshold have been moderately frequent at some locations in both the Queen Charlotte/Tory and Pelorus systems. Time-series of DO minima were extracted from the CTD profiling data for Queen Charlotte/Tory (Figure 6-1) and Pelorus (Figure 6-2). In both sounds, DO minima tend to be lowest during late summer/early autumn and the most extreme minima tend to occur near the seabed. The minima tend to be lower at the innermost stations (QCS-1, QCS-2 and PLS-1 & PLS-2) than elsewhere.

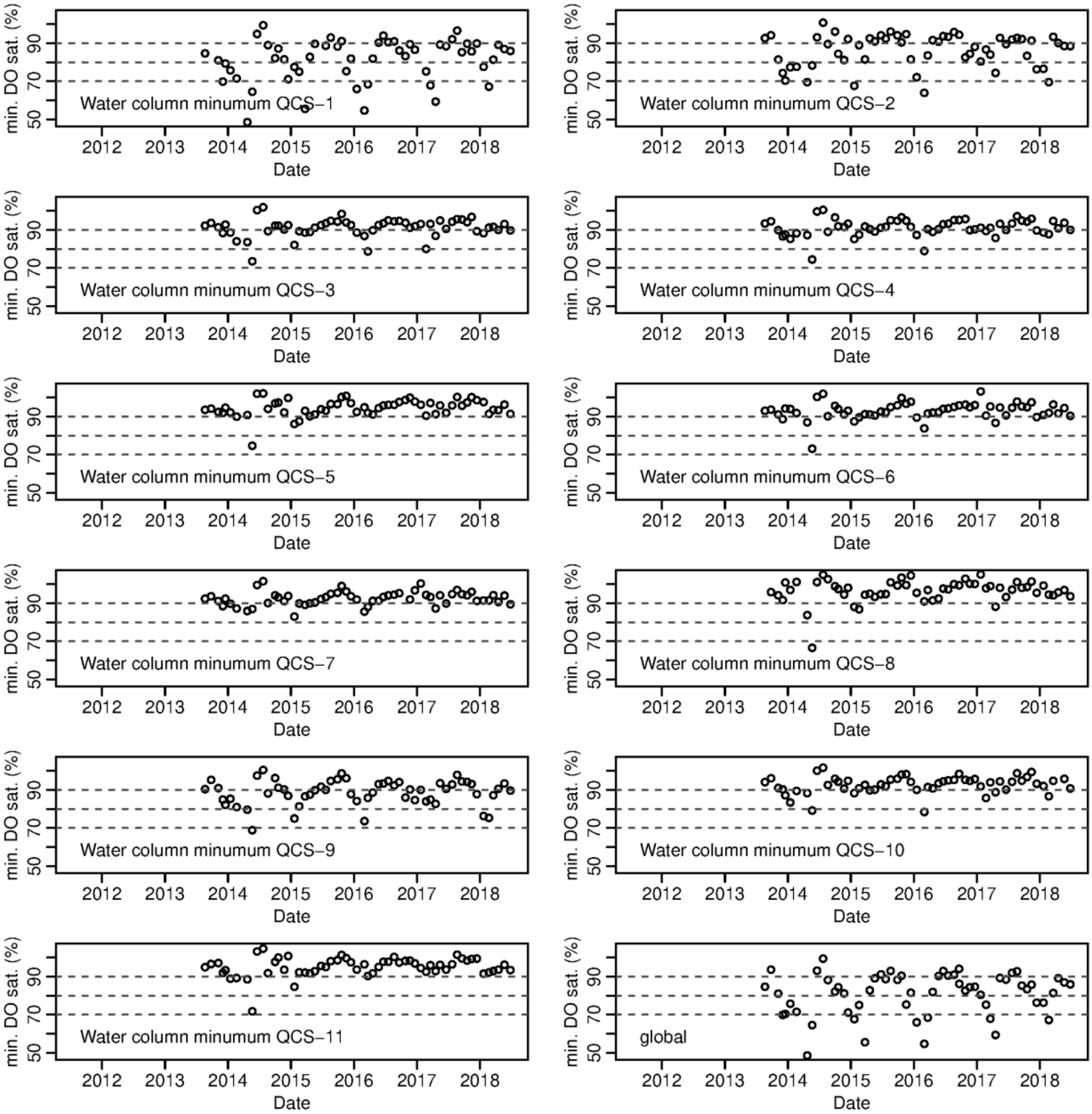

Figure 6-1: Time-series of the minimum DO recorded anywhere within the water-column during each EXOsonde cast in Queen Charlotte Sound/Tory Channel. Time-series are shown for each site (panels QCS-1 – QCS-11). The panel 'global' shows the minimum (across all sites and all depths) DO saturation recorded in each month. The raw data were binned into 1 m intervals. Averages were calculated for each interval, and the smallest average from each profile is reported.

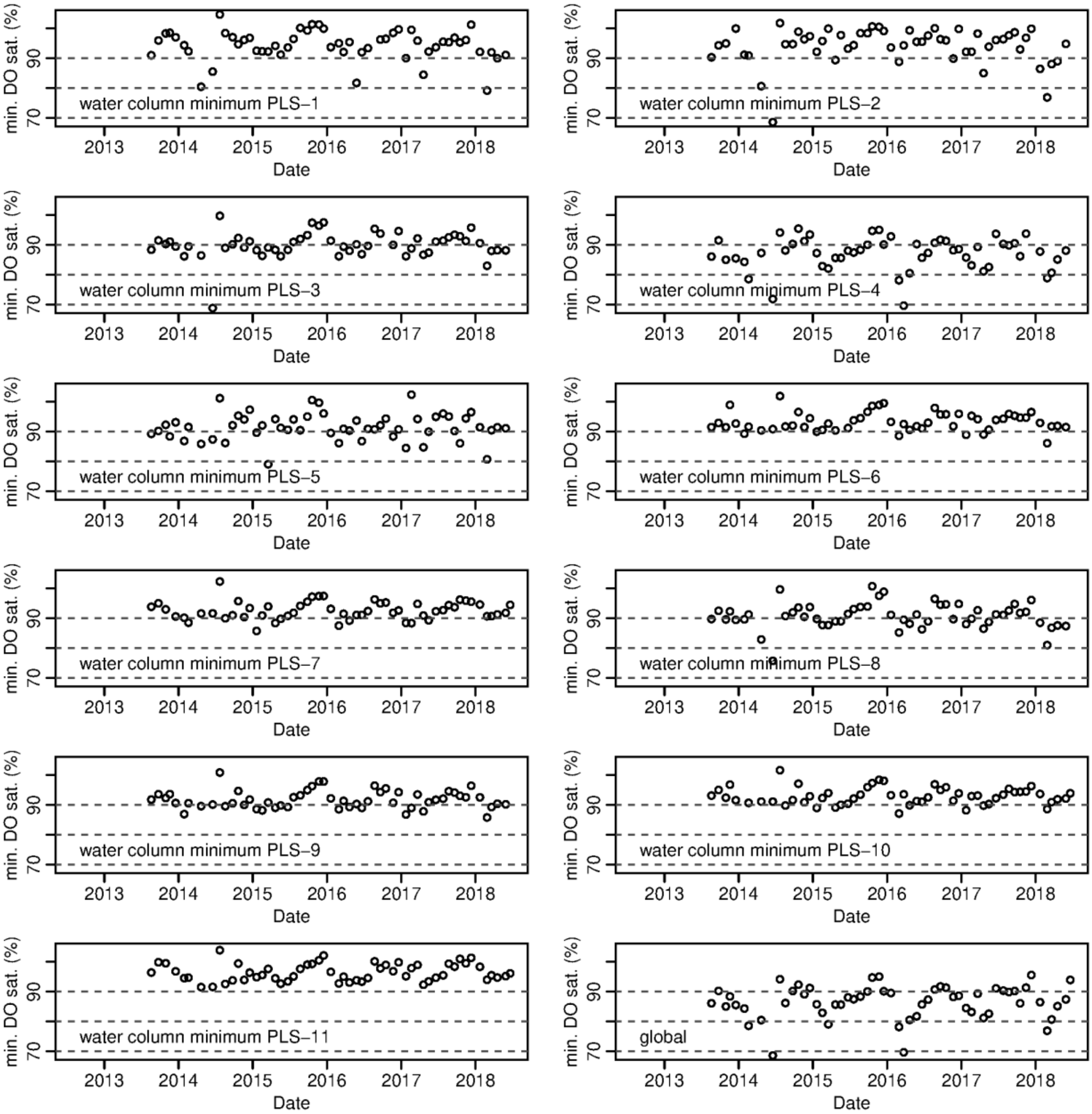

Figure 6-2: Time-series of the minimum DO recorded anywhere within the water-column during each EXOsonde caste in Pelorus Sound. Time-series are shown for each site (panels PLS-1 – PLS-11). The panel 'global' shows the minimum (across all sites and all depths) DO saturation recorded in each month. The raw data were binned into 1 m intervals. Averages were calculated for each interval, and the smallest average from each profile is reported.

Table 6-1 lists the details of records where the minimum oxygen saturation within the water-column fell below each of 90%, 80%, 70% and 60% in one or other of Pelorus and Queen Charlotte Sounds.

There were 632 useable DO profiles (collected across 84 unique sampling dates) in Queen Charlotte Sound. Amongst these, there were 160 profiles (from 46 unique sampling dates) in which the DO saturation fell below 90%, 48 profiles (20 unique sampling dates) where the DO saturation was below 80%, 16 profiles (11 unique sampling dates) where it was below 70% and four (four sampling dates) where it was below 60%. There are six different sequences in which the DO saturation was below 90% for three or more sequential sampling dates. There are no sequences in which the saturation fell below 70% on three or more occasions. Saturation below 60% was recorded on four different (non-sequential) occasions. The lowest saturation recorded was around 48%.

In Pelorus Sound, the total number of profiles in which the DO saturation has fallen below 90%, 80%, 70% and 60% are 160, 11, 3 and 0 respectively (out of a total of 610 useable profiles). The total number of unique dates on which DO saturation has fallen below these four thresholds are 39, 6, 2 and 0 respectively. There are two distinct sequences of three-or-more successive sampling dates in which the DO saturation fell below 90%. The DO saturation minimum never fell below 80% on three or more successive occasions. The lowest recorded saturation was around 68%.

The instances of 'low' dissolved oxygen (i.e., <90%) tend to arise during late summer/early autumn and are restricted to near-bed waters – usually in the inner parts of the Sounds (esp. inner Queen Charlotte). The cause(s) of the low DO are not definitively known, but it is probable that they arise from a combination of benthic oxygen demand, net respiration in nearbed waters and stratification (which inhibits mixing of near-bed and surface waters (surface waters are usually oxygen-rich due to photosynthesis and atmospheric exchange)).

We note: (a) the 70% saturation near-farm threshold stems from a 'close to farm' threshold that is specified within the *Salmon Aquaculture Dialogue: Final standards for responsible salmon aquaculture* (SalmonAquacultureDialogue 2012)[13]. That document requires that oxygen be measured only at 5 m below the surface. It does not stipulate any oxygen saturation thresholds for far-field water and does not require that near-bed waters maintain oxygen concentrations above 70% (let alone 90%). The provisional MDC/NZKS standards are, therefore, much more stringent than those proposed in the salmon aquaculture dialogue. The MDC data indicate that the threshold '[Dissolved oxygen saturation] *should not drop below 90% for any consecutive 3 months (beyond 250 m from any farm)'* has been violated repeatedly over the course of several years. These violations should trigger an assessment of whether the violations can be attributed to the new farms (Ngamahau, Richmond, Waitata). An intervention will be required only if they are deemed to be the cause of the breach. In anticipation of that review, we note that some of the violations arose before the farms to which this threshold applies were even in the water. Furthermore, it is far from clear (and, perhaps unlikely) that the seasonal depression of deep-water dissolved oxygen saturation arises from the activities of the other fish-farms in the Sounds. Thus, the far-field 90% threshold may be overly restrictive and in need of revision to avoid triggering too many 'false positives'.

[13] Specifically, the Salmon Aquaculture Dialogue guidelines suggest that the at-farm weekly average dissolved oxygen saturation levels at 5 m depth should not fall below 70% unless the saturation levels at a reference site are also falling below 70% – in which case those at the farm should not be lower than those of the reference site. Literature suggests that, even amongst taxa that require relative high oxygen concentrations, few species would experience more than mild stress until oxygen saturations fell below circa 60% Vaquer-Sunyer, R., Duarte, C.M. (2008) Thresholds of hypoxia for marine biodiversity. *Proceedings of the National Academy of Science of the United States of America*, 105(40): 15452-15457. doi:10.1073/pnas.0803833105. Interestingly, salmon are amongst the more sensitive taxa. They appear to begin to suffer mild stress when dissolved oxygen saturation falls below about 70-80% Stien, L.H., Bracke, M.B., Folkedal, O., Nilsson, J., Oppedal, F., Torgersen, T., Kittilsen, S., Midtlyng, P.J., Vindas, M.A., Øverli, Ø., Kristiansen, T.S. (2013) Salmon Welfare Index Model (SWIM 1.0): a semantic model for overall welfare assessment of caged Atlantic salmon: review of the selected welfare indicators and model presentation. *Reviews in Aquaculture*, 5: 33-57. 10.1111/j.1753-5131.2012.01083.x.

Table 6-1: Instances where the DO saturation at one or more of the sampling sites in Pelorus or Queen Charlotte fell below nominated thresholds. The nominated levels are 90%, 805, 70% and 60%. The minimum saturation recorded anywhere within the water-column was compared with these thresholds. The * symbol indicates occasions on the DO threshold-flag was raised in a single (isolated) month. The ':' symbol denotes a sampling occasion where the DO-flag was raised in two sequential months. The "$" symbol denotes occasions where the DO flag was raised in three or more sequential months.

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
Pelorus: all CTD stations combined	90	5	1	5	160	39	*2013-08-20	3 4 5 8
							$2013-10-30	4 8
							$2013-11-19	5
							$2013-12-18	3 4 8
							$2014-01-29	3 4 5 6 8 9
							$2014-02-19	3 4 7
							*2014-04-22	1 2 3 4 5 8 9
							*2014-06-18	1 2 3 4 5 8
							*2014-08-19	3 4 5 9 10
							*2014-11-20	3
							$2015-01-20	3 4 5 6 7 8 9 10
							$2015-02-17	3 4 8 9
							$2015-03-18	3 4 5 8
							$2015-04-22	2 3 4 7 8 9 10
							$2015-05-19	3 4 7 8 9
							$2015-06-23	3 4 9
							$2015-07-21	4
							$2015-08-23	4
							$2016-01-20	5

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							$2016-02-29	2 3 4 5 6 7 8 9 10
							$2016-03-23	3 4 8
							$2016-04-21	3 4 7 8 9 10
							$2016-05-26	1
							$2016-06-21	3 4 5 8 9
							$2016-07-21	3 4 8
							$2016-11-22	2 4 5 8
							$2016-12-19	4
							$2017-01-24	3 4 5 6 7 8 9 10
							$2017-02-20	3 4 7 8 9
							$2017-03-22	4
							$2017-04-20	1 2 3 4 5 6 8 9 10
							$2017-05-16	3 4 5 7 8
							$2017-08-23	4
							$2017-10-17	4 5
							$2018-01-23	2 4 8
							$2018-02-27	1 2 3 4 5 6 8 9 10
							$2018-03-21	2 3 4 8 9
							$2018-04-19	1 2 3 4 8
							$2018-05-30	3 4 8

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
Pelorus: All CTD stations jointly	80	4	1	0	11	6	*2014-02-19	4
							*2014-06-18	2 3 4 8
							*2015-03-18	5
							:2016-02-29	4
							:2016-03-23	4
							*2018-02-27	1 2 4
Pelorus: All CTD stations jointly	70	3	0	0	3	2	*2014-06-18	2 3
							*2016-03-23	4
Pelorus: All CTD stations jointly	60	0	0	0	0	0		
QCS/Tory: All CTD stations jointly	90	3	1	5	192	46	*2013-08-21	1
							$2013-11-06	1 2 4
							$2013-12-02	1 2 3 4 6 7 9
							$2013-12-17	1 2 4 9 10
							$2014-01-15	1 2 3 4 7 9 10 11
							$2014-02-20	1 2 3 4 5 7 9 10
							:2014-04-23	1 2 3 4 6 7 8 9 10 11
							:2014-05-22	1 2 3 4 5 6 7 8 9 10 11
							*2014-08-21	1 2 3 4 9
							$2014-10-01	1
							$2014-10-20	1 2
							$2014-11-23	1 2

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							$2014-12-16	1 9
							$2015-01-21	1 2 3 4 5 6 7 8 9 10 11
							$2015-02-18	1 2 3 4 5 6 7 8 9
							$2015-03-24	1 2 3 7 9
							$2015-04-21	1 3 7 9 10
							$2015-05-20	1 4 9
							*2015-07-22	1
							*2015-09-28	1
							$2015-11-18	1
							$2015-12-15	1 2 9
							$2016-01-18	1 2 3 4 6 9
							$2016-03-02	1 2 3 4 6 7 9 10
							$2016-03-22	1 2 3 7 9
							$2016-04-20	1 3 4 9
							$2016-09-21	1
							$2016-10-26	1 2 9
							$2016-11-21	1 2 4
							$2016-12-20	1 2 9
							$2017-01-23	2
							$2017-02-23	1 2 3 4 9 10
							$2017-03-20	1 2 9
							$2017-04-19	1 2 3 4 6 7 8 9 10
							$2017-05-15	1
							$2017-06-19	1 2 4 7
							$2017-09-19	1

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							$2017-10-19	1 2
							$2017-11-14	1
							$2017-12-14	1 2 3 4 6 9
							$2018-01-22	1 2 3 4 9
							$2018-02-22	1 2 4 9 10
							$2018-03-20	1 9
							$2018-04-18	1
							$2018-05-23	1 2
							$2018-06-27	1 2 3 7 9
QCS/Tory: All CTD stations jointly	80	1	1	5	48	20	$2013-12-02	1 2
							$2013-12-17	1 2
							$2014-01-15	1 2
							$2014-02-20	1 2
							:2014-04-23	1 2 9
							:2014-05-22	1 2 3 4 5 6 8 9 10 11
							$2014-12-16	1
							$2015-01-21	1 2 9
							$2015-02-18	1
							$2015-03-24	1
							*2015-11-18	1
							$2016-01-18	1 2
							$2016-03-02	1 2 4 9 10
							$2016-03-22	1 3
							$2017-02-23	1

Site	Saturation threshold (%)	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length three or more	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							$2017-03-20	1
							$2017-04-19	1 2
							$2017-12-14	2
							$2018-01-22	1 2 9
							$2018-02-22	1 2 9
QCS/Tory: All CTD stations jointly	70	4	2	1	16	11	*2013-12-02	1
							:2014-04-23	1 2
							:2014-05-22	1 8 9
							*2015-01-21	2
							*2015-03-24	1
							$2016-01-18	1
							$2016-03-02	1 2
							$2016-03-22	1
							:2017-03-20	1
							:2017-04-19	1
							*2018-02-22	1 2
QCS/Tory: All CTD stations jointly	60	4	0	0	4	4	*2014-04-23	1
							*2015-03-24	1
							*2016-03-02	1
							*2017-04-19	1

6.2 Chlorophyll

The consent conditions governing the operation of some of the NZKS salmon farms require that the frequency of blooms (where a bloom is defined as chlorophyll concentration > 5 mg Chl m^{-3}) should not increase. To guard against that possibility, New Zealand King Salmon Ltd and Marlborough District Council have agreed to a set of provisional standards to govern farm operations (Morrisey, Anderson et al. 2015). One of these relates to chlorophyll and states: *"[Chlorophyll concentration] must not exceed 3.5 mg/m^3 in an integrated 15 m deep sample for three successive months at any site(s)"*.

Time-series of station-specific and chlorophyll concentrations within the upper 15 m are presented in Figure 6-3 and Figure 6-4 (see also sections 4.20 and 5.20). The figures also show the time-series of the Sound-wide maximum 15 m depth-averaged chlorophyll concentrations.

Table 6-1 provides details of the occasions where the 15 m depth-averaged chlorophyll concentrations have exceeded 3.5 mg Chl m^{-3} in each Sound. In both Sounds, exceedances have been most common at the inner stations and stations in side-bays, but 3.5 mg m^{-3} has been exceeded (or nearly so) on at least one occasion at all stations other than QCS-11, PLS-8 – PLS-11.

In Queen Charlotte Sound, 3.5 mg Chl m^{-3} (15 m depth average) has been exceeded in 25 hose samples (from 19 distinct dates) and 11 fluorometer profiles from six dates. In the hose data, there was one sequence where chlorophyll exceeded 3.5 mg m^{-3} on three sequential sampling occasions (July – Sept 2017) but there were no such examples in the fluorometer data. Indeed, in the fluorometer data, the 15 m depth averaged chlorophyll did not exceed 3.5 m^{-3} on even one occasion during the July – Sept 2017 exceedance period.

In Pelorus Sound, 3.5 mg Chl m^{-3} (15 m depth average) has been exceeded in 22 hose samples (from 15 distinct dates) and 4 fluorometer profiles from 4 dates. In the hose data, there was one sequence where chlorophyll exceeded 3.5 mg m^{-3} on three sequential sampling occasions (March – May 2014). In the fluorometer data, the four individual exceedances were isolated from one another (i.e., none were immediately sequential).

There have been more exceedances recorded in the hose samples than in the fluorometer ones. This arises for two reasons: (a) the fluorometer data are available for fewer sampling occasions, (ii) the regression-relationship used to calibrate the fluorometer sensor against the hose-sampling data tends to reduce extrema that are evident in the raw fluorometer data.

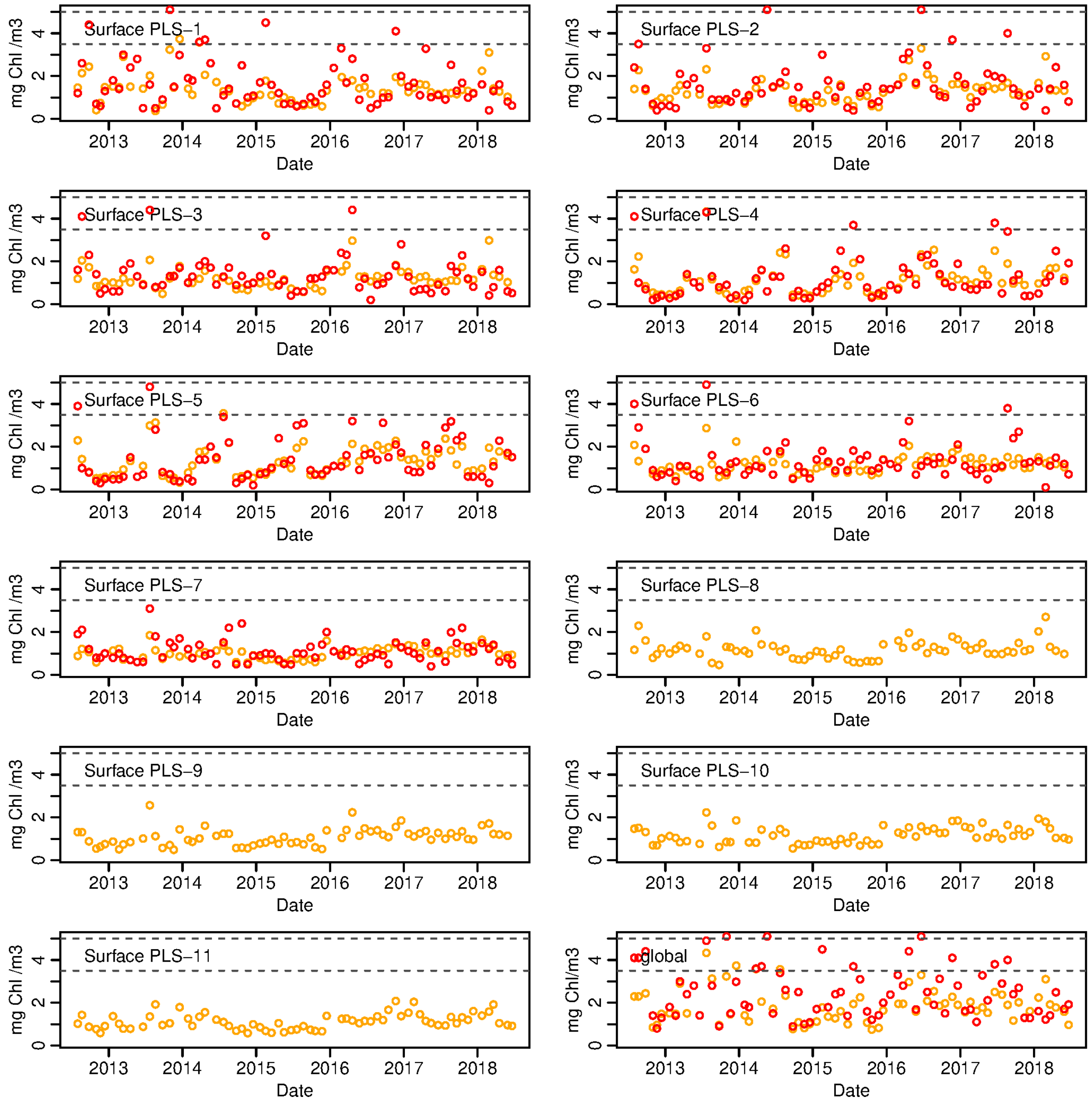

Figure 6-3: Time-series of station-specific and Sound-wide chlorophyll concentrations measured in the upper 15 m of Queen Charlotte Sound. Red symbols denote hose-sampling data. Orange symbols denote data from the profiling fluorometer. Note that the latter data are not entirely independent of the former because the hose-data were used when calibrating the raw fluorometer data. The two horizontal dashed lines denote the 3.5 and 5.0 mg m^{-3} thresholds. The panel 'global' shows the chlorophyll value (maximum across all sites and all depths) recorded in each month.

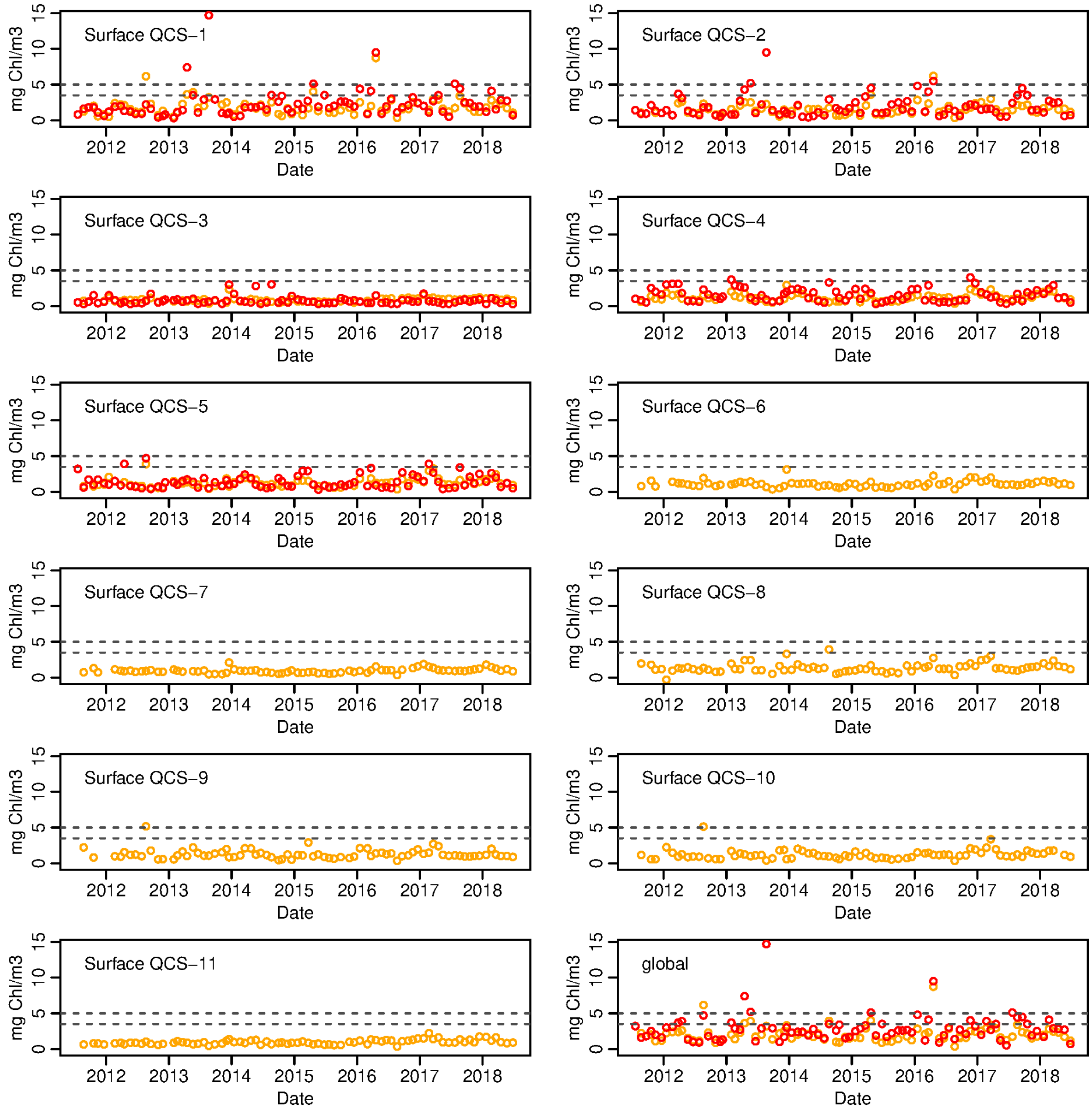

Figure 6-4: Time-series of station-specific and Sound-wide chlorophyll concentrations measured in the upper 15 m of Pelorus Sound. Time-series of station-specific and Sound-wide chlorophyll concentrations measured in the upper 15 m. Red symbols denote hose-sampling data. Orange symbols denote data from the profiling fluorometer. Note that the latter data are not entirely independent of the former because the hose-data were used when calibrating the raw fluorometer data. The two horizontal dashed lines denote the 3.5 and 5.0 mg m^{-3} thresholds. The panel 'global' shows the chlorophyll value (maximum across all sites and all depths) recorded in each month.

Table 6-2: Details of dates and locations where 15 m depth-averaged chlorophyll has exceeded 3.5 mg Chl m^{-3} in each Sound. The asterisk symbol denotes occasions when an exceedance occurred in isolation (i.e., without one also occurring in the preceding and/or succeeding sampling campaign). The colon symbol denotes occasions where the exceedance happened together with one on either the preceding or succeeding sampling occasion. The dollar symbol denotes sampling occasions where the exceedance happened as a part of a run of three or more sequential exceedances.

Site	Nature of sampling	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length 3 or greater	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
Pelorus: all WQ stations combined	Water samples	9	0	2	22	15	$2012-07-31	4 5 6
							$2012-08-21	3
							$2012-09-25	1
							*2013-07-23	3 4 5 6
							*2013-10-31	1
							$2014-03-26	1
							$2014-04-22	1
							$2014-05-20	2
							*2015-02-17	1
							*2015-07-21	4
							*2016-04-22	3

Site	Nature of sampling	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length 3 or greater	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							*2016-06-21	2
							*2016-11-22	1 2
							*2017-06-20	4
							*2017-08-23	2
Pelorus: All CTD stations jointly	Fluorometer casts on CTD	4	0	0	4	4	*2013-07-23	4
							*2013-12-18	1
							*2014-03-26	1
							*2014-07-23	5
							*2016-08-23	4
							*2017-04-20	2
							:2017-06-20	4
							:2017-07-26	5
							*2017-10-17	5
							*2018-02-27	1 2 3 8

Site	Nature of sampling	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length 3 or greater	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
QCS/Tory: All WQ stations jointly	Water samples	10	3	1	25	19	$2012-03-26	2
							$2012-04-16	5
							*2012-08-20	5
							*2013-01-29	4
							:2013-04-16	1 2
							:2013-05-21	2
							*2013-08-21	1 2
							*2015-04-22	1 2
							*2015-06-26	1
							*2016-01-18	1 2
							:2016-03-22	1 2
							:2016-04-20	1 2
							*2016-11-21	4
							*2017-02-23	5
							*2017-04-19	1

Site	Nature of sampling	Isolated Flags	Number of amber sequences of length 2	Number of amber sequences of length 3 or greater	Total flagged records	Total unique flagged dates	Flagged dates	Stations triggering the flag
							$2017-07-24	1
							$2017-08-22	1
							$2017-09-29	2
							*2018-02-22	1
QCS/Tory: All CTD stations jointly	Fluorometer casts on CTD	4	1	0	11	6	$2012-08-20	1 5 9 10
							$2013-04-16	1
							$2013-05-21	1 8
							$2014-08-21	8
							:2015-04-21	1 2
							:2016-04-20	1 2

6.3 Temporal auto-correlation in chlorophyll and particulate organic matter

The auto-correlation coefficient measures the degree of correlation between values measured across a given lag-interval. The partial auto-correlation coefficient measures the excess (or additional) correlation at a given lag that cannot be explained by correlations arising at shorter lags (Chatfield 1984).

Figure 6-5 and Figure 6-6 illustrate the chlorophyll anomalies and correlation coefficients for the Queen Charlotte and Pelorus stations respectively. The largest anomalies approach 5 mg m^{-3}. Furthermore, whilst the majority of anomalies are less than 1 mg m^{-3}, inspection of the chlorophyll plots in Table B-1 reveals that 1 mg m^{-3} is not negligibly small in comparison with the annual averages (or seasonal maxima).

At lags greater than zero (sampling occasions), the auto-correlations are small (absolute values <0.2) and only rarely exceed the approximate threshold for 95% confidence. Furthermore, the patterns of coefficient change with respect to lag are not strongly coherent across stations. Given that there is essentially no correlation at lags greater than zero, it is not surprising to find that the partial auto-correlation coefficients are also small and rarely attain statistical significance. Collectively, this implies that the anomalies (departures from the seasonal medians) are essentially uncorrelated across sequential months.

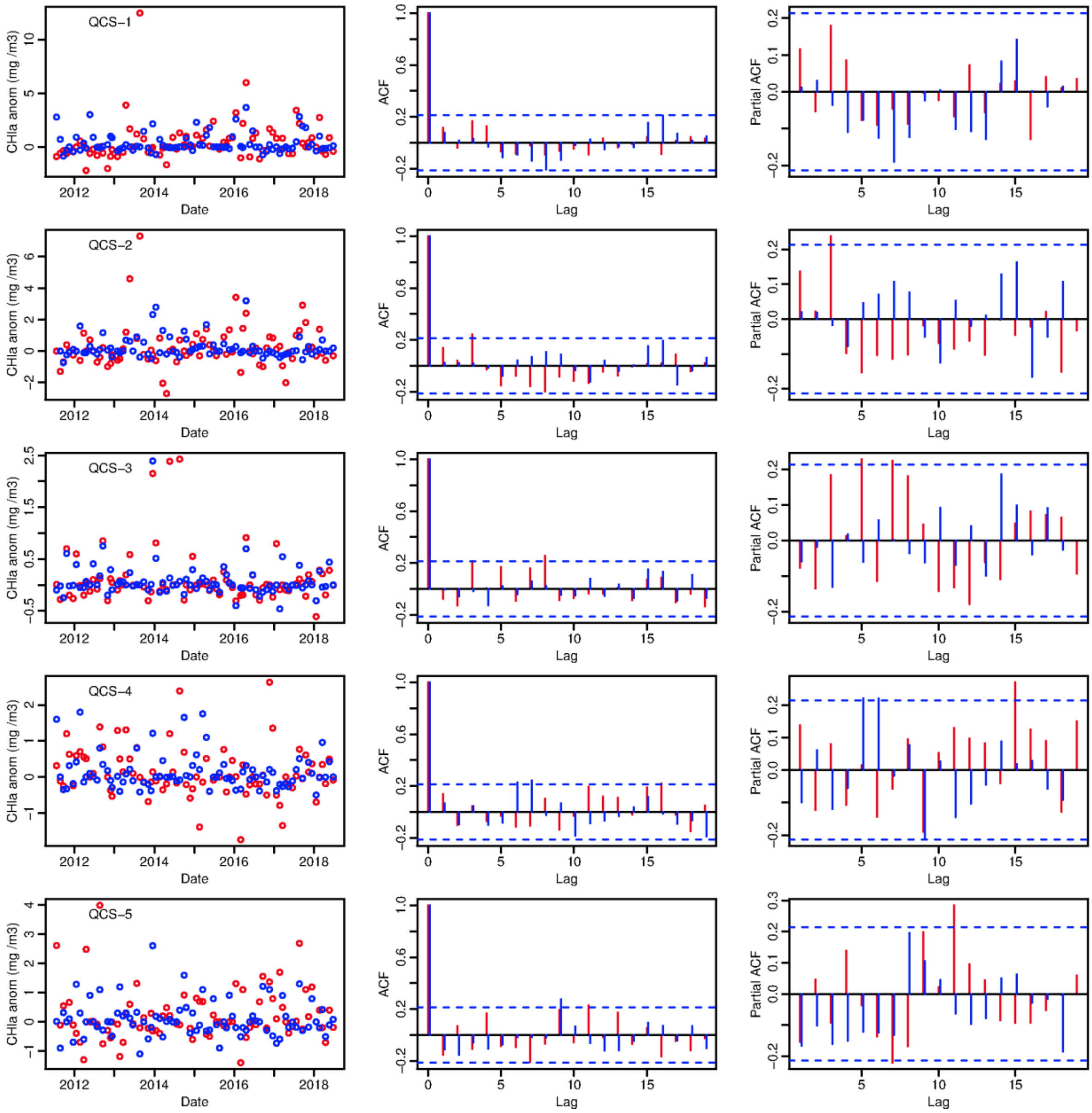

Figure 6-5: Seasonal chlorophyll anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the five Queen Charlotte water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

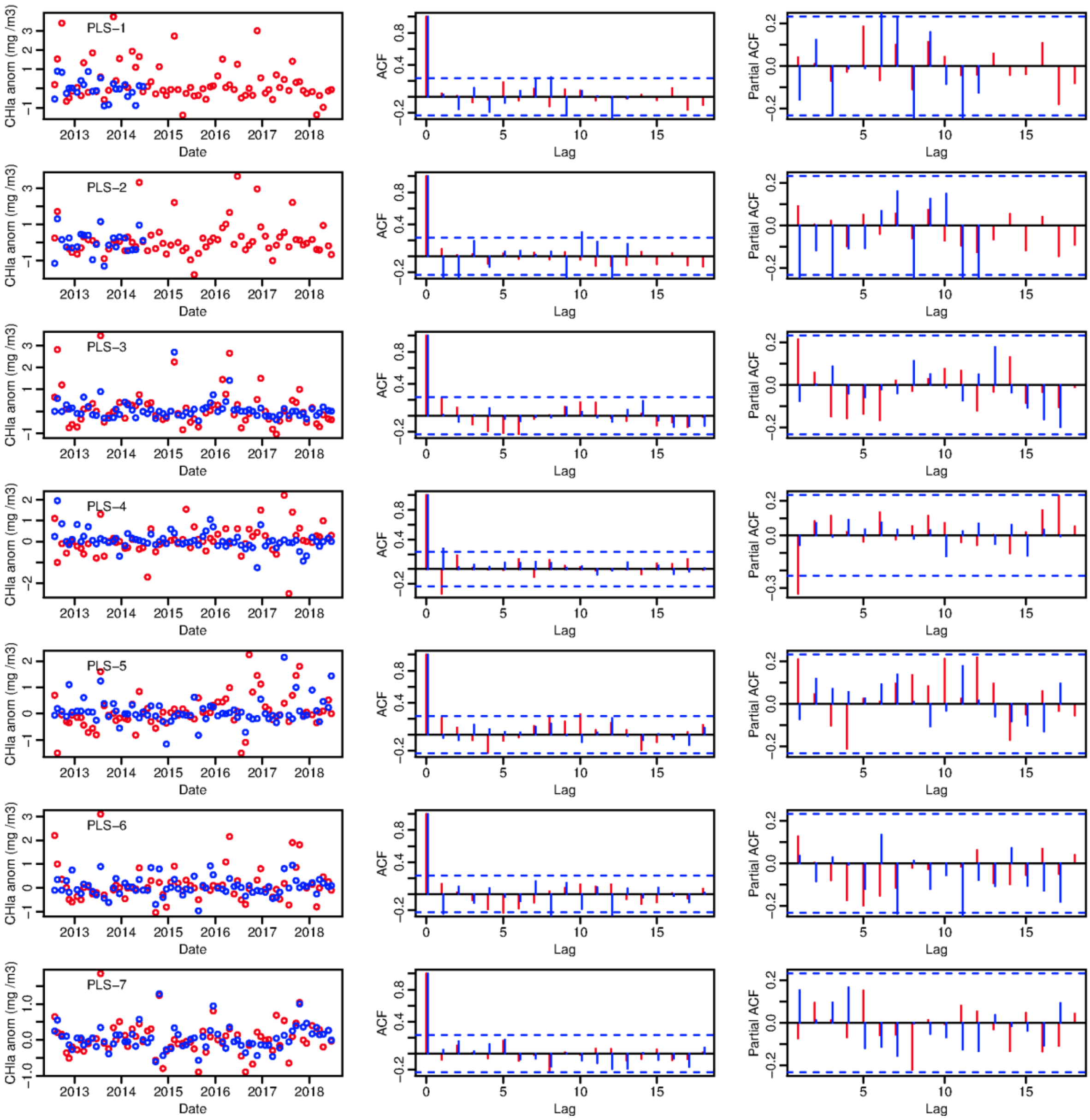

Figure 6-6: Seasonal chlorophyll anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the seven Pelorus Sound water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

Time-series and auto- and partial auto-correlation plots for PC in Queen Charlotte Sound and Pelorus Sound are shown in Figure 6-7 and Figure 6-8 respectively. Those for PN are shown in Figure 6-9 and Figure 6-10. In Queen Charlotte Sound, the auto-correlation coefficients for PC and PN generally exceed the 95% threshold out to lags of around six months in the near-bed waters. These correlation coefficients are positive and have magnitudes between circa 0.2 and 0.4. The partial autocorrelation plots suggest that most of the long-term correlation is driven by correlation occurring on time-scales of one-two months.

Auto-correlation is weaker in the near-surface waters and rarely attains statistical significance. Statistical significance is attained more frequently at sites QCS-3 – QCS-5 than at sites QCS-1 and QCS-2. This may indicate that auto-correlation is being driven by water imported from Cook Strait rather than from local processes.

In Pelorus Sound, the PC auto-correlation coefficients at the central- and outer-Sound locations also sometimes exceed the 95% significance threshold at lags out to several months – but usually in the near-surface (rather than near-bed) waters[14]. The partial auto-correlation plots suggest that the correlations that is evident out to lags out to six months arises from processes happening at time-scales of one-two months.

The fact that auto-correlation appears to be stronger towards the Cook Strait end of the Sound may (again) indicate that it is driven by processes arising in Cook Strait – but we note that the strongest auto-correlations arise in the surface waters. The strong estuarine circulation implies that much of this water will recently have flowed out from inner parts of the Sound (though it may previously have originated from Cook Strait at an even earlier time).

[14] There also appears to be some long-term auto-correlation in the near-bed waters of PLS-2, but the time-series there contains only 24 data-points.

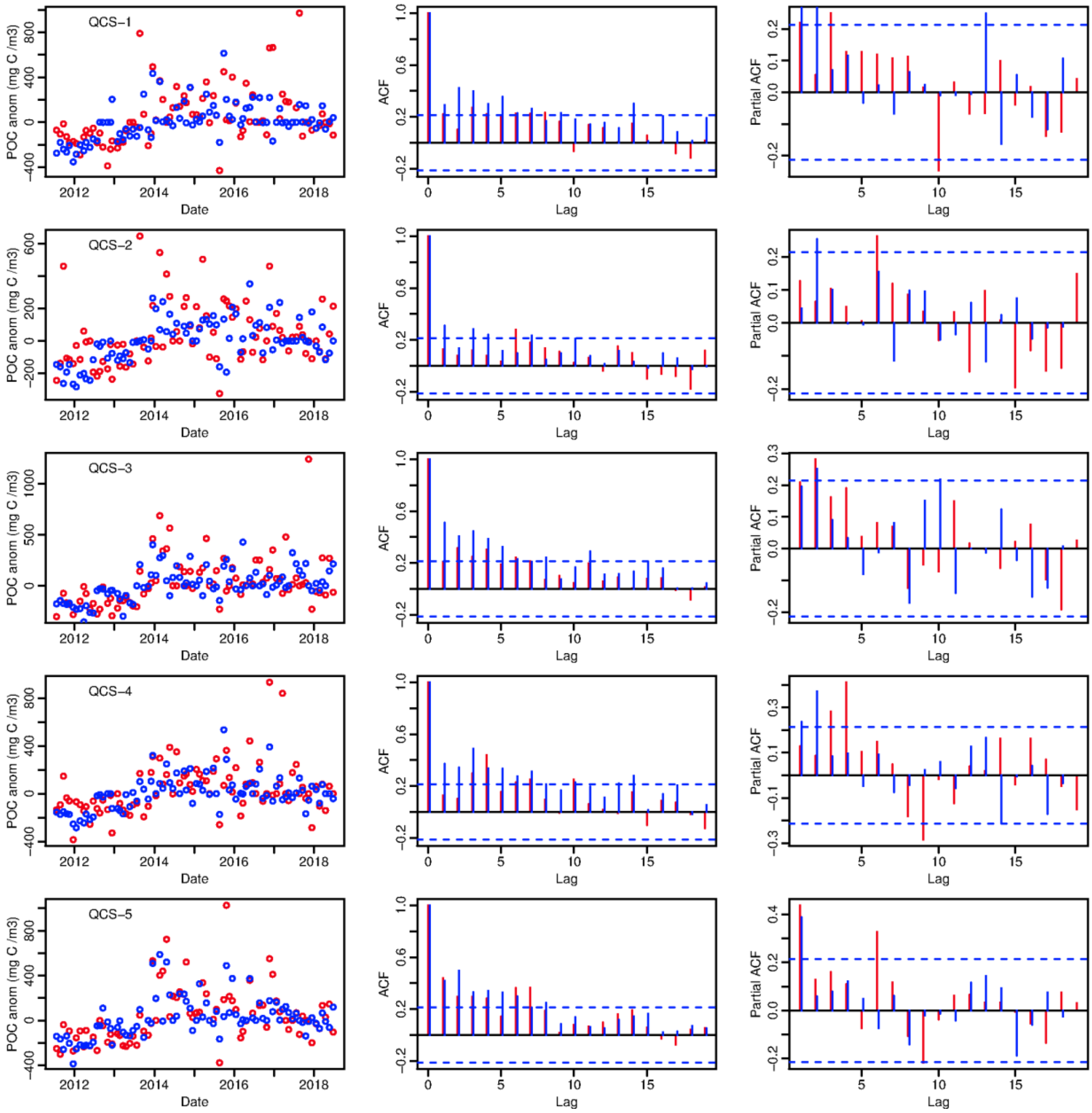

Figure 6-7: Seasonal PC anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the five Queen Charlotte water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

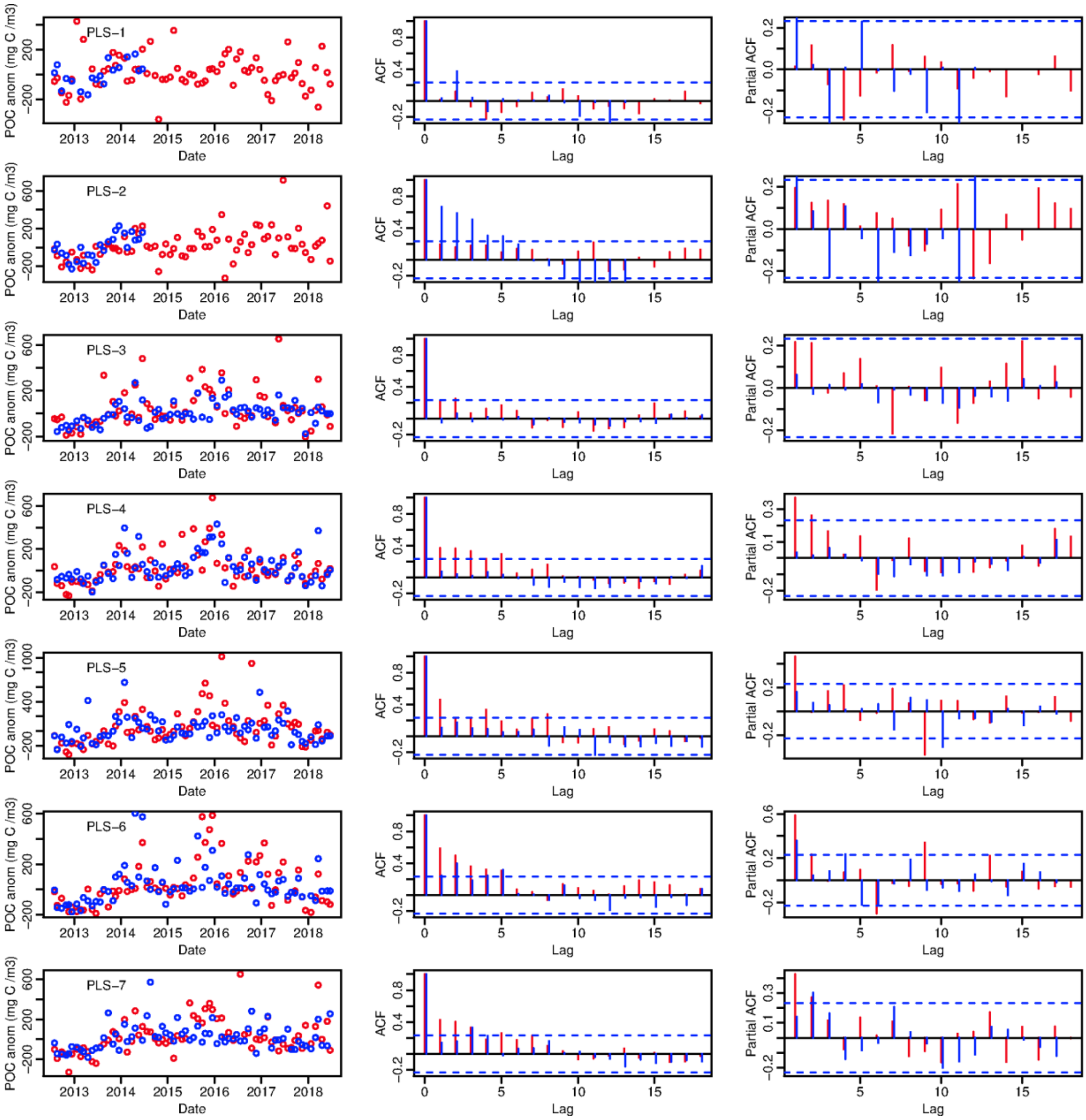

Figure 6-8: Seasonal PC anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the seven Pelorus Sound water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

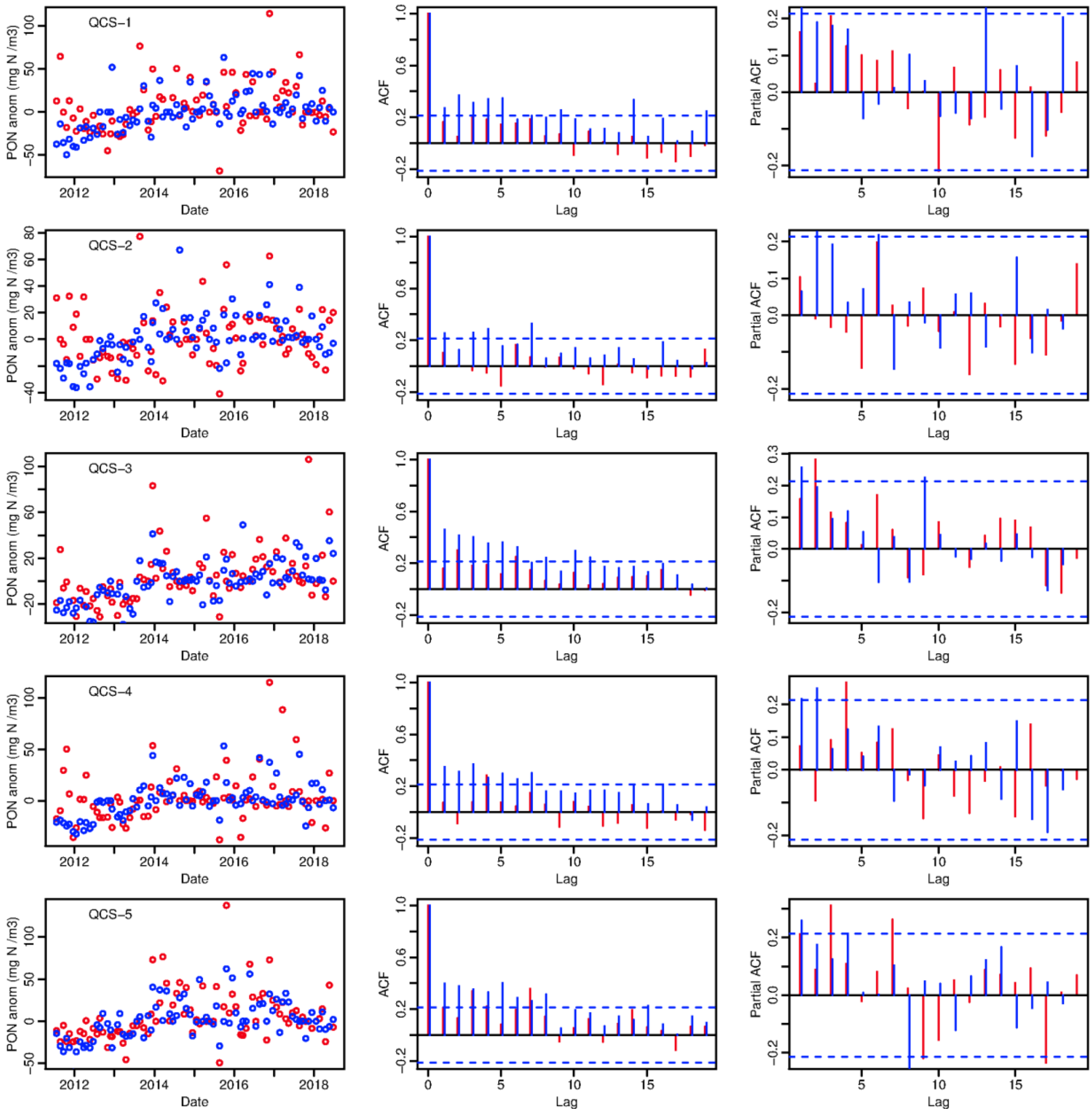

Figure 6-9: Seasonal PON anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the five Queen Charlotte water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

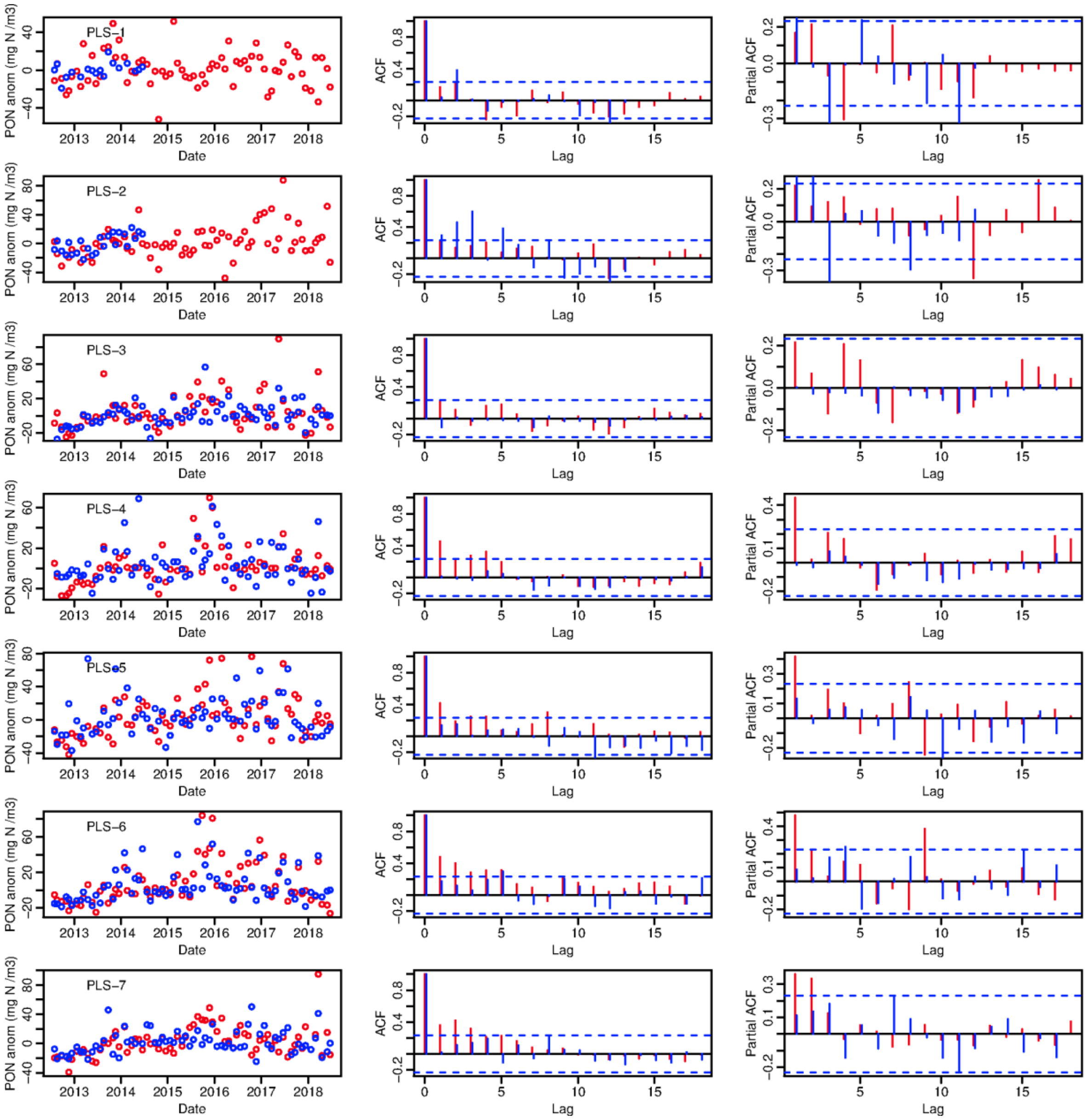

Figure 6-10: Seasonal PON anomalies (left panels), auto-correlation (middle panels) and partial auto-correlation (right panels) coefficients at the seven Pelorus Sound water-quality sites. Red symbols & vertical lines: near surface samples. Blue symbols & vertical lines: near-bed samples. The horizontal dashed lines are the approximate thresholds for significance at the 95% level.

6.4 Spatial auto-correlation in chlorophyll and particulate matter

Figure 6-11 shows spatial-autocorrelation for chlorophyll anomalies at lags of -1, 0 and +1 (sampling occasions) in Queen Charlotte Sound. The lag-0 correlation coefficients are stronger than those at lags -1 and +1. This suggests that rapid, local-scale growth/death processes (often, influenced by regional-scale climatic events) are more important than between-site transport processes in determining month-to-month temporal anomaly fluctuations.

Except for QCS-3, the correlation between corresponding near-surface and near-bed stations is weaker than the correlation coefficients between horizontally adjacent near-surface (or near-bed) stations. In the horizontal, correlation coefficients tend to decline as stations become more distant from one another, but for the most part correlation coefficients are positive at zero-time lag.

In Queen Charlotte Sound, the surface water chlorophyll concentrations at stations QCS-1 and 2 are particularly closely correlated with one another. Similarly, the near-bed chlorophyll concentrations at stations QCS-2 and QCS-4 are particularly closely correlated. This is consistent with the concept of inner Queen Charlotte being somewhat isolated from the clockwise residual circulation that is believed to transport water in through Tory Channel and out past Long Island. The correlation between deep-water chlorophyll at stations QCS-2 and QCS-4 may indicate that when water does exchange between inner Queen Charlotte and outer Queen Charlotte it does so close to the bed.

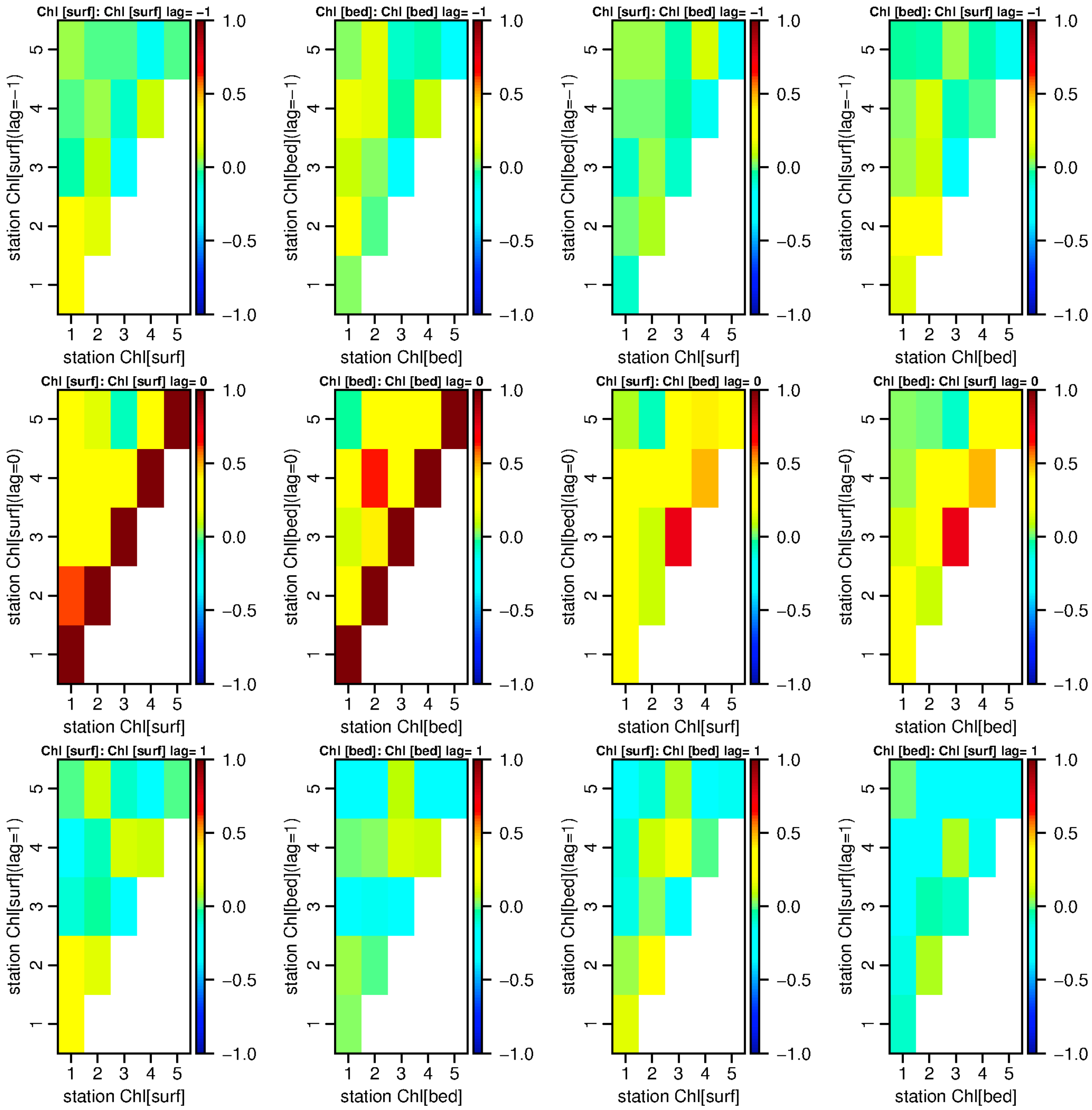

Figure 6-11: Spatial auto-correlation for chlorophyll anomalies at lags of -1, 0 and +1 sampling occasions in Queen Charlotte Sound. The lag-figure (in main title and in y-axis label of each figure) indicates the temporal relationship between x- and y-variates. A lag of 0 (middle row) indicates that correlations are between chlorophylls collected on the same sampling date. A lag of -1 (upper row) indicates that the correlation is between chlorophyll measured at station m at time t+1 (y-axis) has been correlated with chlorophyll measured at station n at time t (x-axis). Conversely, a lag of +1 (lower row) indicates that the correlation is between chlorophyll measures at time t on the y-axis and at time t+1 on the x-axis. The highest correlations (yellow-red values) among stations are found in the centre row of panels, where time lags are 0. Correlations are also higher when comparing samples from the same depths (i.e., surface: surface or bed:bed, rather than surface:bed or bed:surface) (left two columns vs right two columns).

Figure 6-12 presents the corresponding correlation information for Pelorus Sound. Again, correlations are strongest at lag zero. The stations within the main channel (PLS-1,2,3,6,7) tend to be more strongly correlated with one another than with PLS-4 and PLS-5. This is consistent with the concept of an estuarine circulation along the main-stem of the Sound.

In both Sounds, the majority of spatial cross-correlation coefficients are comparatively weak (absolute cross correlation coefficients <0.5).

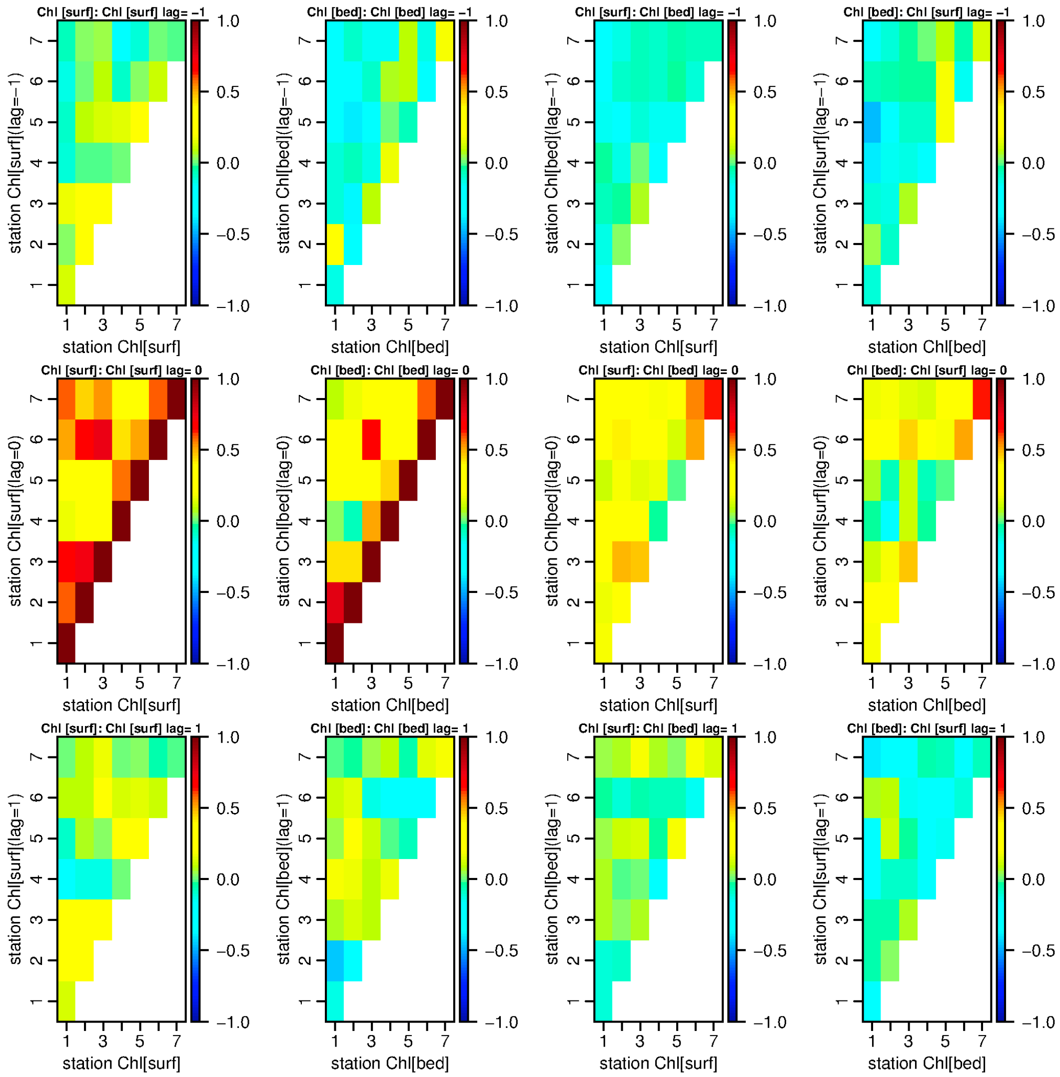

Figure 6-12: Spatial auto-correlation for chlorophyll anomalies at lags of -1, 0 and +1 sampling occasions in Pelorus Sound. The lag-figure (in main title and in y-axis label of each figure) indicates the temporal relationship between x- and y-variates. A lag of 0 (middle row) indicates that correlations are between chlorophylls collected on the same sampling date. A lag of -1 (upper row) indicates that the correlation is between chlorophyll measured at station m at time t+1 (y-axis) has been correlated with chlorophyll measured at station n at time t (x-axis). Conversely, a lag of +1 (lower row) indicates that the correlation is between chlorophyll measures at time t on the y-axis and at time t+1 on the x-axis. The highest correlations (yellow-red values) among stations are found in the centre row of panels, where time lags are 0. Correlations are also higher when comparing samples from the same depths (i.e., surface: surface or bed:bed, rather than surface:bed or bed:surface) (left two columns vs right two columns). The highest correlations (yellow-red values) among stations are found in the centre row of panels, where time lags are 0. Correlations are also higher when comparing samples from the same depths (i.e., surface: surface or bed:bed, rather than surface:bed or bed:surface) (left two columns vs right two columns).

In Queen Charlotte Sound, the patterns of spatial correlation for particulate carbon and particulate nitrogen anomalies are similar to one another (Figure 6-13). The correlations are strongest at lag zero. They tend to be stronger across the surface layer than across the bed layer and tend to be stronger across horizontal space than across vertical space. The correlation coefficients for particulate carbon tend to be larger than those for particulate nitrogen.

PC PN

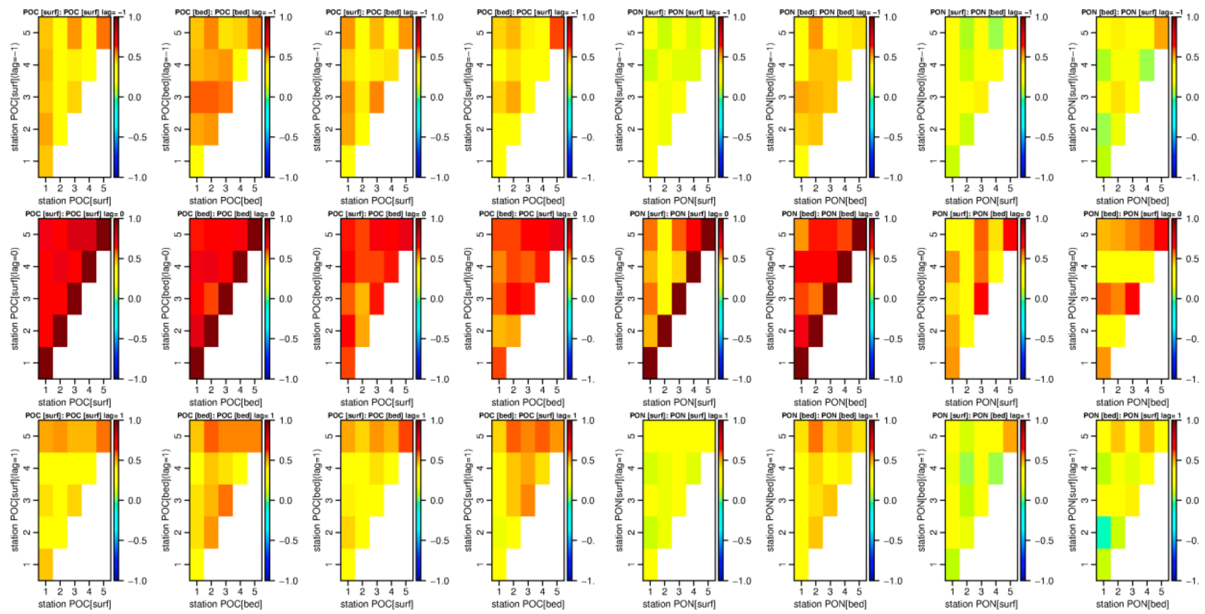

Figure 6-13: Spatial auto-correlation for particulate carbon (left) and particulate nitrogen (right) anomalies at lags of -1, 0 and +1 sampling occasions in Queen Charlotte Sound. The lag-figure (in main title and in y-axis label of each figure) indicates the temporal relationship between x- and y-variates. A lag of 0 (middle row) indicates that correlations are between chlorophylls collected on the same sampling date. A lag of -1 (upper row) indicates that the correlation is between chlorophyll measured at station m at time t+1 (y-axis) has been correlated with chlorophyll measured at station n at time t (x-axis). Conversely, a lag of +1 (lower row) indicates that the correlation is between chlorophyll measures at time t on the y-axis and at time t+1 on the x-axis.

The situation is more complex in Pelorus Sound (Figure 6-14). Again, the correlations tend to be strongest at lag zero and stronger within a layer (surface or bottom) than across layers. On the other hand, within a layer, there is lesser spatial coherence than is the case for Queen Charlotte. In the surface layer, PLS-1 is poorly correlated with all the other sites (to a lesser extent, this is also true of PLS-2). In the near-bed layer, PLS-1 and PLS-2 are poorly correlated with all the other sites (but recall that near-bed sampling at PLS-1 and PLS-2 was restricted to only the first two years).

PC PN

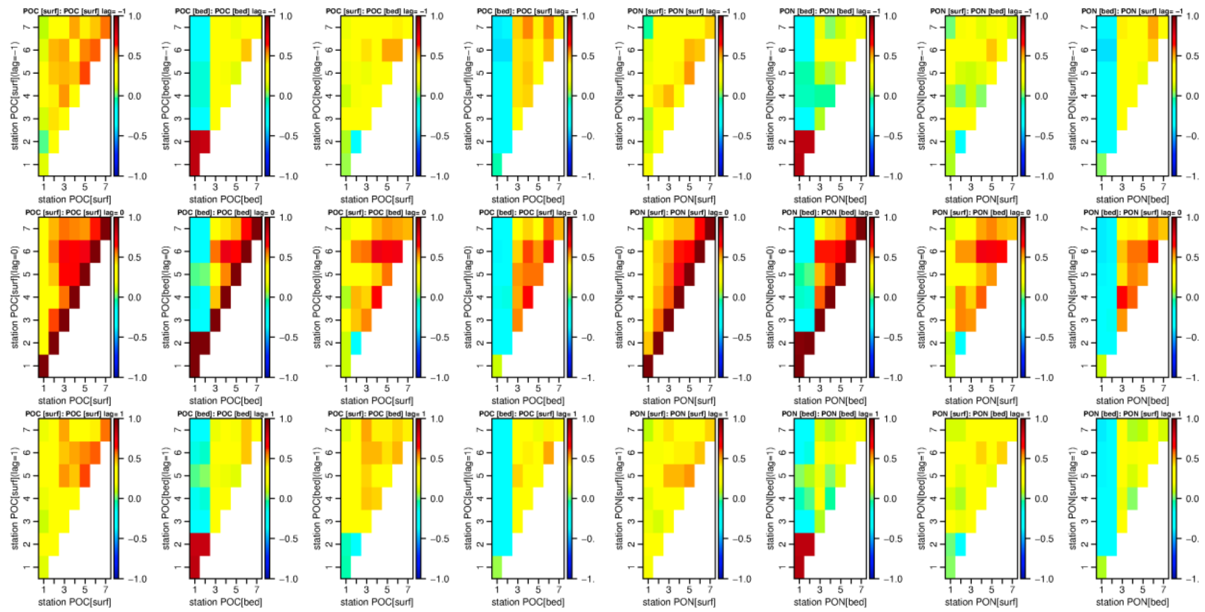

Figure 6-14: Spatial auto-correlation for particulate organic carbon (left) and particulate nitrogen (right) anomalies at lags of -1, 0 and +1 sampling occasions in Pelorus Sound. The lag-figure (in main title and in y-axis label of each figure) indicates the temporal relationship between x- and y-variates. A lag of 0 (middle row) indicates that correlations are between chlorophylls collected on the same sampling date. A lag of -1 (upper row) indicates that the correlation is between chlorophyll measured at station m at time t+1 (y-axis) has been correlated with chlorophyll measured at station n at time t (x-axis). Conversely, a lag of +1 (lower row) indicates that the correlation is between chlorophyll measures at time t on the y-axis and at time t+1 on the x-axis.

6.5 Cross correlation between PN and chlorophyll

Chlorophyll is a protein found in living phytoplankton. As such, it contains both carbon and nitrogen and these will both contribute to the overall pools of PC and PN. To good approximations, all particulate nitrogen will be derived from protein, whereas PC will derive from a mix of protein, lipid and carbohydrate. Thus, one might anticipate a closer correlation between chlorophyll and particulate nitrogen than between chlorophyll and particulate carbon.

Figure 6-15 and Figure 6-16 illustrate the time-series of chlorophyll/PC and chlorophyll/PN at the Queen Charlotte and Pelorus stations respectively. Loosely, the chlorophyll concentration amounts to about 0.5% of the PC concentration or about 5% of the PN concentration – but there is considerable scatter about these ratios. Furthermore, the ratios tended to decline over the course of the first 18 months or so – driven by increases in the concentrations of PC and PN (rather than declines in the concentrations of chlorophyll) (see Figure 4-19, Figure 4-20, Figure 5-19 and Figure 5-20).

Within a living phytoplankton cell, carbon:chlorophyll ratios can vary from about 35:1 (healthy diatoms) to >200:1 (stressed dinoflagellates) (Bowie, Mills et al. 1985). Given that the phytoplankton cell count data indicate that phytoplankton biomass is usually dominated by diatoms, the PC:chlorophyll ratios that arise in the Sounds imply that living phytoplankton rarely contribute more than 50% of the total mass of PC in the water (and often much less than this).

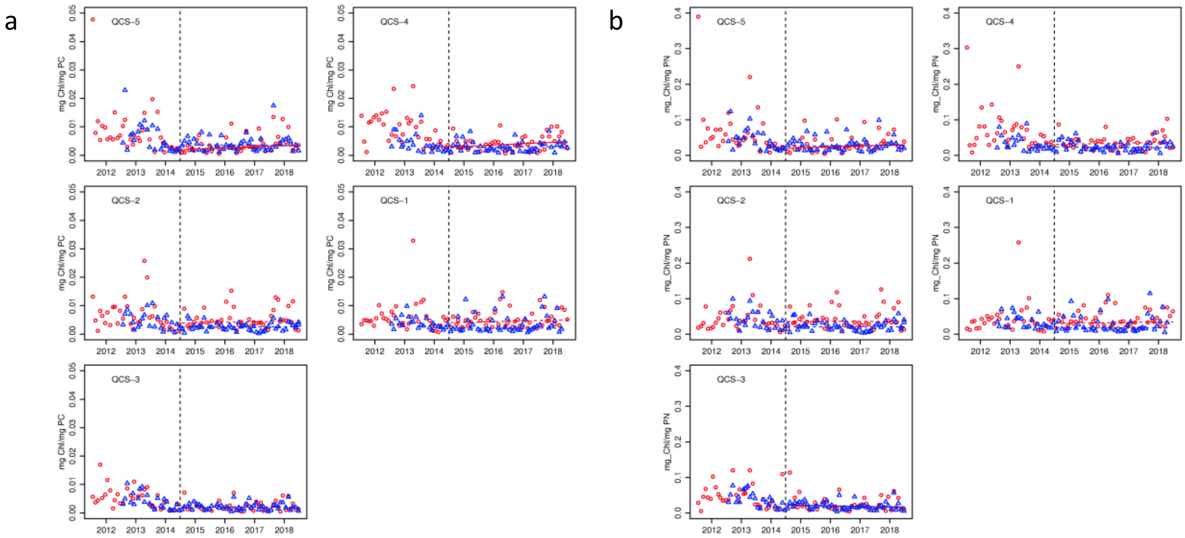

Figure 6-15: Time-series of the chlorophyll:PC and chlorophyll:PN ratios at the Queen Charlotte Sound monitoring stations.

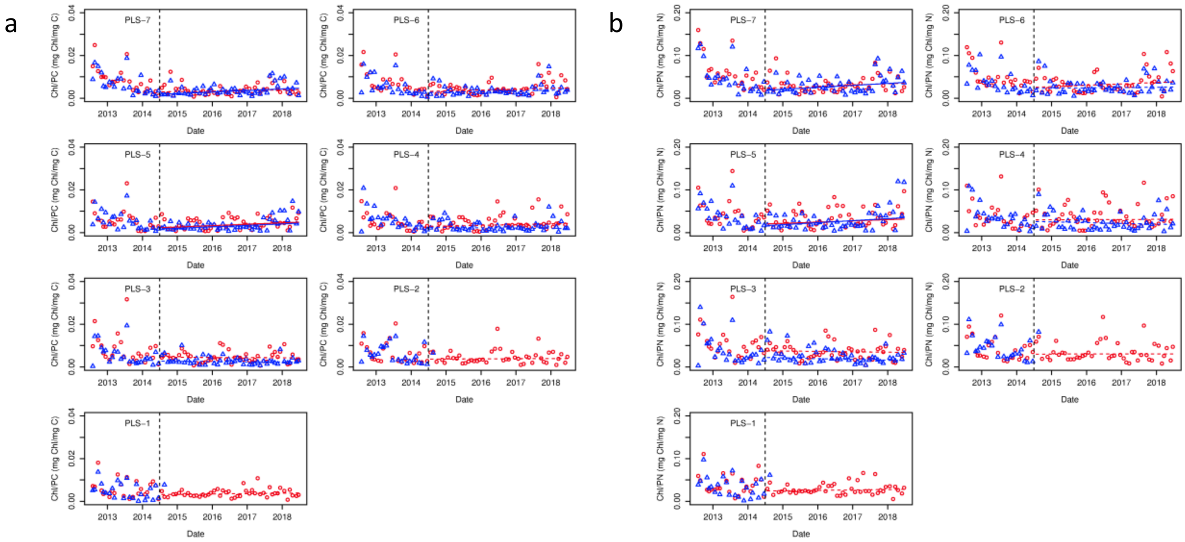

Figure 6-16: Time-series of the chlorophyll:PC and chlorophyll:PN ratios at the Pelorus Sound monitoring stations.

The patterns of correlation between the anomalies for chlorophyll, PC and PN in Queen Charlotte Sound are illustrated in Figure 6-17. Those for Pelorus Sound are illustrated in Figure 6-18. The cross-correlation coefficients between PC (or PN) and chlorophyll tend to be greatest at lag 0. Contrary to expectation, the correlation between chlorophyll and PC is usually stronger than the corresponding correlation between chlorophyll and PN. Correlations tend to be greater amongst stations across horizontal space than across depth at any given station.

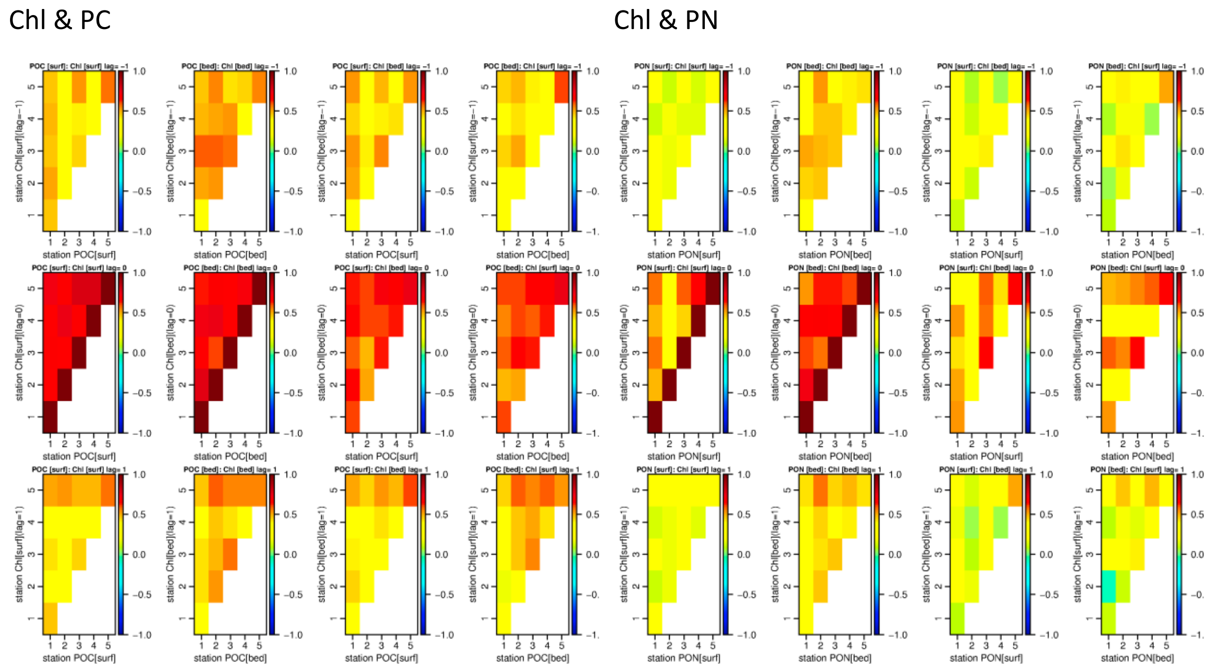

Figure 6-17: Spatial correlation between chlorophyll and particulate carbon (left) and chlorophyll and particulate nitrogen (right) anomalies at lags of -1, 0 and +1 sampling occasions in Queen Charlotte Sound. The lag-figure (in main title and in y-axis label of each figure) indicates the temporal relationship between x- and y-variates. A lag of 0 (middle row) indicates that correlations are between chlorophylls collected on the same sampling date. A lag of -1 (upper row) indicates that the correlation is between chlorophyll measured at station m at time t+1 (y-axis) has been correlated with chlorophyll measured at station n at time t (x-axis). Conversely, a lag of +1 (lower row) indicates that the correlation is between chlorophyll measures at time t on the y-axis and at time t+1 on the x-axis.

In Pelorus Sound, the correlations of among chlorophyll and PC and PN anomalies also tend to be strongest at lag zero. Again, those for PC tend to be stronger than those for PN. Within a layer, the correlations between chlorophyll in the present and PC or PN one sampling in the past, tend to be stronger than correlations between chlorophyll one sampling in the past and PC or PN in the present. This may indicate that mineralization of organic detritus has a greater impact upon phytoplankton dynamics than death of living phytoplankton has upon dynamics of organic detritus.

Chl & POC   Chl & PN

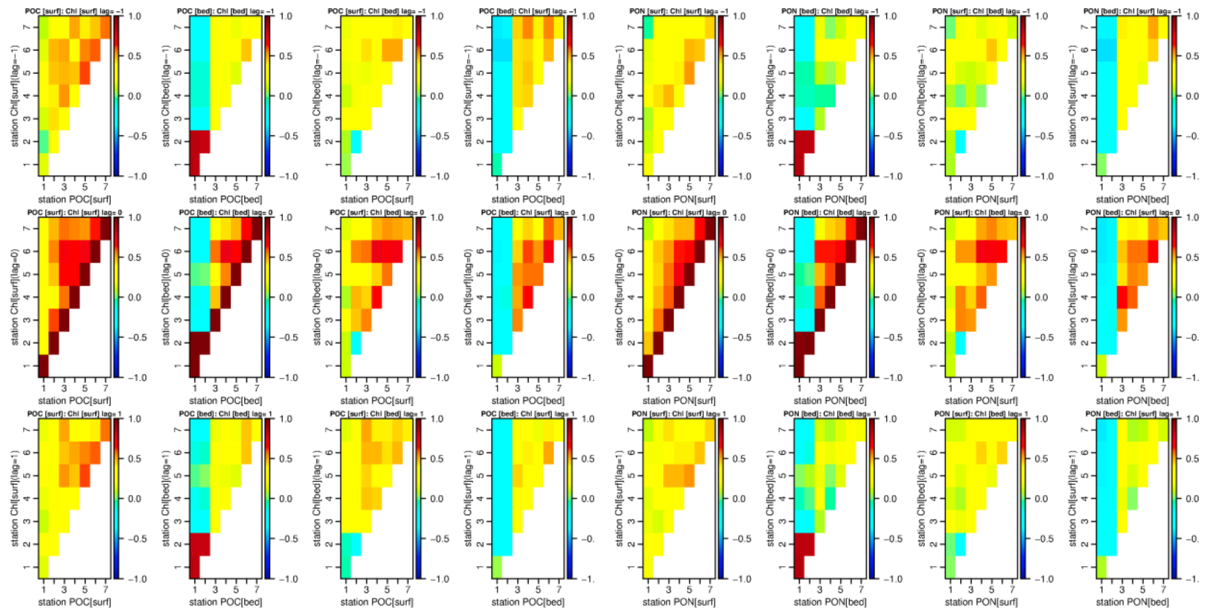

Figure 6-18: Spatial correlation between chlorophyll and particulate carbon (left) and chlorophyll and particulate nitrogen (right) anomalies at lags of -1, 0 and +1 sampling occasions in Pelorus Sound. A lag of -1 (on the y-axis) implies that the y-variate at time t+1 has been correlated with the x-variate at time t.

7 Data exclusions and other matters

Table 7-1 tabulates issues related to data consistency etc., that we discovered during the process of analysing the data-files that were provided to us by Marlborough District Council for this review. It also describes the steps that we took to remedy the issues. We recommend that MDC use this table as a guide when reviewing the integrity of their database.

Table 7-1: Summary of sampling records which are considered dubious and of records which have been rejected. See also Table 6-1 of (Broekhuizen and Plew 2015). In this table 'MDC" is Marlborough District Council.

File	Rows	Issue in files received from MDC	Resolution
All_QCS_newStd_up to Jan 2016.xlsx	8050-8180	MDC Site code reported in site-name column.	Amended in my (now, modified) copies of the files that I received MDC.
	8181-8364	Columns MDC-id onwards shifted one place to right.	Amended in my (now, modified) copies of the files that I received from MDC.
WQSummary_QCS summary up to April 2018.xls		Date for Deep QCS1 is said to be 20/02/2014, but all other Feb 2014 sampling was on 21 Feb according to your spreadsheet. I have assumed that 21/02/2014 is the correct date and amended the DEEP QCS1 date.	MDC confirms that all sites were sampled on same day (20 Feb).
All_Pelorus_newStd_March 2016.xlsx	5769	Date should likely be should be 23/04/2015 rather than 23/03/2015.	No response yet but I have implemented this change.
All_Pelorus_newStd_March 2016.xlsx		Pelorus Dec 17 claims that PLS-7 was sampled on 17/12/2017 but that all other sites were sampled on 12/12/2017.	MDC says that all sites were sampled on **11**/12/2017 (so even the 12/12/2017 dates were wrong). I have amended the dates.
All_Pelorus_newStd_March 2016.xlsx	1607, 1608 (Date=22/05/2013)	Site name is given as Pelorus Sound off Dart Rock but site code is given as PLS-3. In reality, the Dart Rock is PLS-5 whereas PLS-3 is near Yncyca bay. Other records around these rows lead us to infer that the site name is likely to be right and the site-code incorrect. Furthermore, earlier in the file, there are records that list the two families (Ebriaceae, OTHER) as being present at PLS-3 on this date.	After consulting with MDC, I have amended the site-code to read PLS-5 for these two records.
Pelorus_Sound_WQ_summary19022014.xls	307	Date gives year as 0218 rather than 2018.	MDC confirms that it should be 2018.

File	Rows	Issue in files received from MDC	Resolution
Pelorus_Sound_WQ_summary19022014.xls	563 (PLS-2 Surface, 19/04/2018)	DRP, NH4, NO3, TDN, Chl all incorrectly reported as zero. Based upon the values in the raw sheets received from the Chem-lab, the right values are: 19, 28, 36, 268, 2.4 DRSi and TDP reported as 1,2 should be 714,18.	MDC acknowledges the zeros, but has not explicitly confirmed that they agree with my suggestions as to the correct values. Nonetheless, I have adopted the original values reported by the NIWA lab.
Pelorus_Sound_WQ_summary19022014.xls	493 (PLS-1 Surface, 19/04/2018)	DRP, NH4, NO3, TDN, Chl all incorrectly reported as zero. Should be: 19, 35, 56, 280, 1.6. DRSi and TDP reported as 1,2 should be 962,20.	See above.
Handheld DO and temp all data.xlsx	1704 (NZKS9, 23 Jan 2018)	DO concentration is implausible. It is numerically equal to the saturation (i.e., =106.5).	MDC reports that it does not have a DO concentration for this record but also that it is not unusual for water to be super-saturated (so the saturation value of 106.5 is plausible). I agree. Note: I do not describe any NZKS data elsewhere in this report.
Handheld DO and temp all data.xlsx	220 (PLS-3 30 May 2018)	Temperature recorded as 132.10.	MDC reports that correct value is 132.10.
Handheld DO and temp all data.xlsx	PLS-5 off Dart Rock – Surface 24-Sep-2014	The DO saturation (8.4%) is inconsistent with all other records and way too small in comparison with the quoted DO concentration.	MDC says "Seems like a lot of values didn't export correctly, because there is no way I would not have seen that (same with yesterday's). At least that means that we should have the correct original values. I am heading to the office this afternoon and will check and fix them then."
Handheld DO and temp all data.xlsx	June 2018	No data.	
Field data incl secchi and sal.xlsx	PLS-6 March 2018	Temperature reported as 7..8 – about 10 degrees too cold for time of year.	Amended to 17.8 pending confirmation from MDC.

8 Conclusions & Recommendations

8.1 Trends

8.1.1 July 2011-June 2014

Whilst MDC started monitoring Queen Charlotte in July 2011 and Pelorus in July 2012, the formal trend analysis has been restricted to the period from July 2014 – present. The earlier data were excluded because the means by which (near-surface) samples were gathered changed abruptly after June 2014.

Whilst we have not made any trend analyses using the data gathered prior to July 2014, some features are notable:

1. In both Sounds, concentrations of particulate organic carbon, particulate organic nitrogen and volatile suspended solids rose rapidly during mid-2013 at most sites (Figure 4-20, Figure 4-23, Figure 5-19, Figure 5-20, Figure 5-23). They tended to remain high (relative to earlier months) from then until the change in sampling in July 2014. The rise occurred at most sites in both Sounds. There were no changes in laboratory methods across the period of the rapid rise and, to the best of our knowledge, no changes in field protocols or protocols used when transporting samples from the field to the laboratory. The cause(s) of this wide-scale, rapid and synchronous rise is unknown.

2. Concentrations of dissolved organic phosphorus and total dissolved phosphorus declined steadily over the first few months of sampling in Queen Charlotte Sound. Thereafter they have remained more stable. (Figure 4-11, Figure 4-12).

8.1.2 July 2014-present

Table 8-1 provides a qualitative summary of the trends (July 2014-present) that have been determined from the water-quality data. For most of the Sen-slope trend lines, the sign of the slope cannot be determined with 95% (or greater) probability. In the IPCC parlance, the signs of these slopes will be somewhere between ‘about as likely as not’ and ‘very likely’ to have been correctly determined. Only a small minority attain ‘extremely likely’ (or greater) status (i.e., carry a probability of 95% or greater). For the sake of brevity, I have referred to these relatively few slopes as being ones which provide ‘convincing evidence of trend’ or as having signs which are ‘confidently determined’. Conversely, I will refer to the remaining slopes as ‘unconvincing’.

Most of the convincing trends are isolated instances (i.e., occur only at one or two sites), but two seem to be more generic: in both Queen Charlotte / Tory and the Pelorus systems, the concentration of oxidized nitrogen (NO_3-N + NO_2-N) seems to have climbed a little whilst the concentration of ammoniacal nitrogen seems to have declined. The trend-direction for concentrations of total dissolved nitrogen, dissolved inorganic nitrogen, particulate nitrogen and total nitrogen remain ‘unconvincing’ at most sites, but a minority have been positive at some sites. Overall, therefore, there is a little evidence that the loading of nitrogen into the Sounds may have increased (or elimination of nitrogen from the Sound may have decreased) and that the increases may have been driven by increased loading of oxidized nitrogen – perhaps combined with increased rates of conversion of ammoniacal nitrogen into oxidized nitrogen.

It is beyond the scope of this report to identify the cause(s) of any accruing changes. We merely note that, whilst the trends may be driven by processes/changes that have occurred within the waters of the sounds, they may also have been driven by changes/processes arising further afield. It is well established that water-quality in Pelorus Sound in influenced by river-flows (and materials imported with those riverine waters) and by exchanges with Cook Strait (Zeldis, J.R., Howard-Williams et al. 2008). Queen Charlotte Sound receives lesser riverine inputs but a recent seabed mapping exercise found evidence of numerous freshwater seeps in the seabed of Queen Charlotte Sound (Neil, Mackay et al. 2018). It is exchanges water with Cook strait and the patterns of exchange may vary year-to-year as they do in Pelorus Sound. Thus, whilst the (weak) upward trends in the nitrogen content of the two Sounds may, at least in part, reflect recent increased fish-feed inputs, there are plausible alternative/additional candidate causes that may be more important drivers of such trends as exist.

Regardless of the cause(s) of any of the trends, we re-iterate that the mere fact that a slope is (for example) 'extremely likely' to be positive (or negative) need not imply that the magnitude of change that has accrued to date is of any ecological significance. It is beyond the scope of this report to attempt to determine whether any of the changes that may be accruing are ecologically significant, but we note that all the apparent accrued changes are small in comparison with the magnitudes of seasonal-scale fluctuations and most are small in comparison with the long-term average.

Table 8-1: Qualitative indication of water quality trends for the period July 2014-June 2018 at each site. + (-) indicates that the trend-slope is positive (negative) with at least 95% probability. Blanks indicate that the trend-slope has not been determined with a probability of 95% or greater. NA indicates that the quantity in question is not sampled at the location.

Location	Temperature (hand-held device at 1 m)	Salinity (hand-held device at 1 m)	DO saturation (hand-held device at 1 m)	SIS	Turbidity	DRP	TDP	DOP	DRSi	TDN	NO_x-N	NH_x-N	DON	PN	PC	TN	VSS	Chl	Secchi
QCS-1 (surface)											+	-			-				
QCS-1 (deep)												-							NA
QCS-2 (surface)											+	-							
QCS-2 (deep)						+	+		+		+				-			-	NA
QCS-3 (surface)									+			-					+		
QCS-3 (deep)									+	+		-		+		+			NA
QCS-4 (surface)											+	-			-				
QCS-4 (deep)											+	-							NA
QCS-5 (surface)						-						-		-	-				
QCS-5 (deep)								+			+	-							
PLS-1 (surface)	-						-	-			+						+		
PLS-1 (deep)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PLS-2 (surface)	-	-					-		+	+	+			+		+	+		
PLS-2 (deep)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PLS-3 (surface)	-	-		+					+		+								
PLS-3 (deep)	NA	NA	NA	NA	NA				+	+	+	-							NA
PLS-4 (surface)	-	-				-	-				+							+	-
PLS-4 (deep)	NA	NA	NA	NA	NA						+							-	NA

Location	Temperature (hand-held device at 1 m)	Salinity (hand-held device at 1 m)	DO saturation (hand-held device at 1 m)	SIS	Turbidity	DRP	TDP	DOP	DRSi	TDN	NO_x-N	NH_x-N	DON	PN	PC	TN	VSS	Chl	Secchi
PLS-5 (surface)	-	-					-	-											-
PLS-5 (deep)	NA	NA	NA	NA	NA	+	+		+		+							+	NA
PLS-6 (surface)	-										+	-							-
PLS-6 (deep)	NA	NA	NA	NA	NA							-							NA
PLS-7 (surface)		-		+							+	-					+		-
PLS-7 (deep)	NA	NA	NA	NA	NA							-		-				+	NA

8.2 Data distributions and Flag values

Appendix C and Appendix D present histograms which illustrate the empirical probability distributions of the values associated with each water-quality variable measured in Queen Charlotte Sound/Tory Channel (Appendix C) and Pelorus Sound (Appendix D). The text within each probability density function plot lists the quantity-values (usually, concentrations) corresponding the 50th, (median), 95th, 98th and 100 percentiles). The data have been divided into sub-categories by sound, season (quarter of year) and depth-band (near-surface versus near-bed). They have not been categorized by site-location. This may become desirable in the future (once more data have been amassed) but doing so now (whilst also retaining the other categorizations) would render the sample sizes too small to enable robust density functions to be constructed.

The density functions will not be discussed in detail since they are merely a different way of summarising the raw data presented in the time-series plots of sections 4 and 5. The percentile distributions can be used to apply a degree of quality control to incoming data (from newly collected samples). For example, one could set upper (and lower) threshold values that incoming data might reasonably be expected to fall within. Should an incoming data item fall outside the specified band, it could be subject to greater-than-normal scrutiny before being accepted (or rejected). For example, should a TSS concentration be unusually high, one might ask questions such as:

- Did the sampler hit the seabed such that sediments could have been stirred up (temporarily raising the concentration of suspended sediments)?
- Were other presumed correlates of suspended sediments (SIS, VSS, PC, PN) also unusually high?
- Did the boat crew report that the water did, indeed, appear unusually turbid?
- Was sediment noted to be especially abundant in the water sample used for counting phytoplankton taxa?
- Had there been a recent river-flood that may have introduced sediment?

Depending upon the answers to questions such as these, the data-administrator could decide whether to accept or reject the data.

Choosing the upper and lower threshold values would be a subjective decision but inspection of the probability density functions suggests:

- For some variables (e.g., DRP), the quantity-values (usually, concentrations) associated with the 95%, 98% and 100%iles differ by only relatively small increments. This tends to imply that values which are dramatically larger than the maximum historical value are unlikely to arise in the future – unless there is an ongoing upward trend in the variable.
- For other variables (e.g., TSS, turbidity, NH_4-N), the increments between the 95%, 98% and 100%iles are relatively larger. Nonetheless, in the majority of even these cases, the cumulative density function (the asymptotic 'curve') has approached close to 1.0 before the 95th percentile. This pattern tends to imply that, whilst future values are unlikely to surpass the historical maximum (unless there is an upward trend with

respect to time), those which do exceed the historical maximum may do so by a large margin.

- For some variables (e.g., NO_3-N), the various percentiles change markedly with season and/or depth. For others, there is little seasonal variation (e.g., near-surface turbidity in Queen Charlotte/Tory).

Choosing 'guard values' is a subjective exercise. If the upper thresholds are set too low, many incoming data will be flagged as deserving additional scrutiny, but subsequently accepted. Conversely, if the upper threshold is set too high, some 'bad' data may slip through without attracting due scrutiny. If guard values are to be based upon the historical data presented in this document one should note:

- Some extreme historical data were excluded before the time-series plots and percentile distributions were made. Thus, the data which we present are only those observations we believe are plausible rather than all of observations. Our judgement of plausibility was based on an informal identification of extreme values followed by inquiries as to what might have driven them (e.g., bias arising because sampling device hit the bottom (reject the data) versus a natural extreme associated with sampling after a river flood (retain the data)).

It is our opinion that:

- guard-values should not be used as the sole means by which to definitively accept or reject incoming data; rather, they should be used to flag data that deserve additional scrutiny
- guard values should be re-evaluated from time-to-time (lest there be long-term water-quality trends)
- data which are rejected, should nonetheless, be recorded elsewhere (so that the data can be re-incorporated in the event subsequent information leads to a change in the criteria used to adjudicate upon 'unusual data'.

The threshold values for TN and chlorophyll (respectively 300 mg N m^{-3} and 3.5 mg Chl m^{-3} in the upper 15 m of the water-column) that were nominated for the purpose of monitoring/regulating the effects of several new NZKS salmon farms were chosen to approximate the 95 percentile of historical data that were available at the time (data to 2014, including MDC data available at that time). The 95 percentiles calculated using all the MDC data now available (and no data from any other studies) remain similar to the threshold values proposed previously in (Morrisey, Anderson et al. 2015).

8.3 Revisions to sampling patterns

8.4 Tory Channel

The CTD and water-quality data from the water-quality station within Tory channel (QCS-3) indicate that the water is invariably well mixed (temperatures, salinities, and concentrations of nutrients and particulate are similar near-bed and near-surface). If a (relatively small) reduction in the cost of the sampling program is desirable, one might consider dropping either the near-surface, or the near-bed water-quality samples since they are essentially replicates of one another.

Even if costs are not an issue, one might consider dropping one of the two depth strata in favour of establishing an additional sampling station elsewhere within Tory/Queen Charlotte. More specifically, there have been anecdotal reports of environmental problems in the East Bay/Otanerau Bay region. Biophysical modelling suggests that East Bay/Otanerau/Onauku Bay may be relatively isolated from the main stem of Queen Charlotte (Hadfield, Broekhuizen et al. 2014). Alternatively, one might consider augmenting the CTD sampling that already occurs within Endeavour Inlet with water-quality sampling.

If an additional station were to be established, one would need to give careful thought to the implications this would have for the agreement between NZKS/MDC concerning the management of NZKS fish farms (Morrisey, Anderson et al. 2015). The 'rules' within the agreement were based around the existing pattern of sampling (and NZKS monitoring data). Given the way that some 'rules' are phrased, adding any additional sampling stations into the network has the potential to increase the likelihood of an 'exceedance' being flagged (even if the environmental conditions at the pre-existing stations do not indicate any change in the frequency of exceedances).

8.5 Handheld temperature, salinity and dissolved oxygen data

The near-surface data (temperature, salinity and dissolved oxygen) stemming from the measurements made at sea with hand-held devices duplicate measurements that are available from the CTD data (and, in the case of salinity, from subsequent measurements of the water-samples which are returned to the laboratory). There have been occasional problems with the CTD data. Similarly, there have been occasional problems with the hand-held data. Having two, independent data-sets provides a valuable means of cross-validation and 'sampling-backup'. On the other hand, it implies a cost burden (increased time at sea, and increased time and resources spent processing and archiving two data-streams). Council might consider ceasing the measurement of near-surface salinity, temperature and dissolved oxygen with the hand-held devices.

8.6 CTD profiling

Our experience shows that obtaining reliable data from CTD profiles requires frequent calibration checks of the sensors. Temperature sensors are generally fairly stable. Similarly, the conductivity sensors on the Seabird instruments, in our experience, are remarkably stable over time. However, those used on the Exosonde have been more problematic. We understand that MDC have been checking calibration of the Exosonde conductivity more regularly, and have recently revised their calibration procedures. Conductivity is used to calculate other parameters including salinity and density, so is an important parameter. We have noted changes in salinity over time (see for example Figure 4-4) that we believe are due to drifts in sensor calibration or in some cases different instruments being used. For example, YSI and Seabird calibrate and calculate conductivity in different ways. Conductivity is temperature dependent, and YSI recommend calibrating to specific conductance (conductivity corrected to 25°C). Seabird and YSI use slightly different coefficients when converting between conductivity and specific conductance, which can result in small differences in salinity and density. However, the effect of the different coefficients is smaller than the apparent differences in salinity observed over time. As noted previously, it may be possible to adjust the salinity values recorded by the CTD using results from the water samples. We have not done this for this report but note that salinity from water samples is reported to 0.1 ppt, which may be sufficient for offsetting CTD salinities sufficiently to allow a comparison over the full monitoring period, but would likely not allow for a complete post-calibration of the sensors. We recommend continuing frequent calibration checks of the conductivity sensor.

It is also preferable to use the same instrument, or when changing instruments to run a comparison between them to ensure data are comparable. If both instruments are calibrated properly then the data should be consistent, however there may be differences in sensor sensitivity that can be identified by a comparison.

We have previous advised that the YSI Exosondes ships with a default 20-30 point moving average filter applied to the data (conductivity, temperature etc., but not pressure (depth)) collected by the sensors. At a sampling frequency of 4 Hz, this means data stored is an average of data collected over the previous 5-7.5 sec. Consequently, inferred vertical profiles are severely affected unless this averaging is turned off. The averaging mode should be set to custom with the lowest possible averaging applied. Marlborough District Council now collect data with the moving average filter turned off, which allows filtering or averaging to be applied in post-processing (we typically bin the data, averaging all data collected within 1m intervals).

Some of the sensors on the Exosonde have slow responses, as indicated by their T63 time (the time taken for the sensor to reach 63% of the final stimulus value when a step change is applied). Differences in response time can cause erroneous results in profiles. As an example, **Figure 8-1** shows CTD data collected in Pelorus Sound during May 2018. Several sites show a sharp interface in temperature and conductivity. Because the conductivity sensor has a slower response, the interface appears at slightly greater depths for conductivity than temperature. The algorithms to calculate salinity and density use conductivity and temperature. As the profiler passes through the interface, the sensors report temperature increasing before conductivity because of the difference in response times (although we would expect the changes to occur together). This results in the calculated salinities and densities decreasing. As a result, the density profile shows an unstable water column with lower density fluid appearing mid-depth rather than at the surface (e.g., PLS-3 and 5), or spikes (e.g., PLS-4). Other parameters that rely on output from multiple sensors (e.g., oxygen) may be also be affected in a similar way by differences in sensor response time. To minimise these factors while using the current Exosonde instrument package, the most practical solution is to lower the instrument slowly. Due to the slow response times, we suggest reducing this to <0.5 m/s.

Sensor	Response time T63 (sec)
Conductivity	<2
Temperature	<1
Pressure	<2
Dissolved oxygen	<5
Chlorophyll, BGA-PC/BGA-PE	<2
Turbidity	<2

We note that the raw fluorescence signal from the fluorometer associated with the CTD was often negative. This may indicate that the fluorometer needs to be calibrated before each sampling campaign.

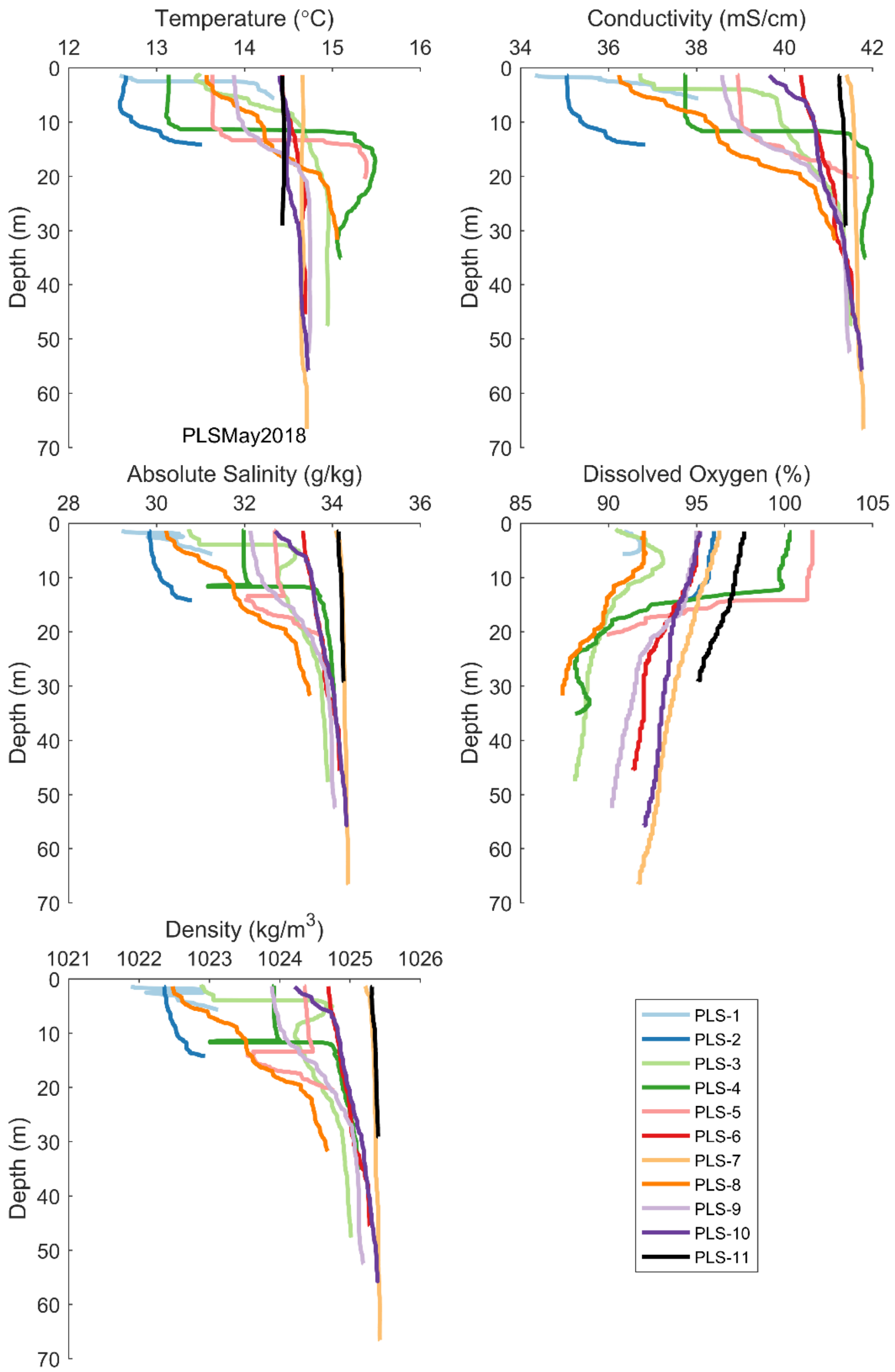

Figure 8-1: Profiles of temperature, conductivity, salinity, dissolved oxygen and density from Pelorus Sound, May 2018. Differences in response time of the conductivity and temperature sensor result in artefacts in salinity and density profiles, as seen at PLS 3, 4 and 5.

8.7 Secchi Disk

Secchi disk measurements have been made because (a) such data are intuitively appealing to a lay-public, (b) Secchi disk measurements are widely used around the world, so provide a means of inter-comparison, (c) as a potential 'backup' proxy for more fundamental properties such as suspended sediment or chlorophyll concentrations (lest the water-samples were spilt prior to lab. analysis), (d) as a potential proxy for direct measurements of the PAR attenuation coefficient.

Variations in Secchi disk depth appears to be most strongly driven by variations in total suspended solids (which are dominated by inorganic solids) (Figure 8-2).

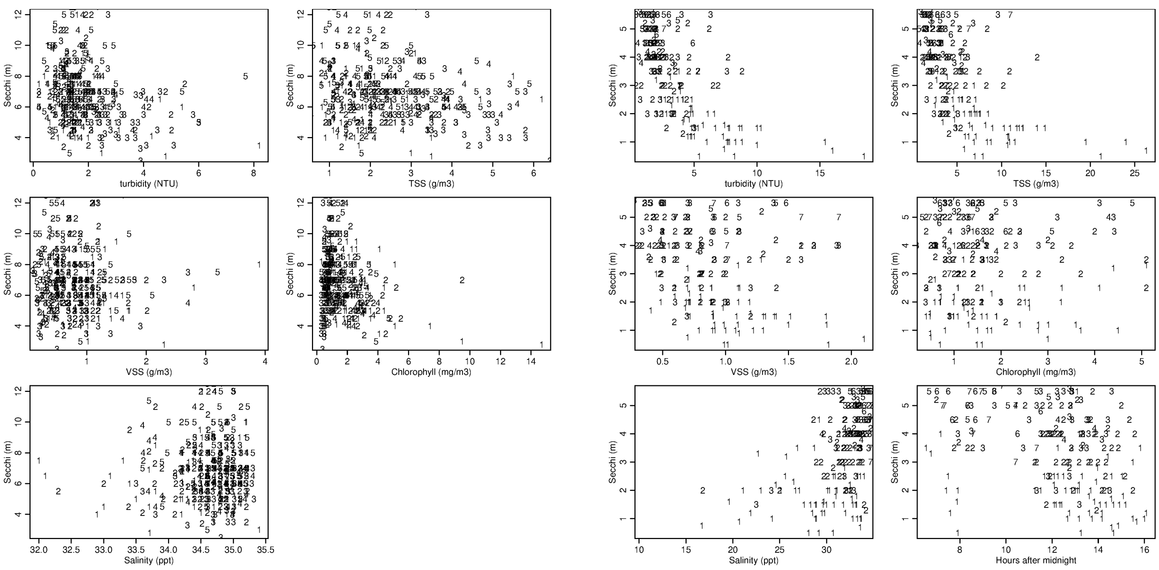

Figure 8-2: Scatter plots illustrating the relationships between Secchi disk depth and candidate water-quality properties that have been measured. The numerals within each plot represent individual data from the corresponding station number. Left hand images: data from Queen Charlotte Sound; right-hand images: data from Pelorus Sound. Note that the ranges spanned by corresponding x-axes and y-axes in the Queen Charlotte and Pelorus plots differ. Shallow Secchi disk depths are often recorded before mid-morning and after mid-day. It is well known that perceived Secchi disk depths tend to be greater when the Sun is high in the sky, but, in this instance, the dominant driver of the pattern appears to be the fact that the turbid inner sites tend to be sampled before mid-morning and after mid-day whilst the clearer sites of the outer Sound tend to be sampled in the late morning.

9 Acknowledgements

The data presented in this report were provided to us by Marlborough District Council. Their staff undertook the sampling. The chemical analyses have been made by NIWA's water-quality laboratory. This report was funded by Marlborough District Council.

10 References

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Appendix A Methods for phytoplankton and zooplankton counts

Phytoplankton > approximately 3 µm, microzooplankton and zooplankton were identified and enumerated in 200 ml subsamples preserved with Lugol's Iodine solution (1% final concentration) using a Leica DMI3000B inverted microscopic. For enumeration, samples were left to settle for >48 h before removing the supernatant and resettling in 10 ml Utermöhl chambers for at least 8 hrs. Samples are then counted and identified with an inverted microscope at 100 x to 600 x magnification. For phytoplankton the dimensions of each taxon were measured and the biovolume estimated from approximated geometric shapes (spheres, cones, ellipsoids), (Hillebrand, Dürselen et al. 1999; Olenina, Hajdu et al. 2006). Phytoplankton biovolumes were then used to calculate cell carbon (mg C m^{-3}) using the regression equations of Menden-Deuer,Lessard (2000) for dinoflagellates and cyanobacteria, that of Cornet-Barthaux, Armand et al. (2007) for diatoms. In the same samples microzooplankton and zooplankton were identified to genus where possible and enumerated but with no differentiation of plastidic ciliates. Ciliate biomass was estimated from dimensions of 10-20 randomly chosen individuals of each taxon. The volumes were estimated from approximate geometric shapes and were converted to carbon biomass using a factor of 0.19 pg C μm^{-3} (Putt and Stoecker 1989). The use of Lugol's iodine for preservation may have resulted in an underestimation of biomass because of cell shrinkage.

For both phytoplankton and microzooplankton the whole chamber was scanned for the enumeration of larger cells. For these the detection limit is 1 in 200 mls for smaller cells. detection limits vary depending on the magnification and the number of Fields of View (FOV) counted. Our counts are conducted with a minimal of 20 FOV.

Counting Random Field

When the distribution of algal objects in the settling chamber can be considered random and conforming to a Poisson distribution, the number of fields or algal objects to count can be set according to what level of precision or detection is required, as the precision/detection limit is dependent on the number of algal objects/fields. The precision (confidence limits) for our methods are given below.

Table A-1: Cell count accuracy. (Lund, Kipling et al. 1958).

Cell no. counted	Accuracy expressed as % of count (95% confidence limits)	Comment
4	+/- 100	
16	+/- 50	
100	+/- 20	=100 units / unicells
400	+/- 10	
1600	+/- 5	

The detection limit calculations are given below. These are calculated for each lens and settling chamber combination presented. The precision (D) of a count can be expressed as either (i) the standard error as a proportion of the mean, or (ii) 95% confidence limits as a proportion of the mean.

NOTE: the precision relates to the type of algal objects counted. If only a single species is to be counted, then the precision should be set for that species; if all taxa are to be counted, then the precision is set for the total number of algal objects. For accredited cell counts, the precision is pre-set.

Detection Limit

The detection limit is an important parameter in phytoplankton surveys. It is defined as the minimum concentration of a specific taxon that will be detected with 99% certainty. Below this limit, detection is a matter of chance. This also implies, that if a particular species has been found, its concentration does not necessarily need to be above the detection limit. The limit of detection does not take account of the skill of the analyst (e.g., algae that are overlooked). The limit of detection, from an identification point of view, corresponds with the laboratory species list.

By contrast to estimates of precision, the detection limit is dependent on the number of fields counted (the absolute volume of viewed sample) rather than the number of algal objects. If the number of algal objects to be counted is fixed, then a variation in the detection limit may occur within the same sample series. The detection limit also applies to the size of algal objects. At a magnification of 400–600x, the smallest countable particles have a size of circa 2 to 4 µm.

Table A-2: Microscope calibration. Description - New Leica. Calculated detection limits in *cells per ml* for 20 FOV (fields of view) for each lens for Settling Chambers of the given diameter.

Objective lens	Settling chamber diameter (mm)		
	26	25	24
x63	693.5	641.2	590.9
x40	271.9	251.4	231.7
x20	67.4	62.3	57.4
x10	16.7	15.4	14.2
x5	4.2	3.9	3.6

The probability with which an object is detected can be determined by Poisson statistics according to:

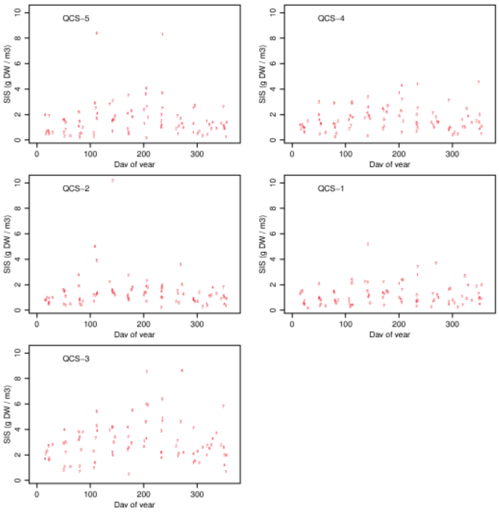
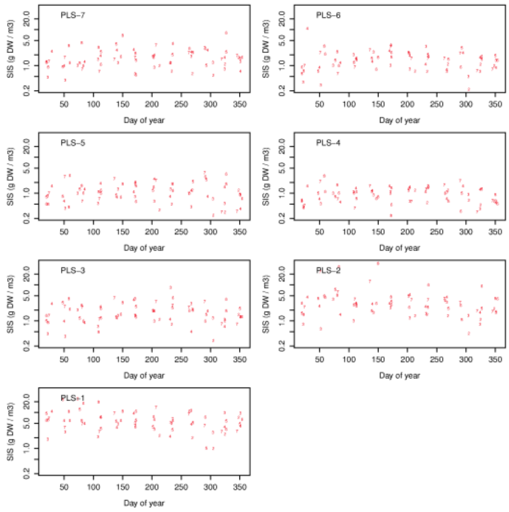
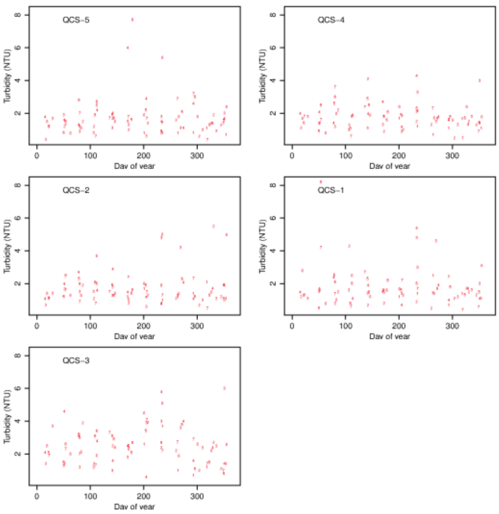
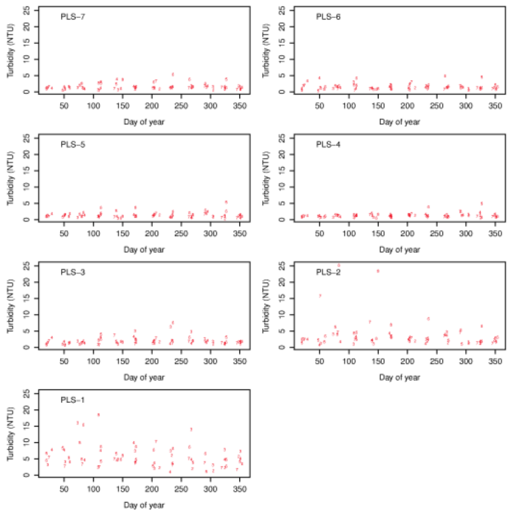
$$n_{det} = -\ln(\alpha) \,.\, f_{total} / (V.\, f_{counted})$$

where α is the level of significance, n_{det} is the detection limit, f_{total} is the total number of microscope fields in the settling chamber, $f_{counted}$ is the number of fields counted, V is the volume of the sub-sample in the settling chamber.

In multi-taxon samples α must be corrected for the number of taxa. The chance of finding each taxon in a sample is determined by the product of the probabilities of each independent taxon. This implies literally that if, for instance, ten taxa each have a concentration equal to the detection limit, n_{det}, the probability that they will all be detected in the same counting at α = 0.01 is only 100 X (1-0.01) X 10 = 90 %. Any knowledge of taxon richness of a sample prior to analysis can be used to correct α and determine a proper detection limit or the number of fields one has to count. In some studies, an α of 0.01 will be sufficient whereas in other studies an α of 0.001 or even less is necessary.

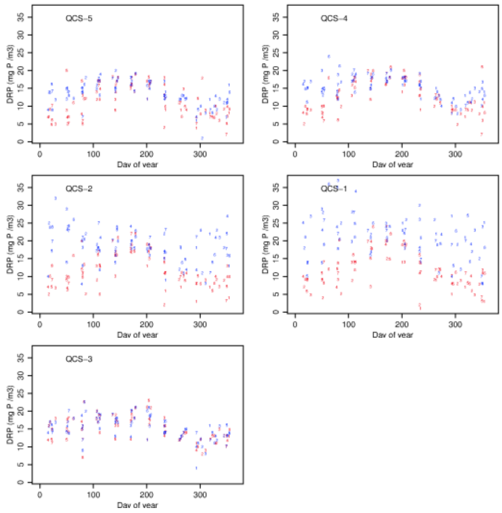
Appendix B Water-quality data plotted by day of year

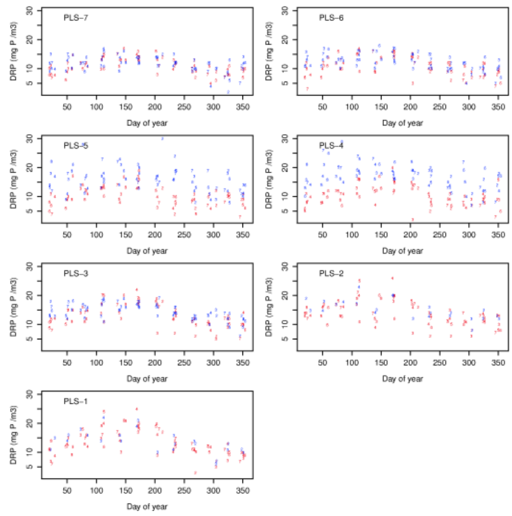
Table B-1: Water quality variables plotted by day-of-year for Queen Charlotte & Pelorus Sounds. Numerals indicate the year (1+2011, 2:2012 etc.,). Red numerals are near-surface data. Blue numerals are near-bed data.

Property	Queen Charlotte	Pelorus
Suspended inorganic solids		
Turbidity		

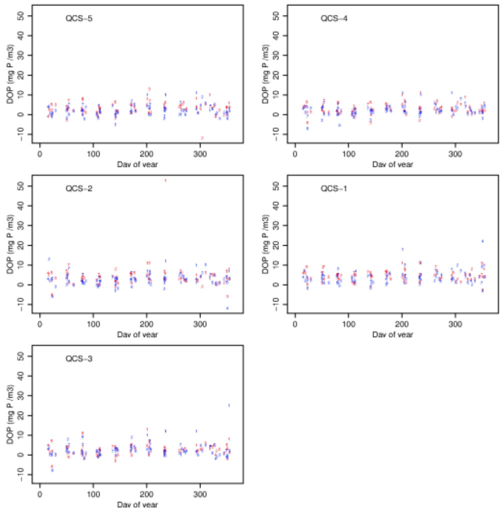
Property	**Queen Charlotte**	**Pelorus**

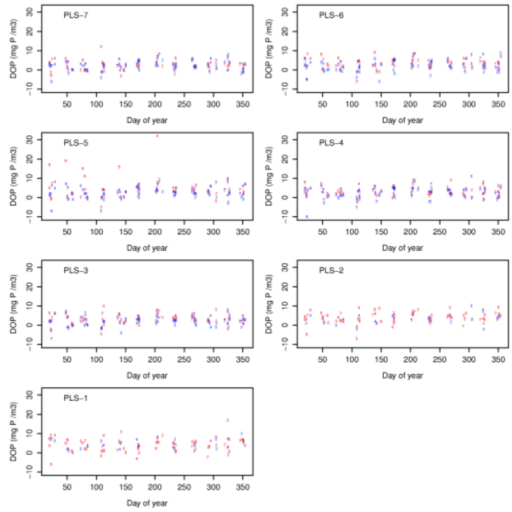
DRP



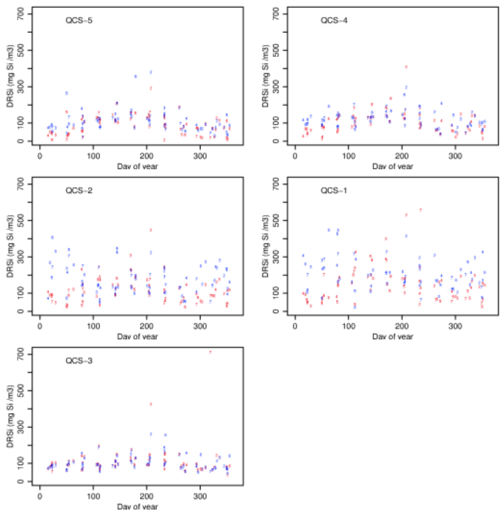


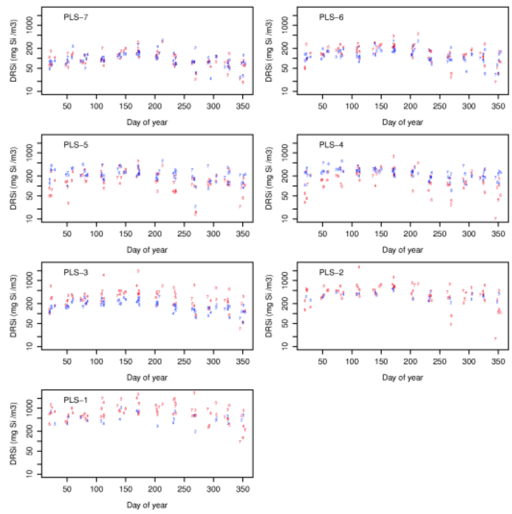
DOP





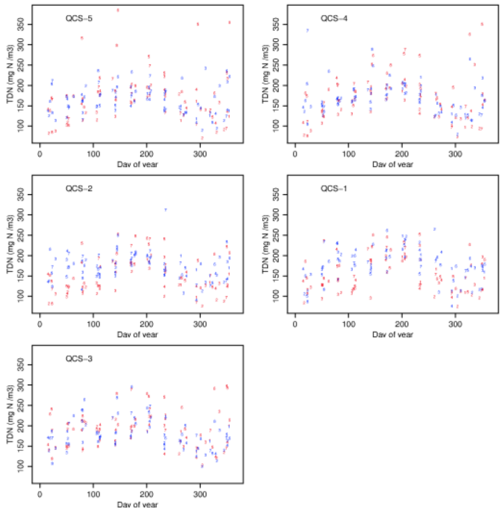
DRSi

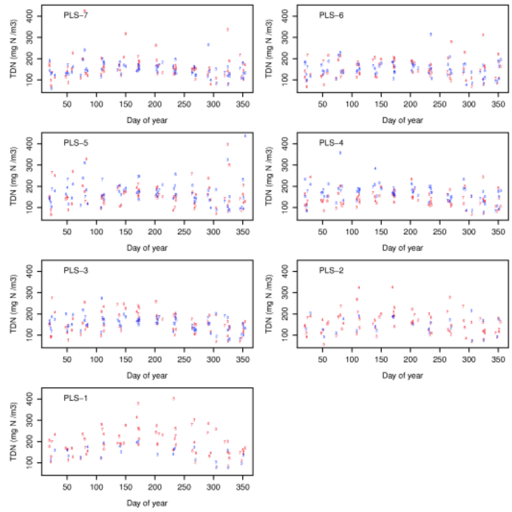




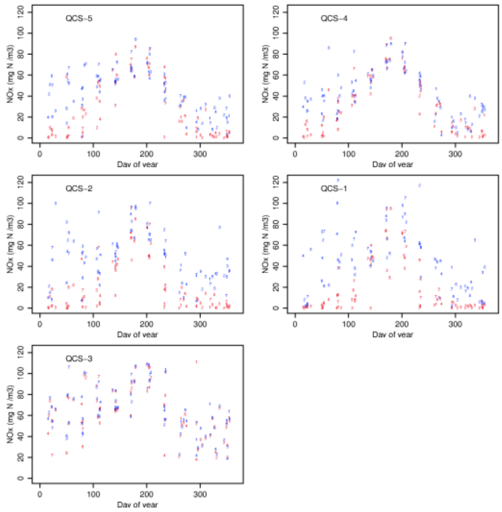
Property **Queen Charlotte** **Pelorus**

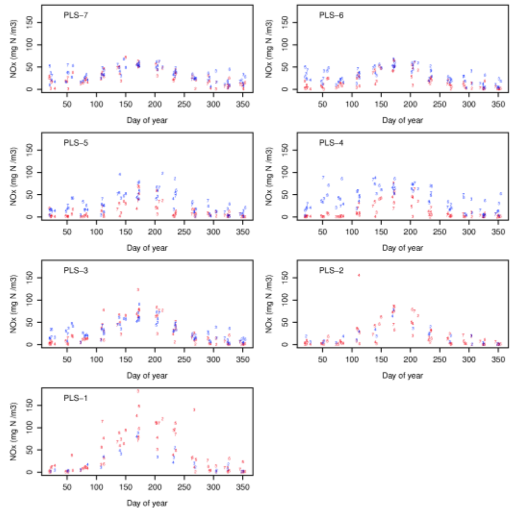
TDN



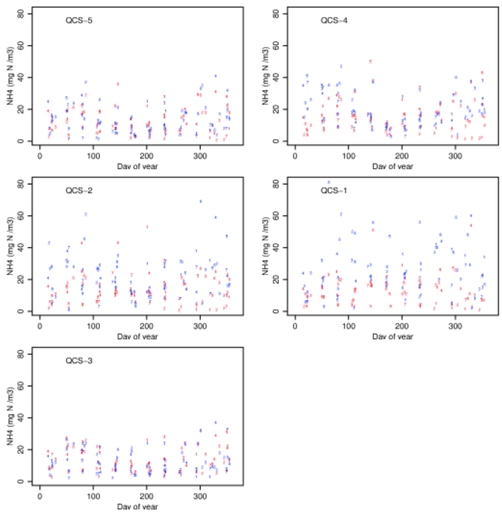


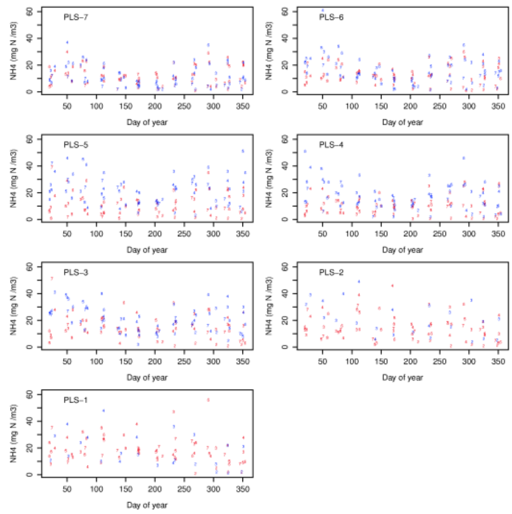
NO$_x$-N

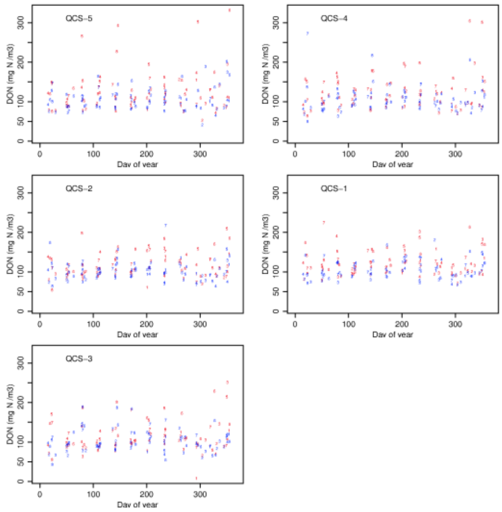
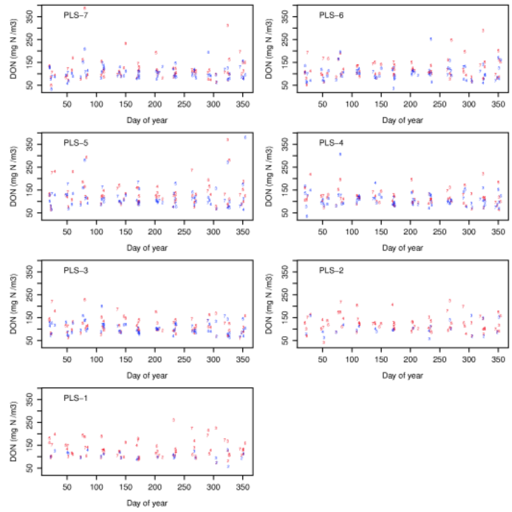
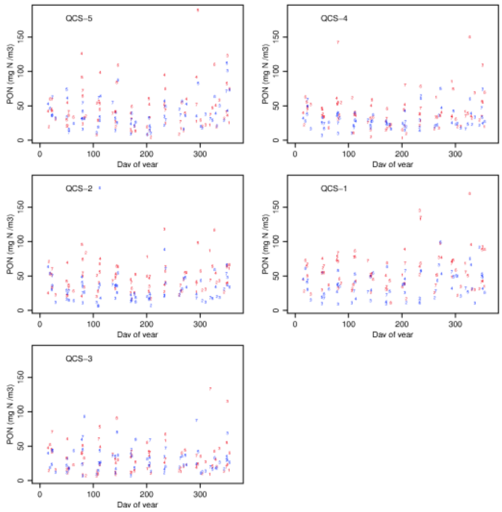
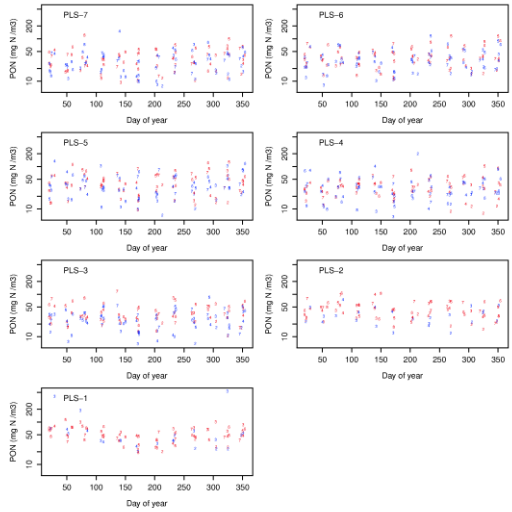
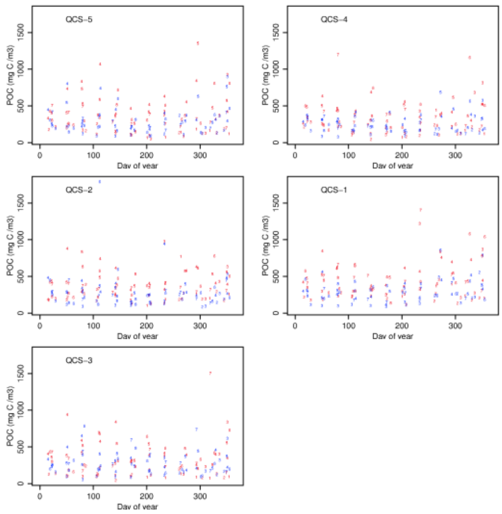
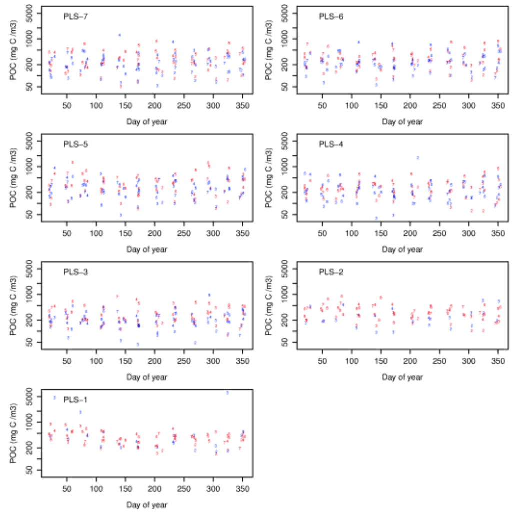


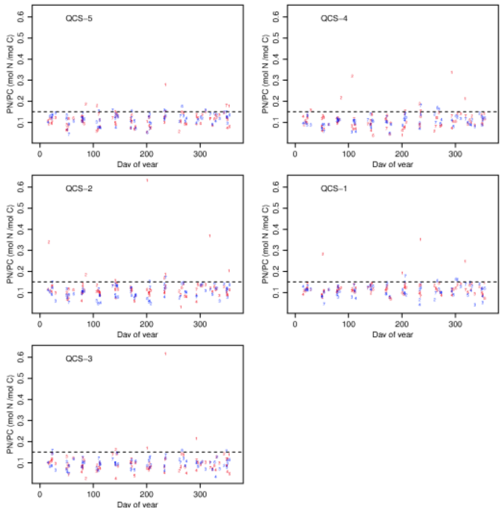
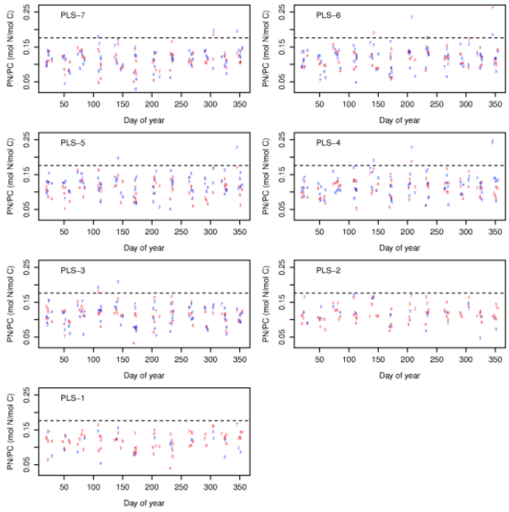
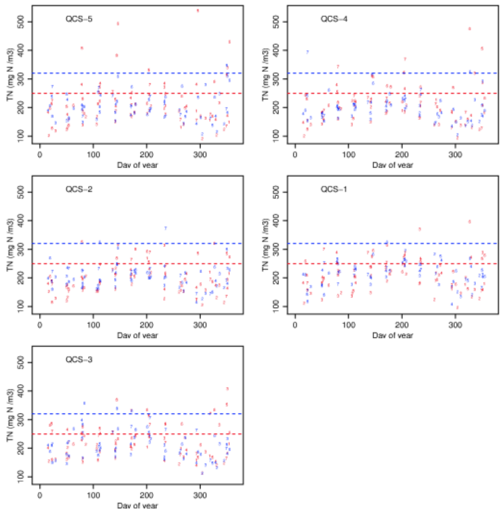
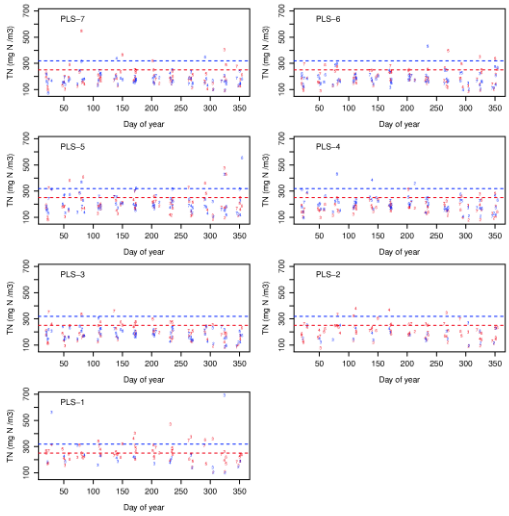
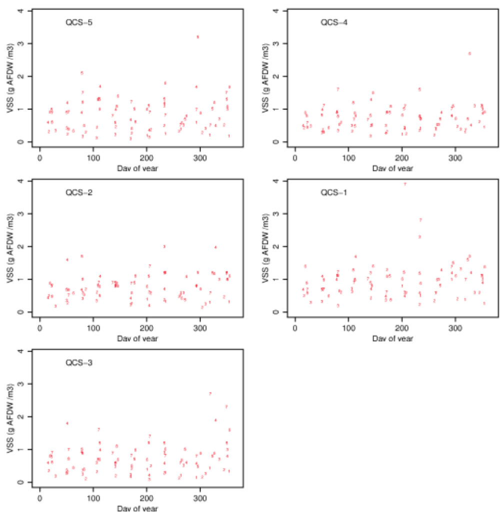
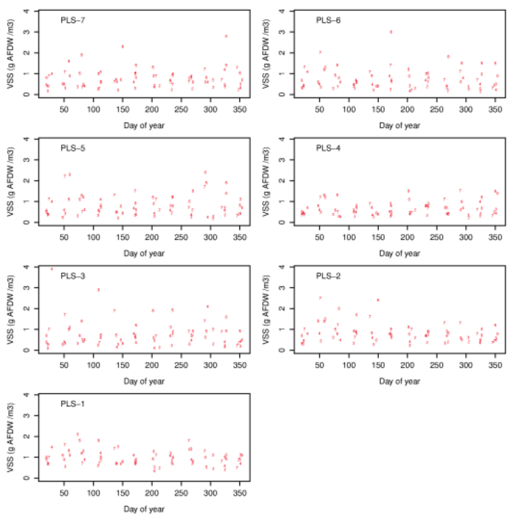


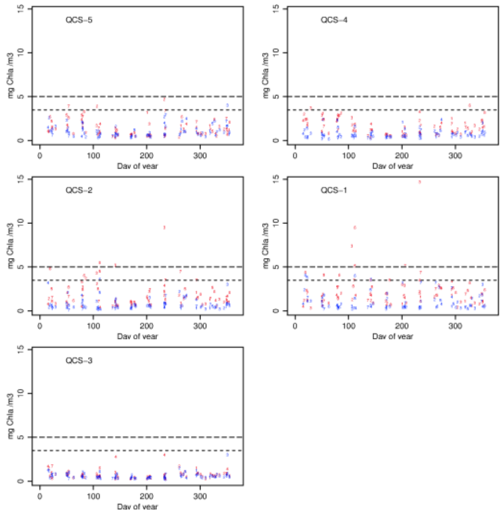
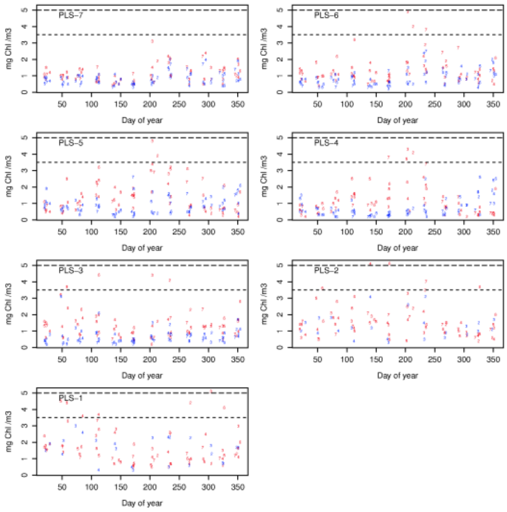
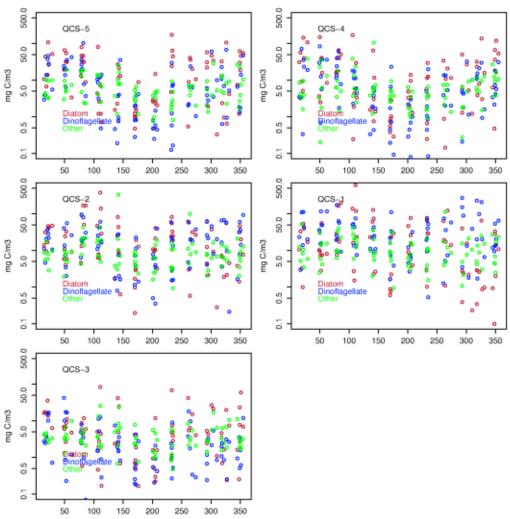
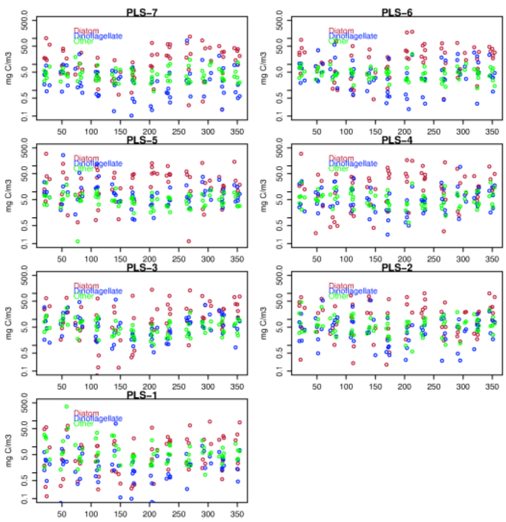
NH$_x$-N





Property	Queen Charlotte	Pelorus
DON		
PN		
PC		

Property	Queen Charlotte	Pelorus
PN:PC		
TN		
VSS		

Property	Queen Charlotte	Pelorus
Chl		
Algal carbon		

# Appendix C	Probability distributions in the Queen Charlotte water-quality data

The following figures illustrate the probability distributions of the recorded water-quality values. For each quantity, records were aggregated by position-within-water-column (near-surface or near-bed) and season-of-year. The members of each aggregate were then binned into bands of concentration/ abundance and the number of records within each bin was recorded. Note that no distinction is drawn between the different stations (QCS-1 – QCS-5). Data-records which Table 7-1 describes as having been rejected were also rejected prior to this analysis.

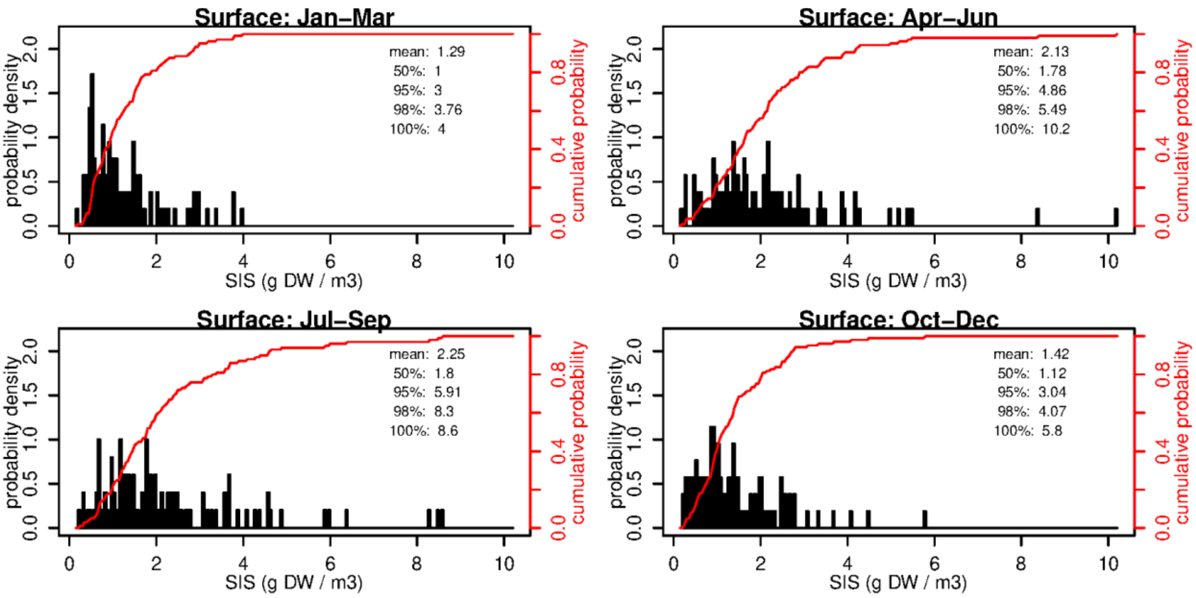


Figure C-1: Empirical probability density distributions for the concentration of near-surface suspended inorganic solids in Queen Charlotte Sound/Tory Channel. The inset text indicates the concentrations corresponding to the 50 (i.e., median), 95, 98 and 100 percentiles.

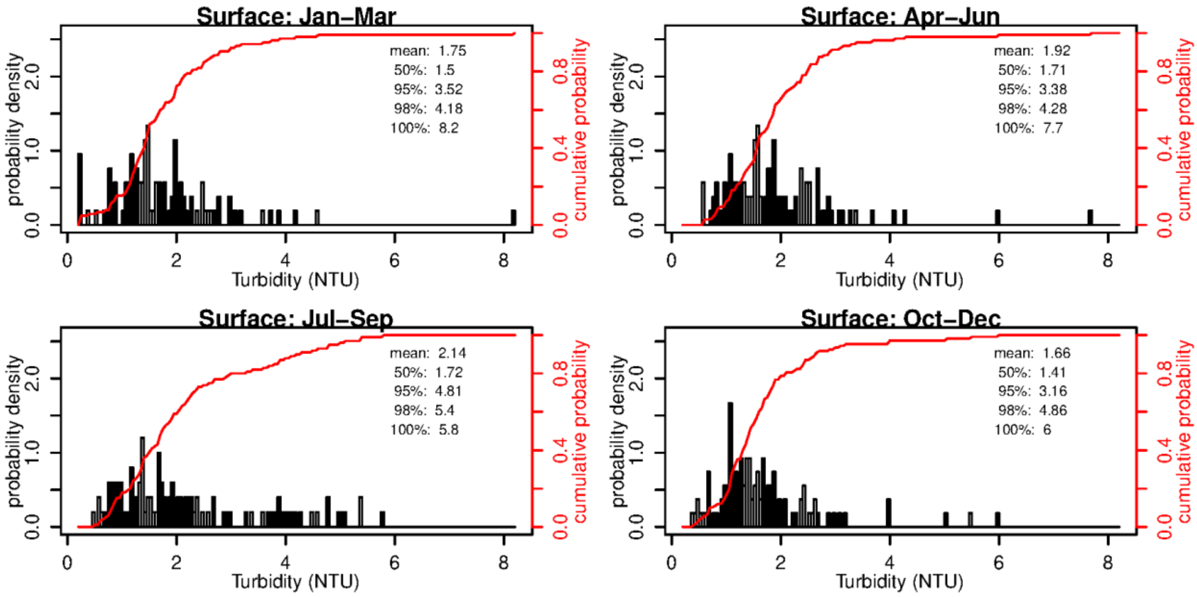


Figure C-2: Empirical probability density distributions for near-surface turbidity in Queen Charlotte Sound/Tory Channel.

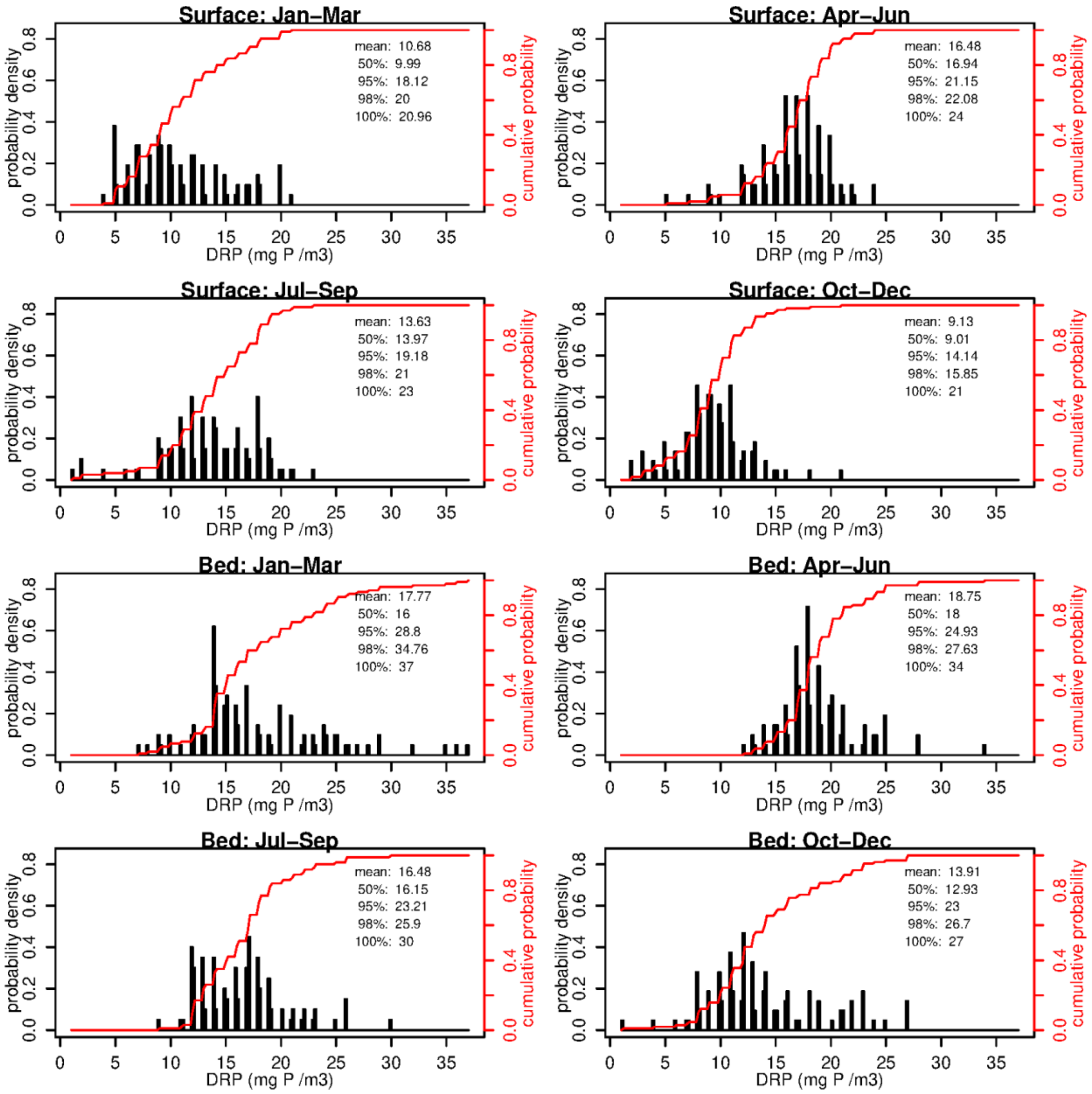


Figure C-3: Empirical probability density distributions for near-surface and near-bed dissolved reactive phosphorus in Queen Charlotte Sound/Tory Channel.

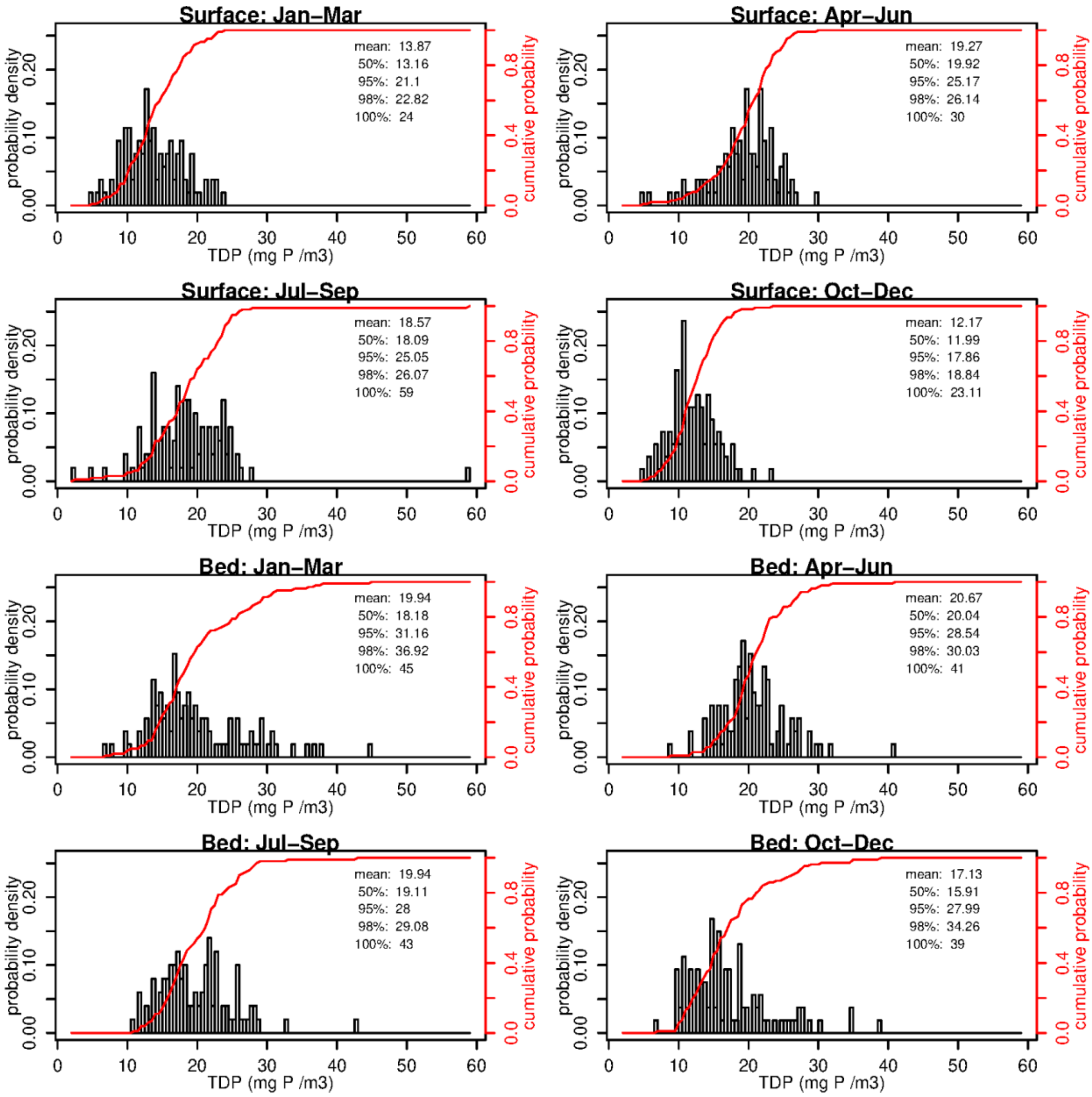


Figure C-4: Empirical probability density distributions for near-surface and near-bed total dissolved phosphorus in Queen Charlotte Sound/Tory Channel.

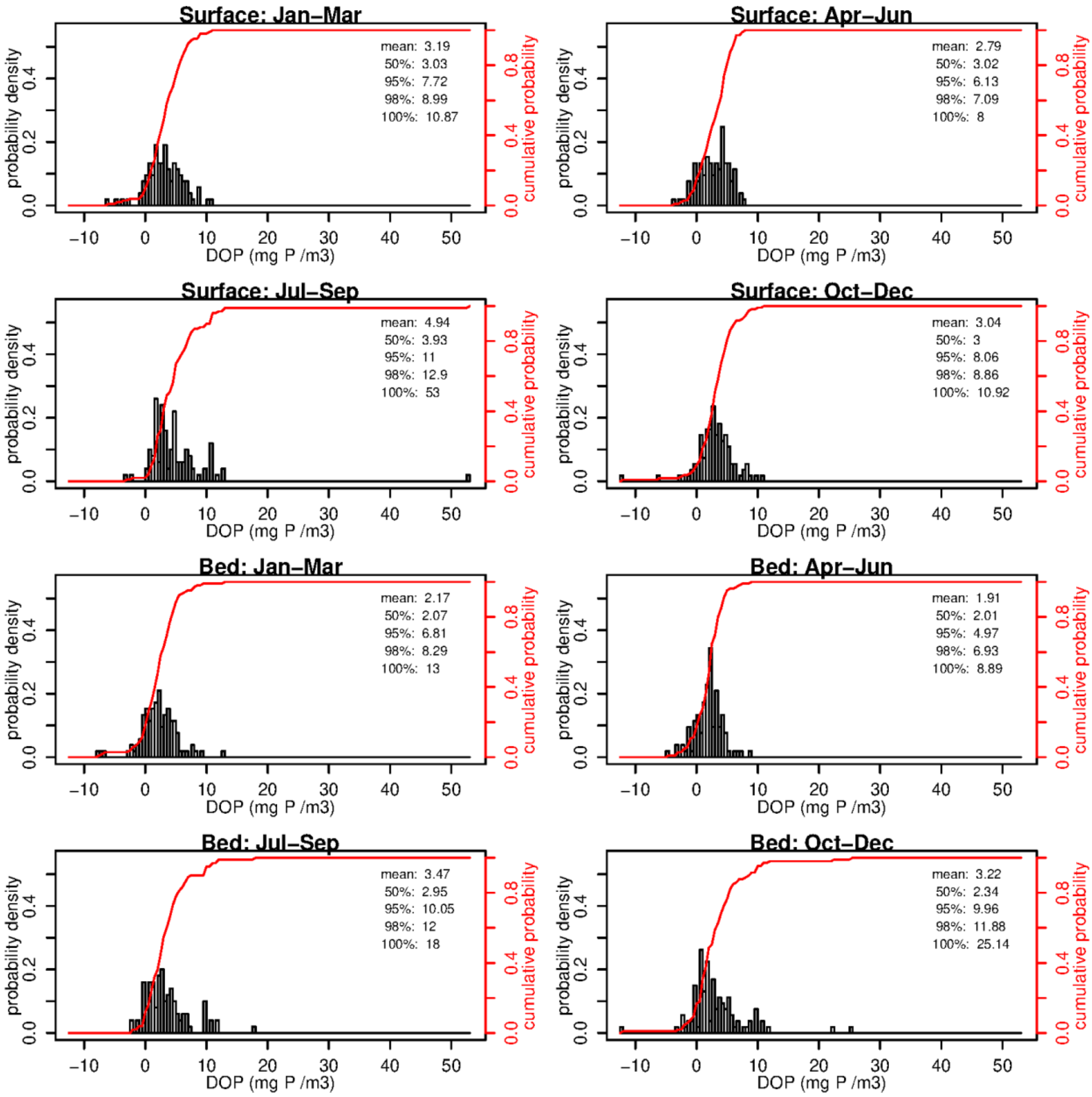


Figure C-5: Empirical probability density distributions for near-surface and near-bed dissolved organic phosphorus in Queen Charlotte Sound/Tory Channel. Dissolved organic phosphorus is calculated by difference; measurement errors in the underlying terms for TDP and DRP can (seemingly) induce negative DOP.

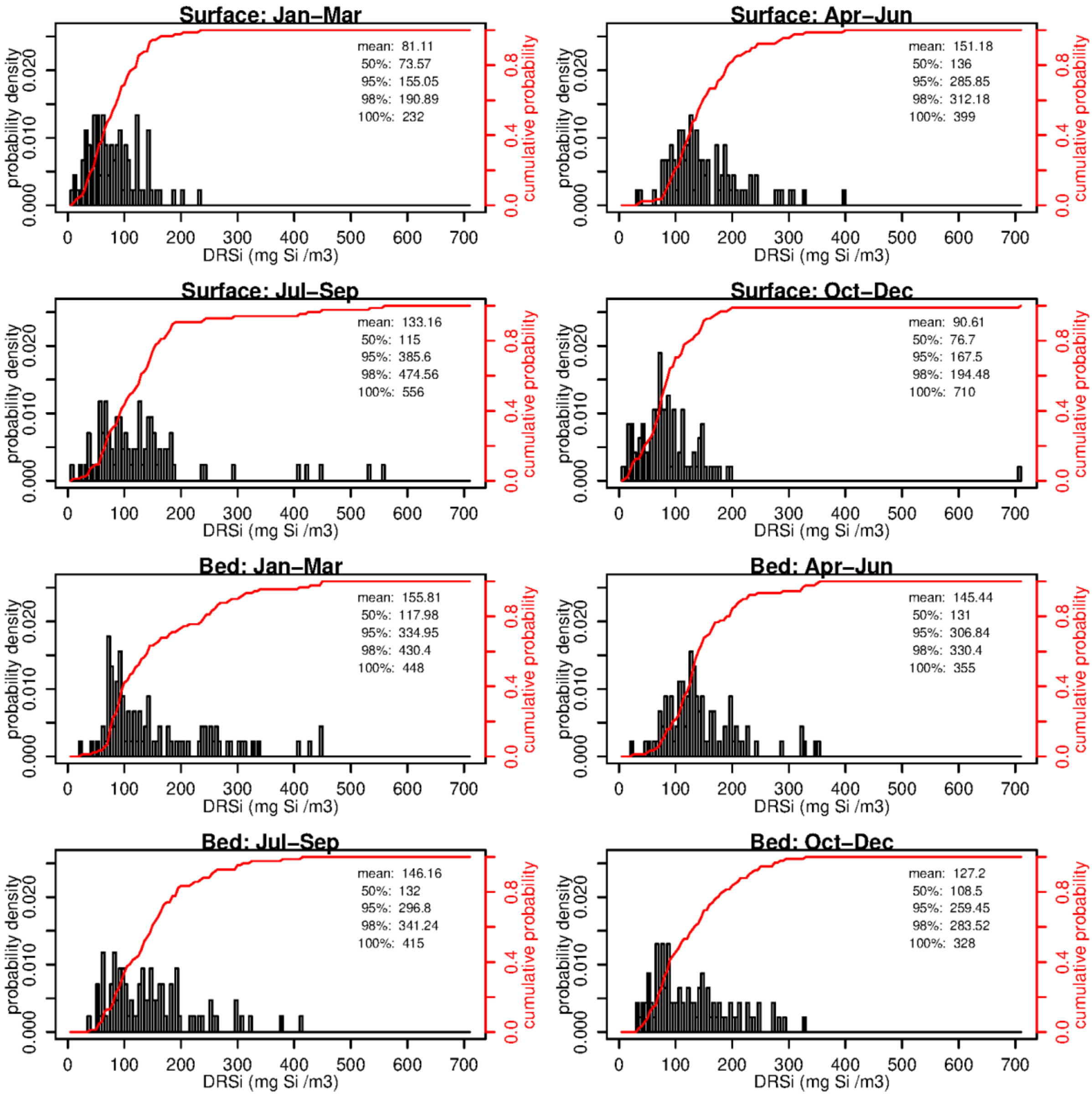


Figure C-6: Empirical probability density distributions for near-surface and near-bed dissolved reactive silicon in Queen Charlotte Sound/Tory Channel.

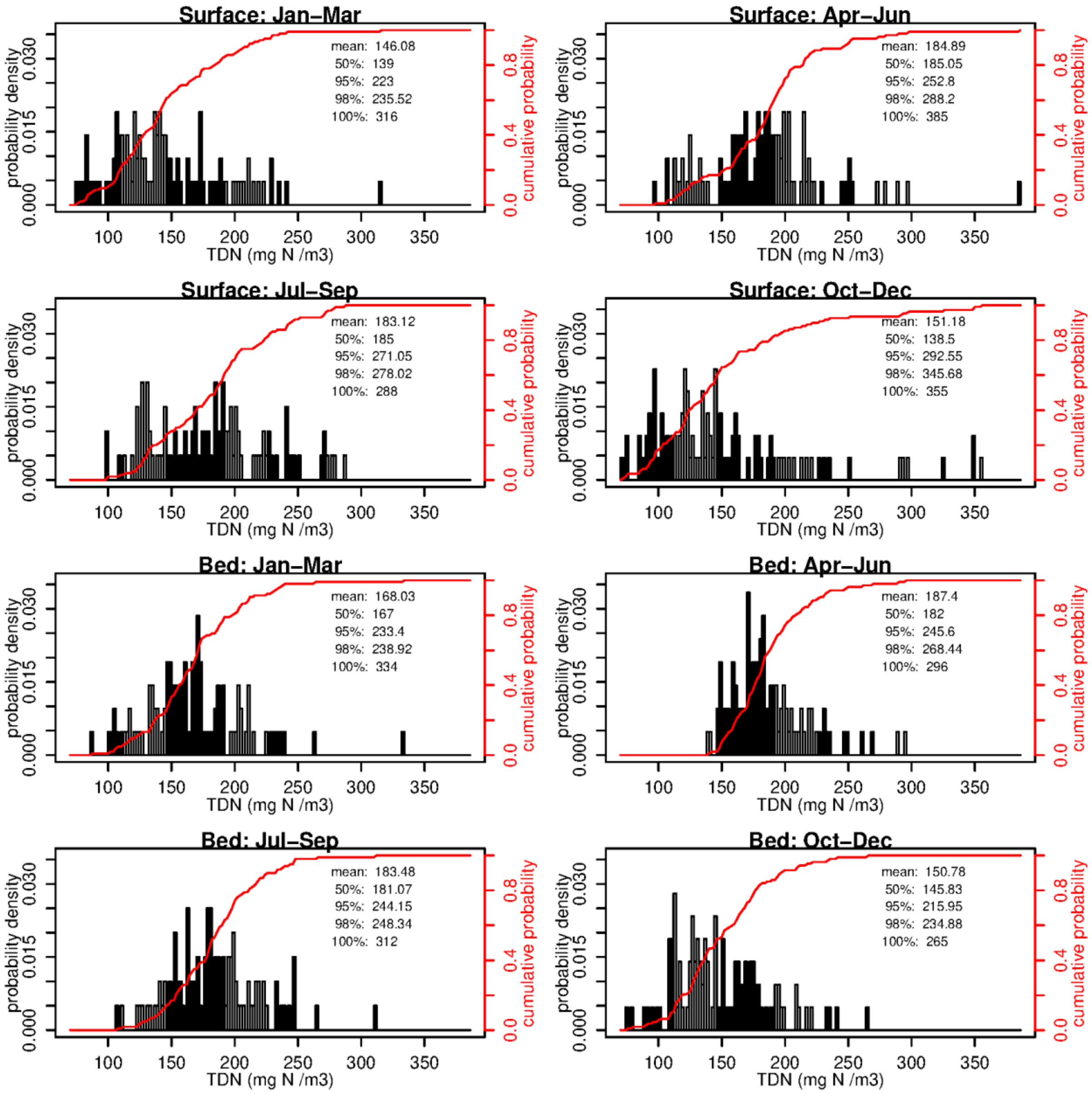


Figure C-7: Empirical probability density distributions for near-surface and near-bed total dissolved nitrogen in Queen Charlotte Sound/Tory Channel.

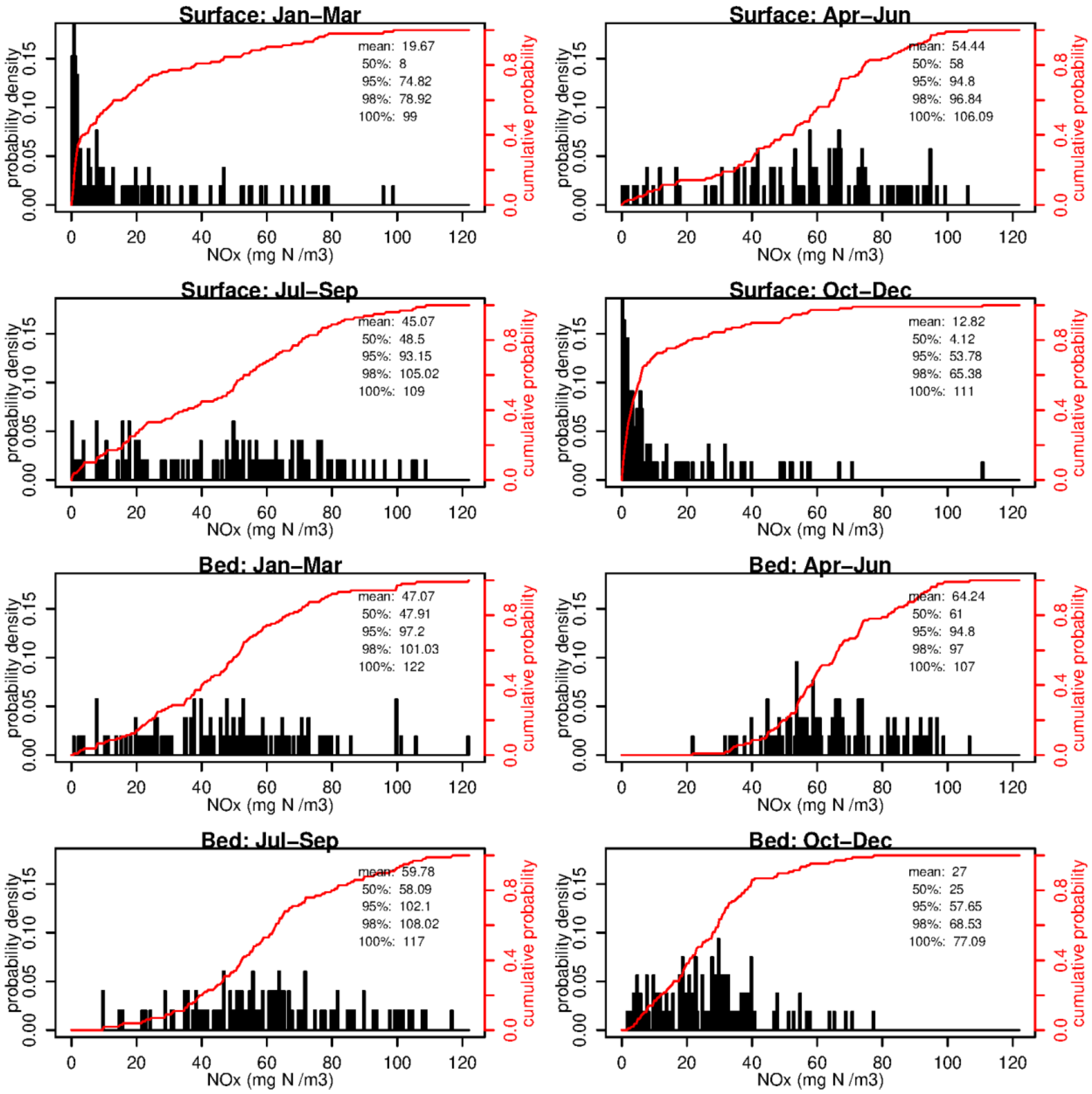


Figure C-8: Empirical probability density distributions for near-surface and near-bed nitrate in Queen Charlotte Sound/Tory Channel.

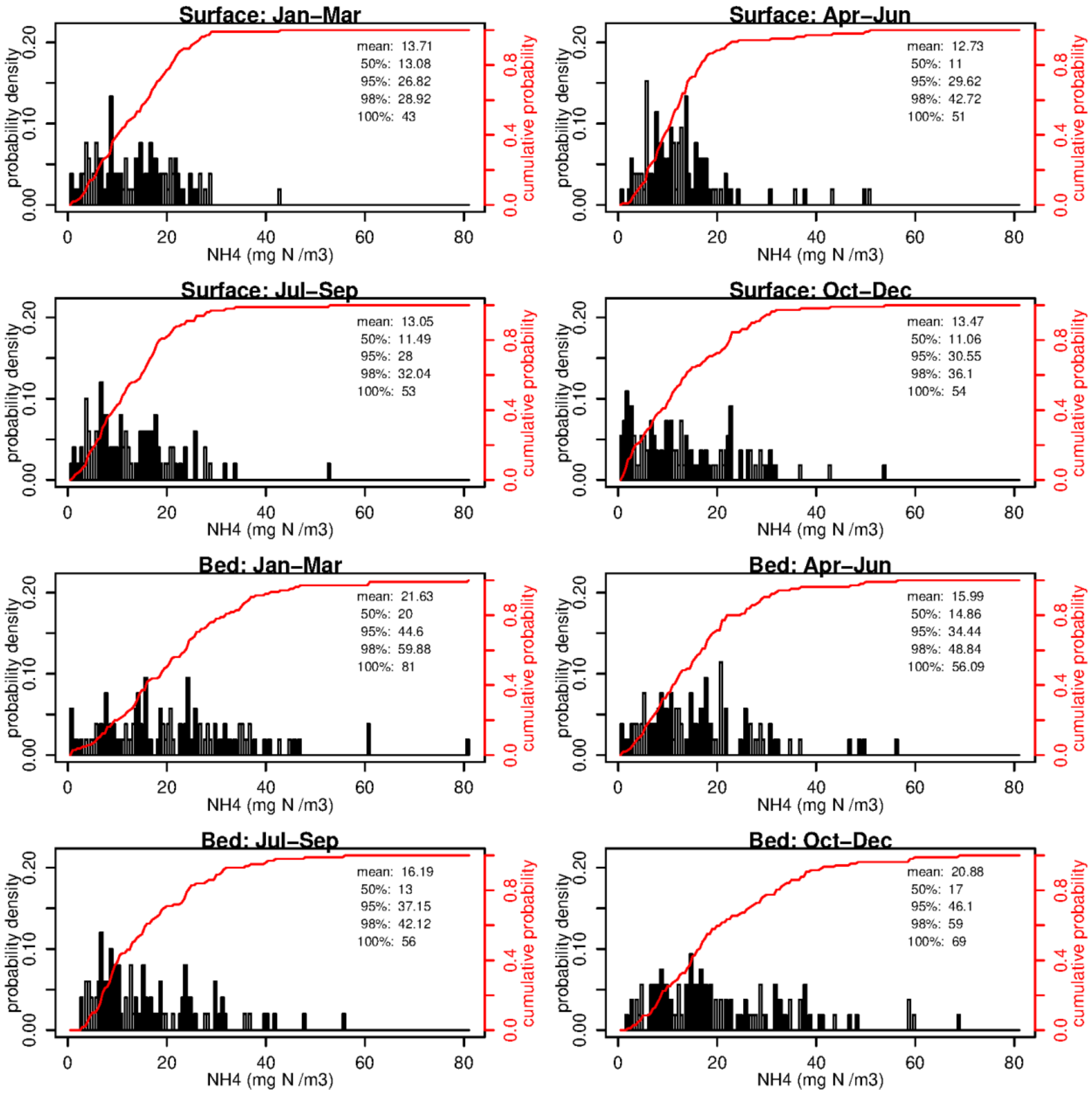


Figure C-9: Empirical probability density distributions for near-surface and near-bed ammoniacal nitrogen in Queen Charlotte Sound/Tory Channel.

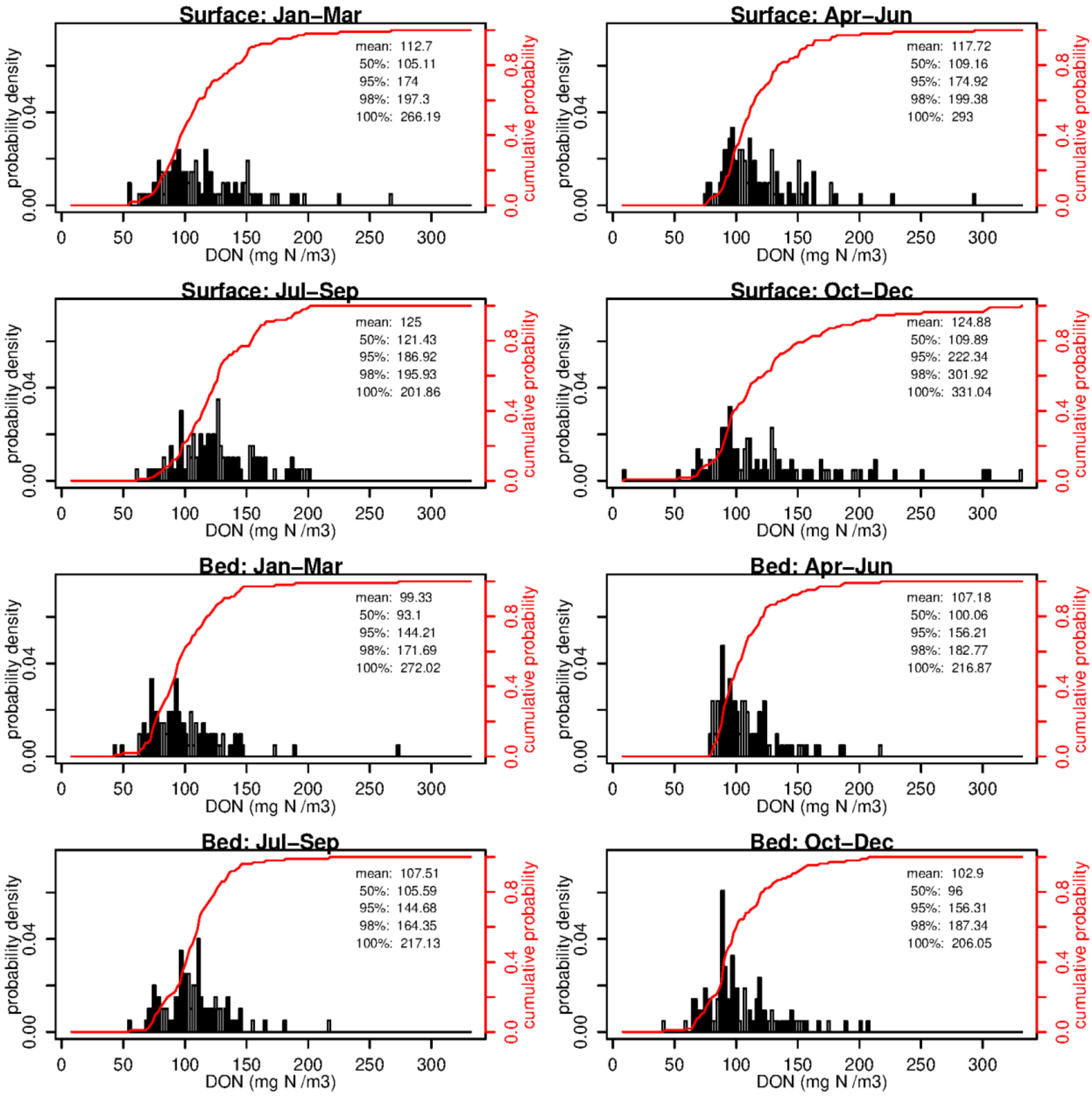


Figure C-10: Empirical probability density distributions for near-surface and near-bed dissolved organic nitrogen in Queen Charlotte Sound/Tory Channel.

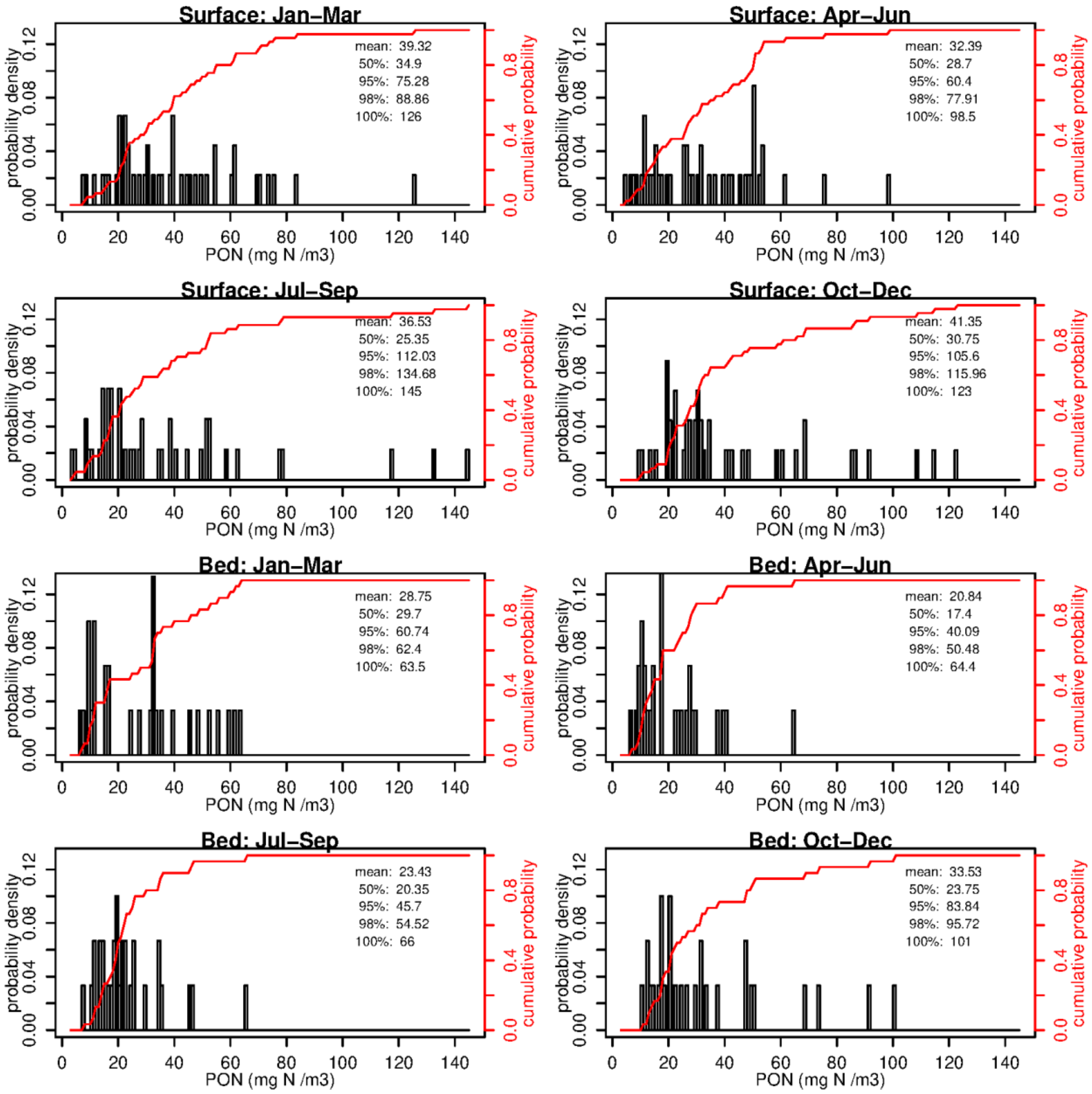


Figure C-11: Empirical probability density distributions for near-surface and near-bed particulate nitrogen (or particulate organic nitrogen in cases where that was measured instead) in Queen Charlotte Sound/Tory Channel.

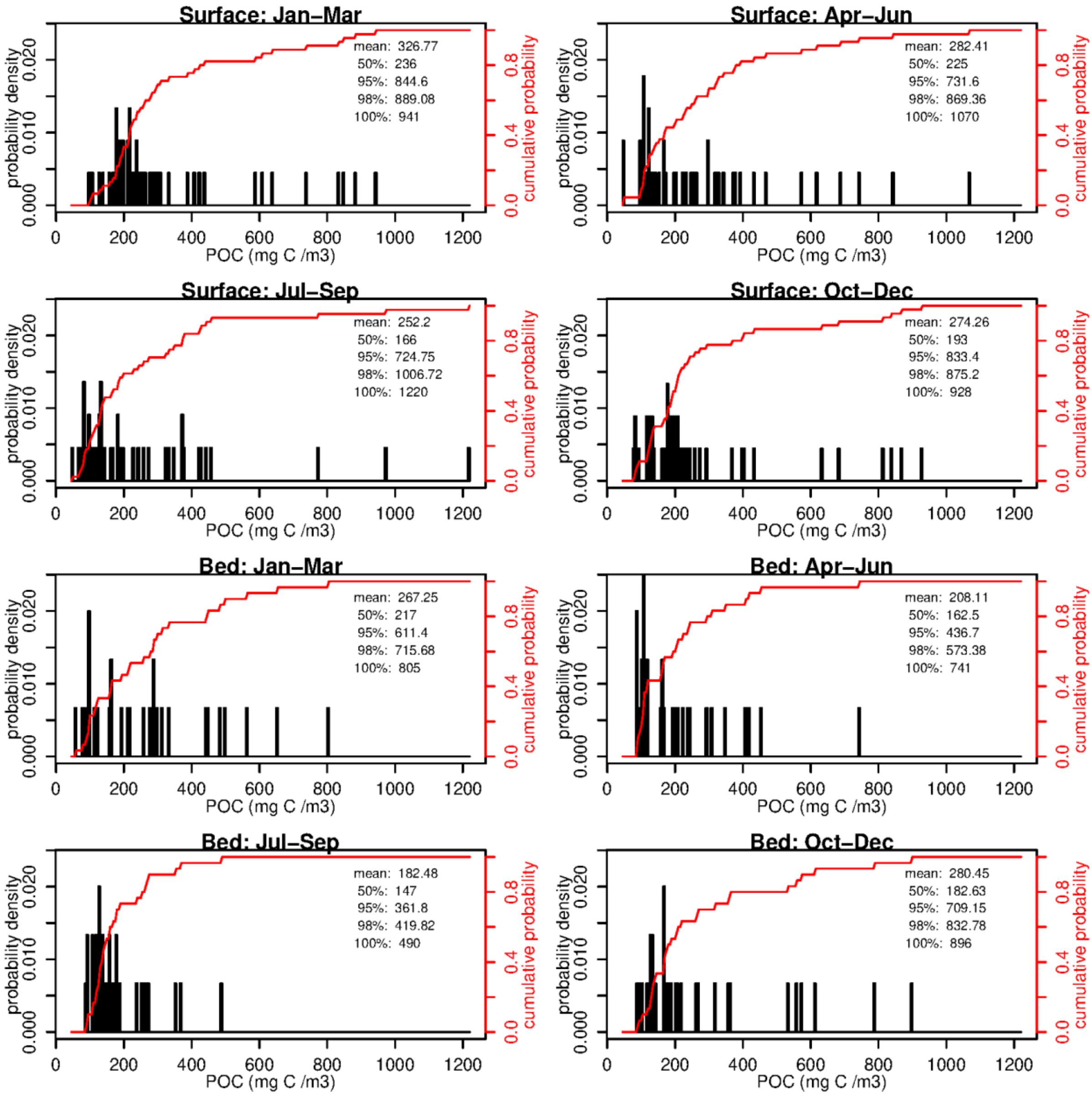


Figure C-12: Empirical probability density distributions for near-surface and near-bed particulate carbon (or particulate organic carbon where that was measured instead) in Queen Charlotte Sound/Tory Channel.

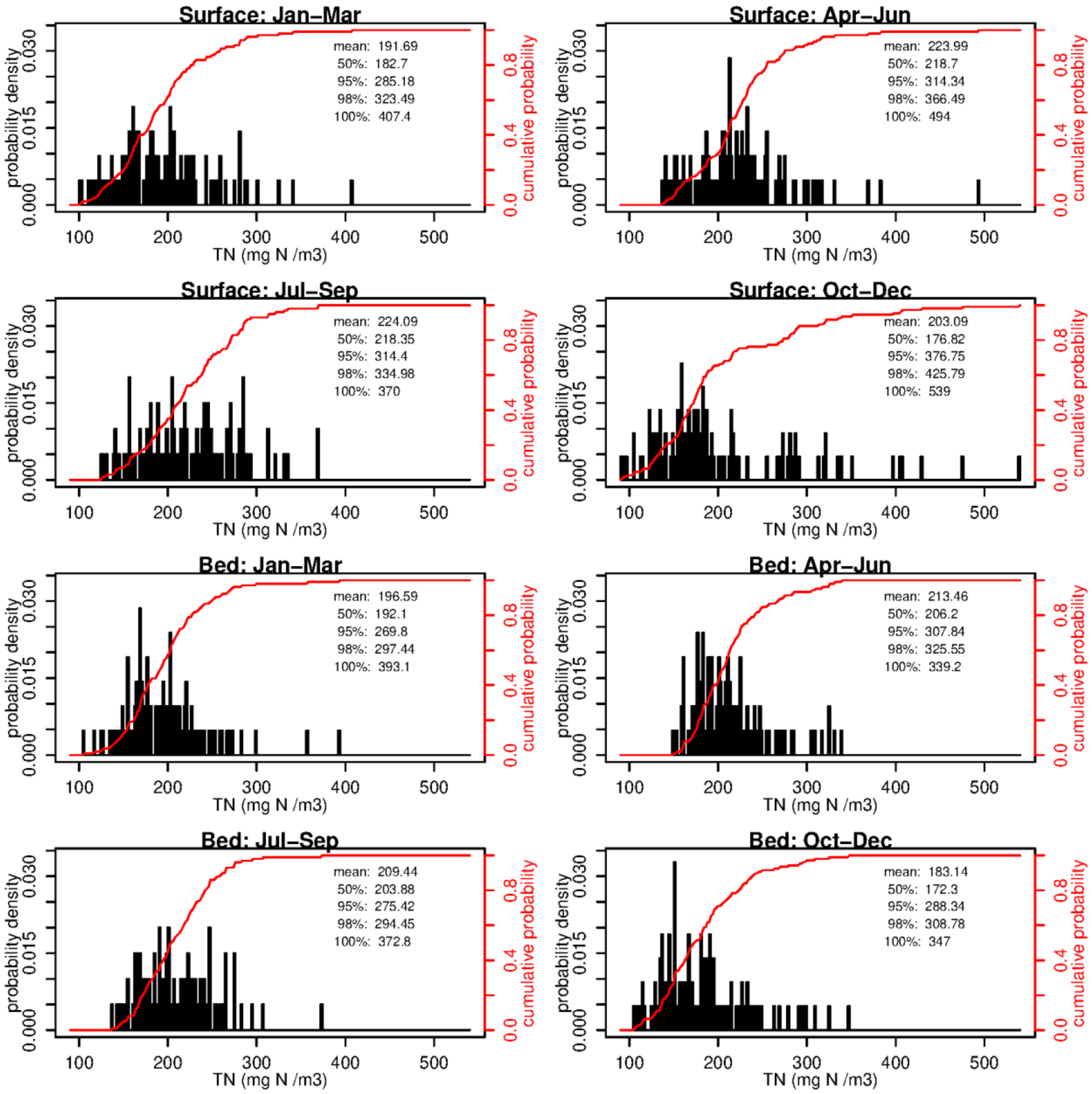


Figure C-13: Empirical probability density distributions for near-surface and near-bed total nitrogen in Queen Charlotte Sound/Tory Channel.

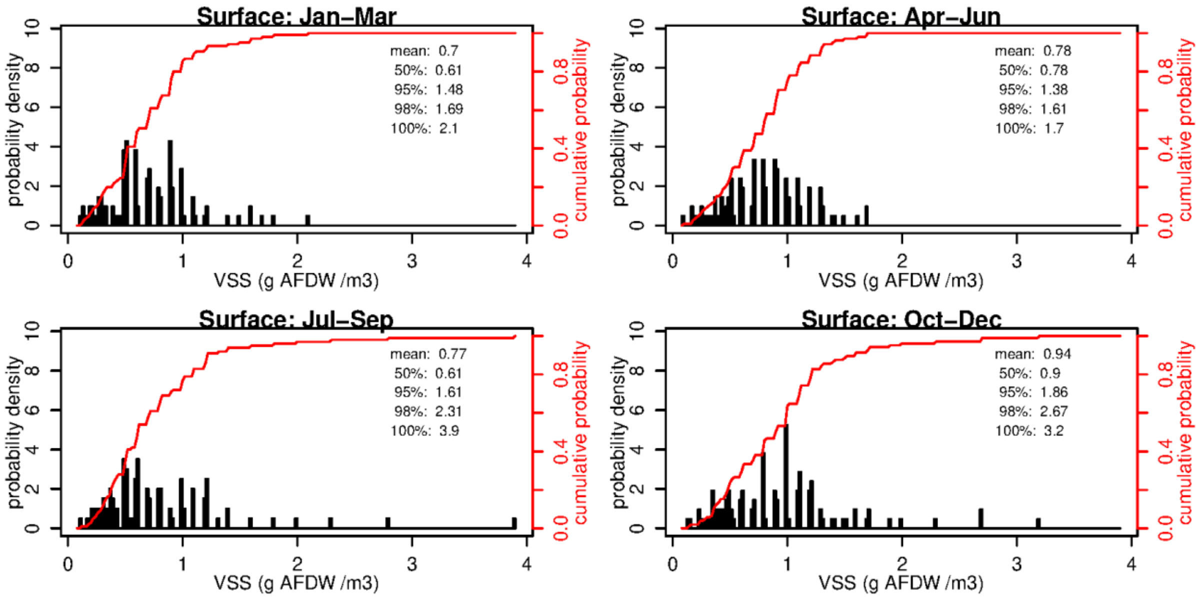


Figure C-14: Empirical probability density distributions for near-surface volatile suspended solids in Queen Charlotte Sound/Tory Channel.

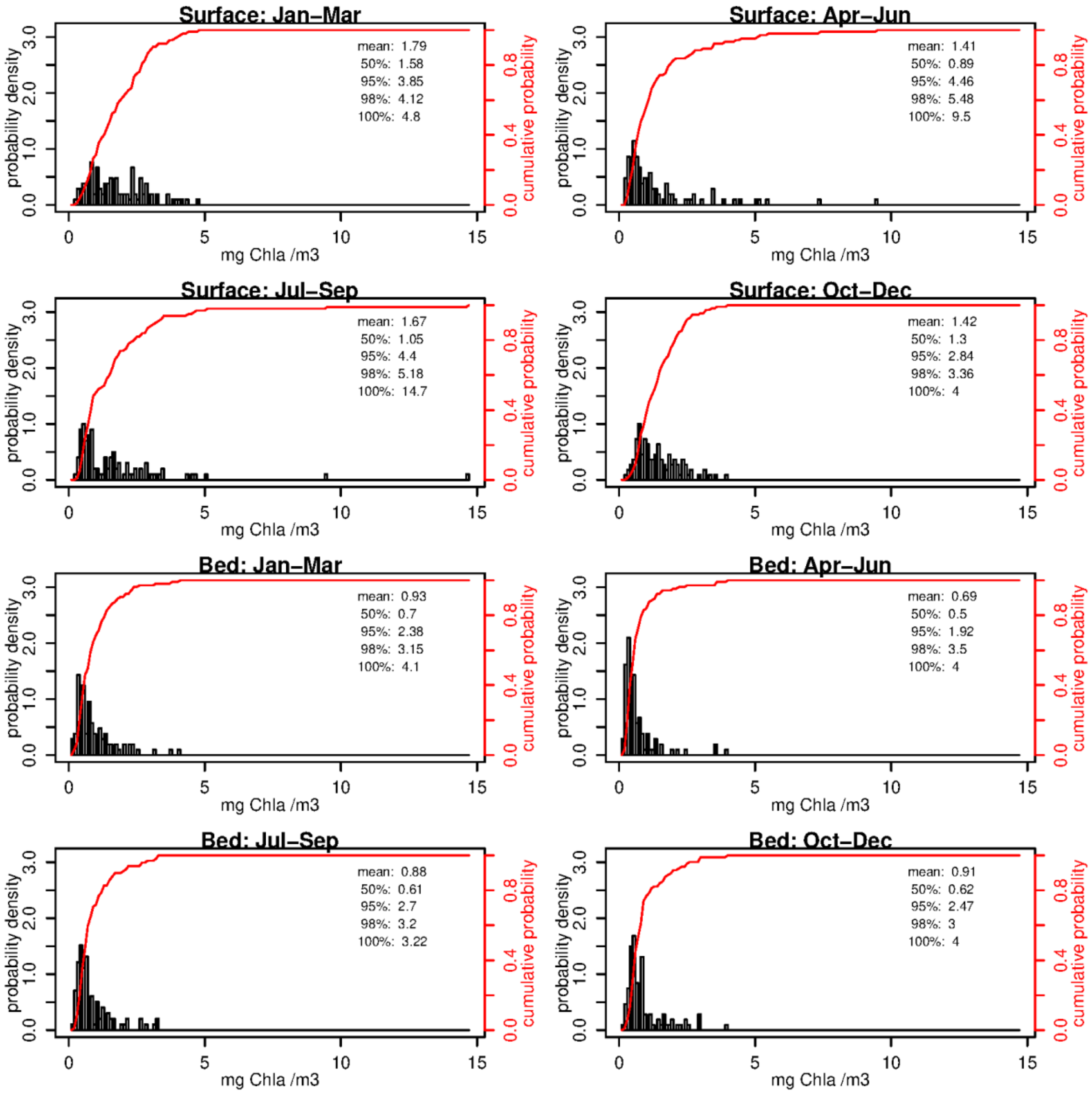


Figure C-15: Empirical probability density distributions for near-surface and near-bed chlorophyll concentration in Queen Charlotte Sound/Tory Channel.

Appendix D Probability distributions in the Pelorus water-quality data

The following figures illustrate the probability distributions of the recorded water-quality values. For each quantity, records were aggregated by position-within-water-column (near-surface or near-bed) and season-of-year. The members of each aggregate were then binned into bands of concentration/ abundance and the number of records within each bin was recorded. Note that no distinction is drawn between the different stations (PLS-1 – PLS-7). Data-records which Table 7-1 describes as having been rejected were also rejected prior to this analysis.

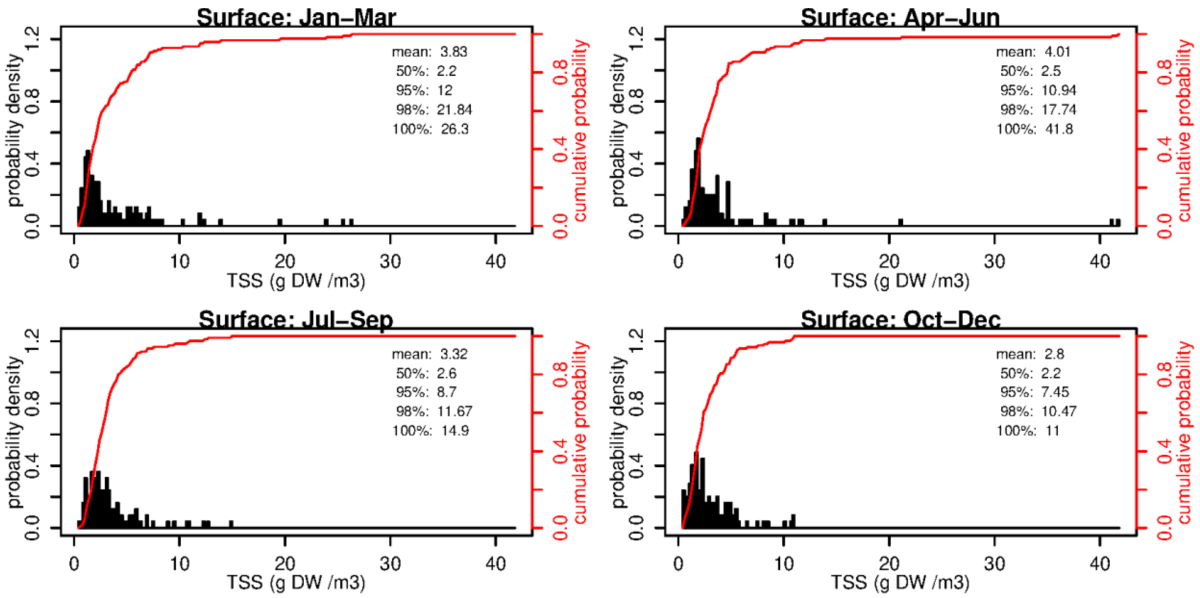


Figure D-1: Empirical probability density distributions for the concentration of near-surface suspended inorganic solids in Pelorus Sound.

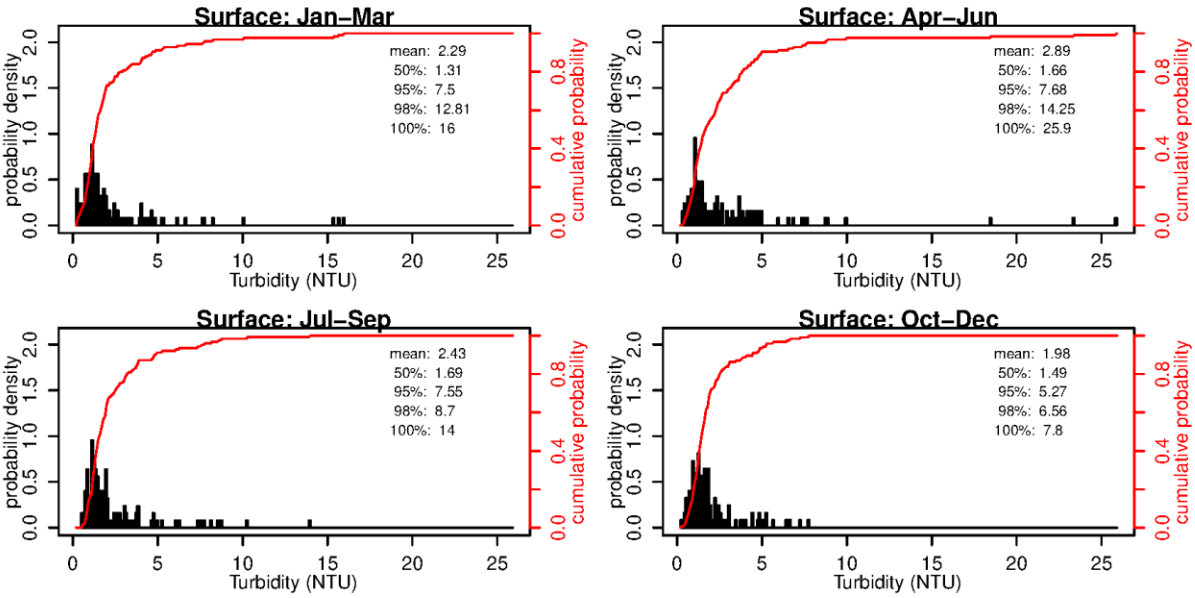


Figure D-2: Empirical probability density distributions for near-surface turbidity in Pelorus Sound.

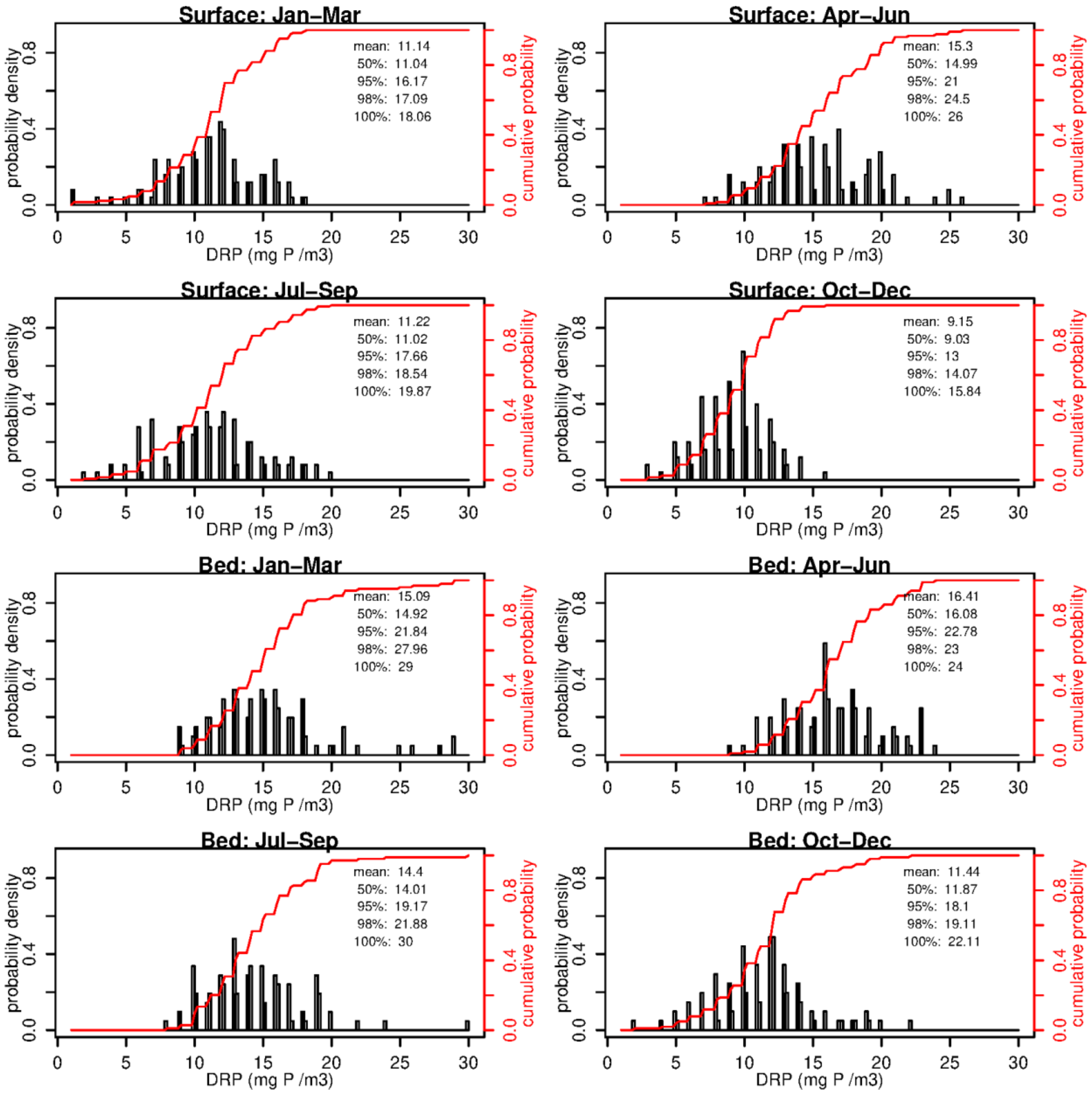


Figure D-3: Empirical probability density distributions for near-surface and near-bed dissolved reactive phosphorus in Pelorus Sound.

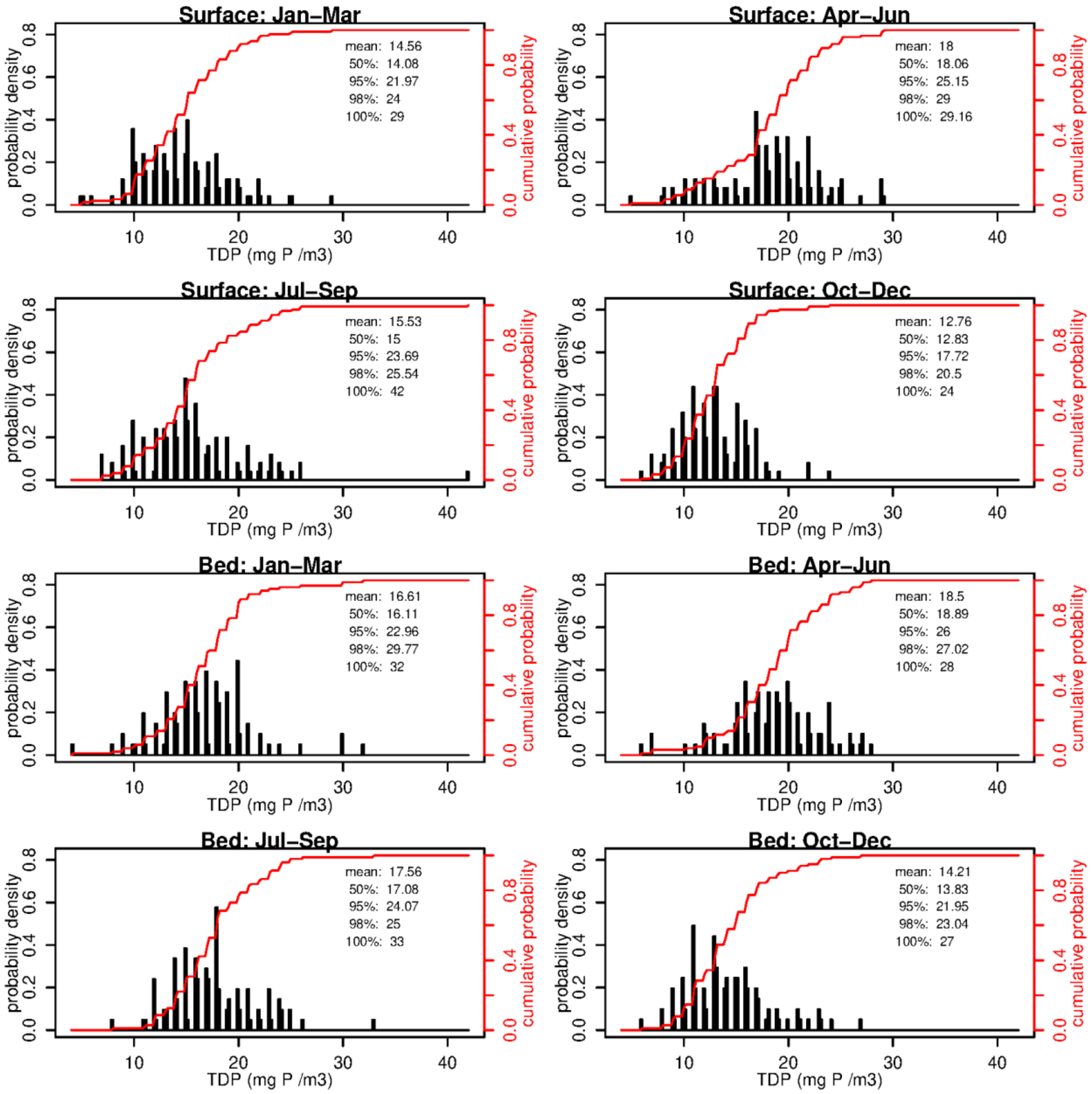


Figure D-4: Empirical probability density distributions for near-surface and near-bed total dissolved phosphorus in Pelorus Sound.

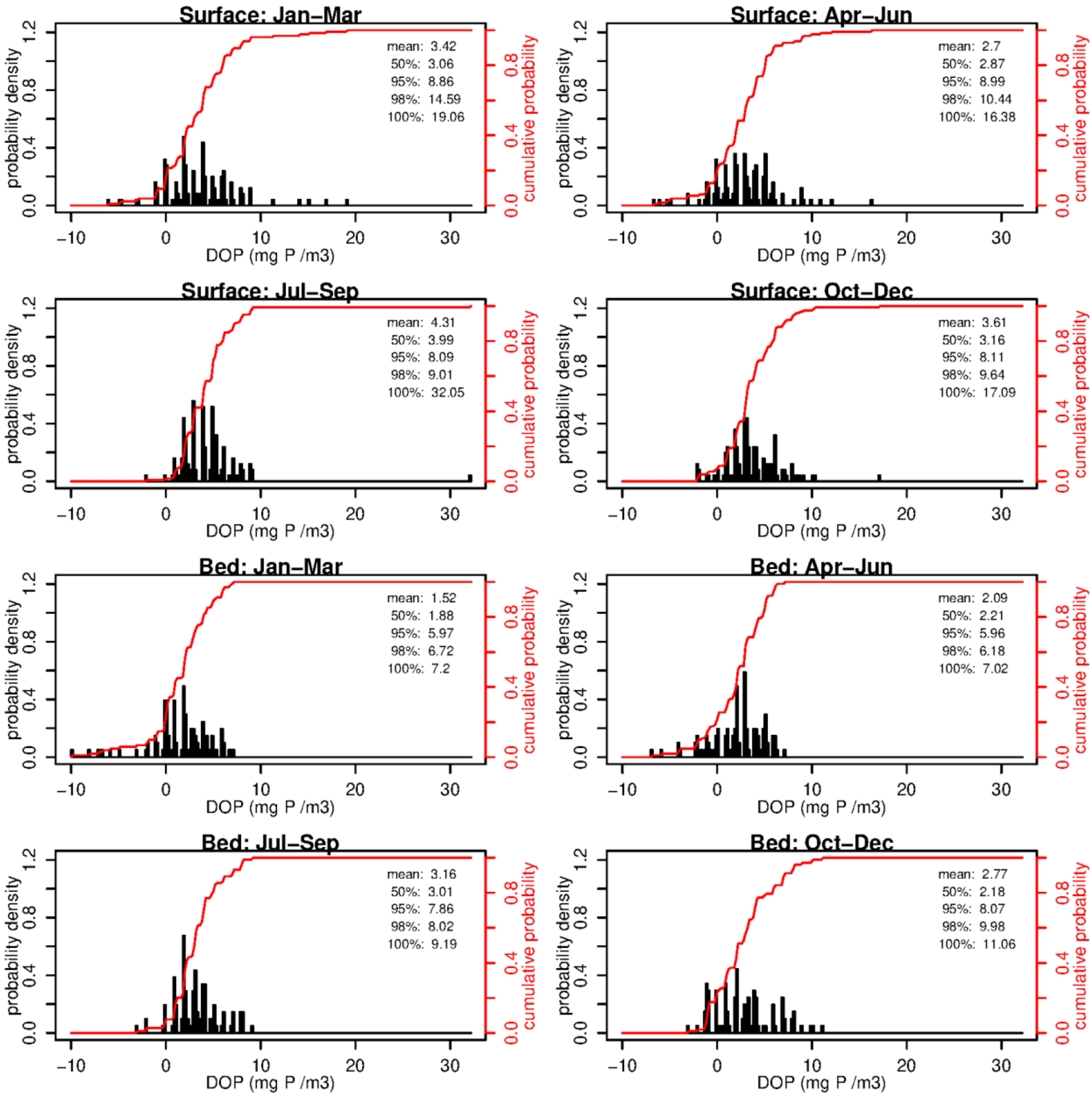


Figure D-5: Empirical probability density distributions for near-surface and near-bed dissolved organic phosphorus in Pelorus Sound. Dissolved organic phosphorus is calculated by difference; measurement errors in the underlying terms for TDP and DRP can (seemingly) induce negative DOP.

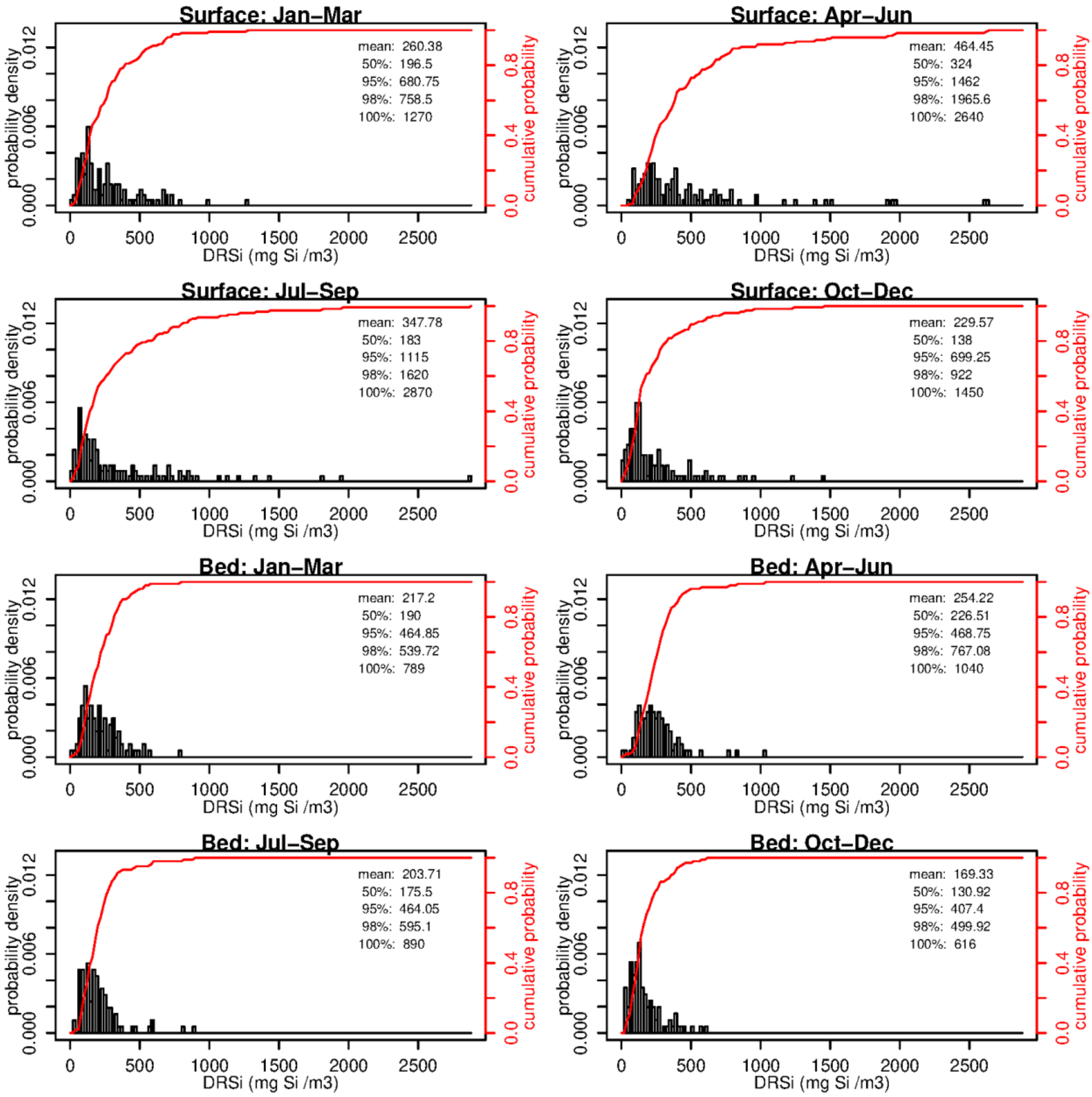


Figure D-6: Empirical probability density distributions for near-surface and near-bed dissolved reactive silicon in Pelorus Sound.

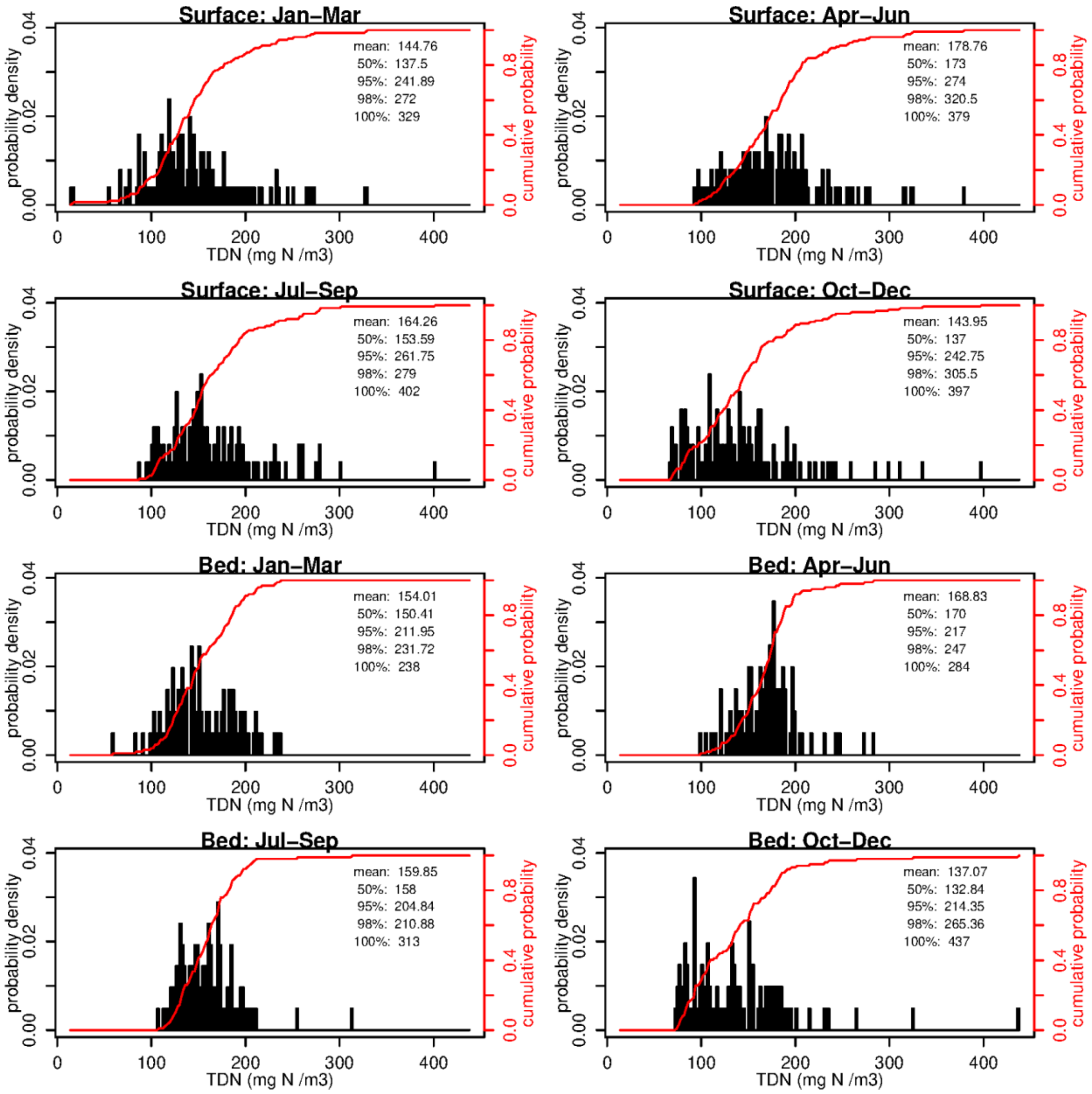


Figure D-7: Empirical probability density distributions for near-surface and near-bed total dissolved nitrogen in Pelorus Sound.

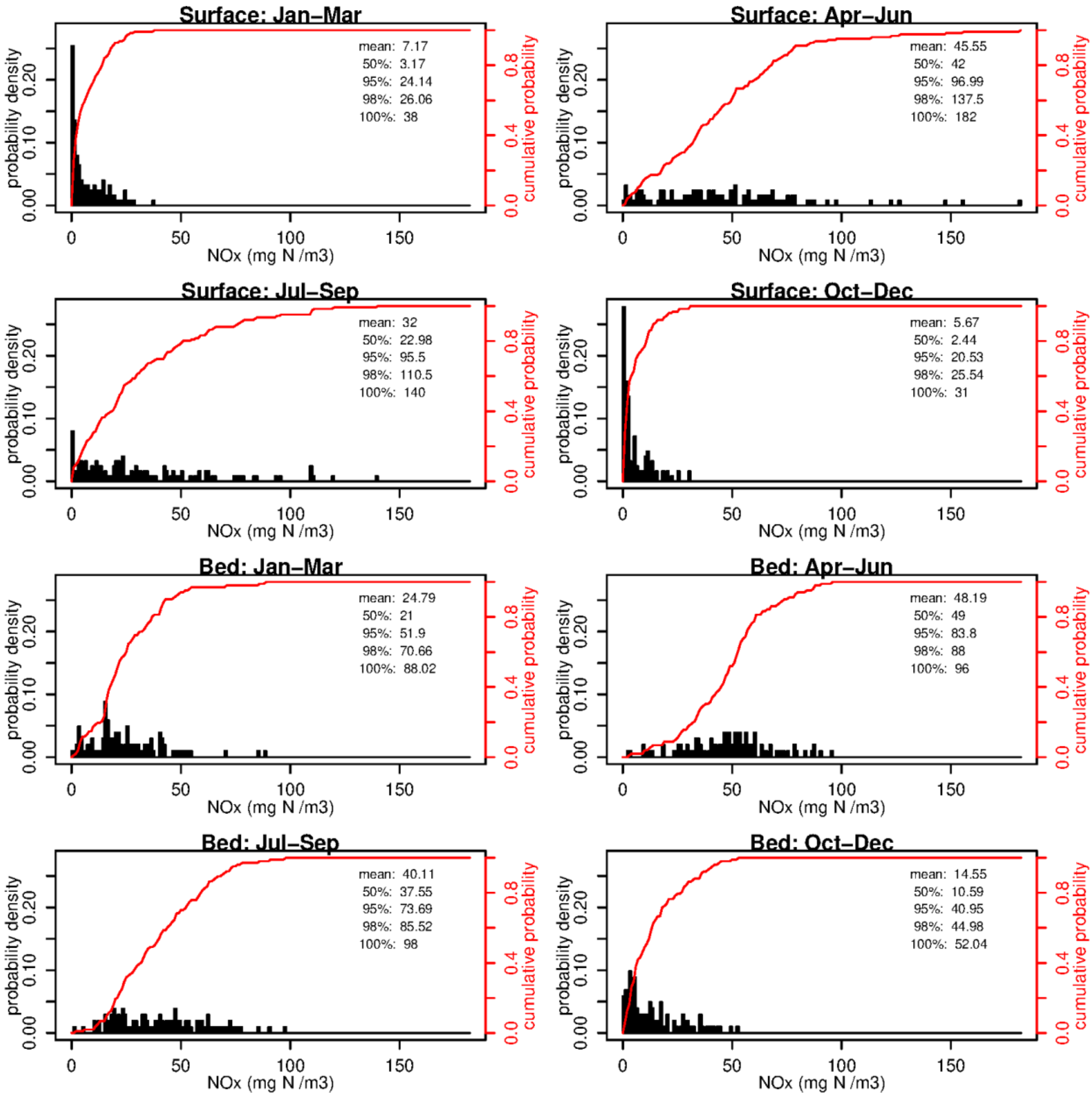


Figure D-8: Empirical probability density distributions for near-surface and near-bed nitrate in Pelorus Sound.

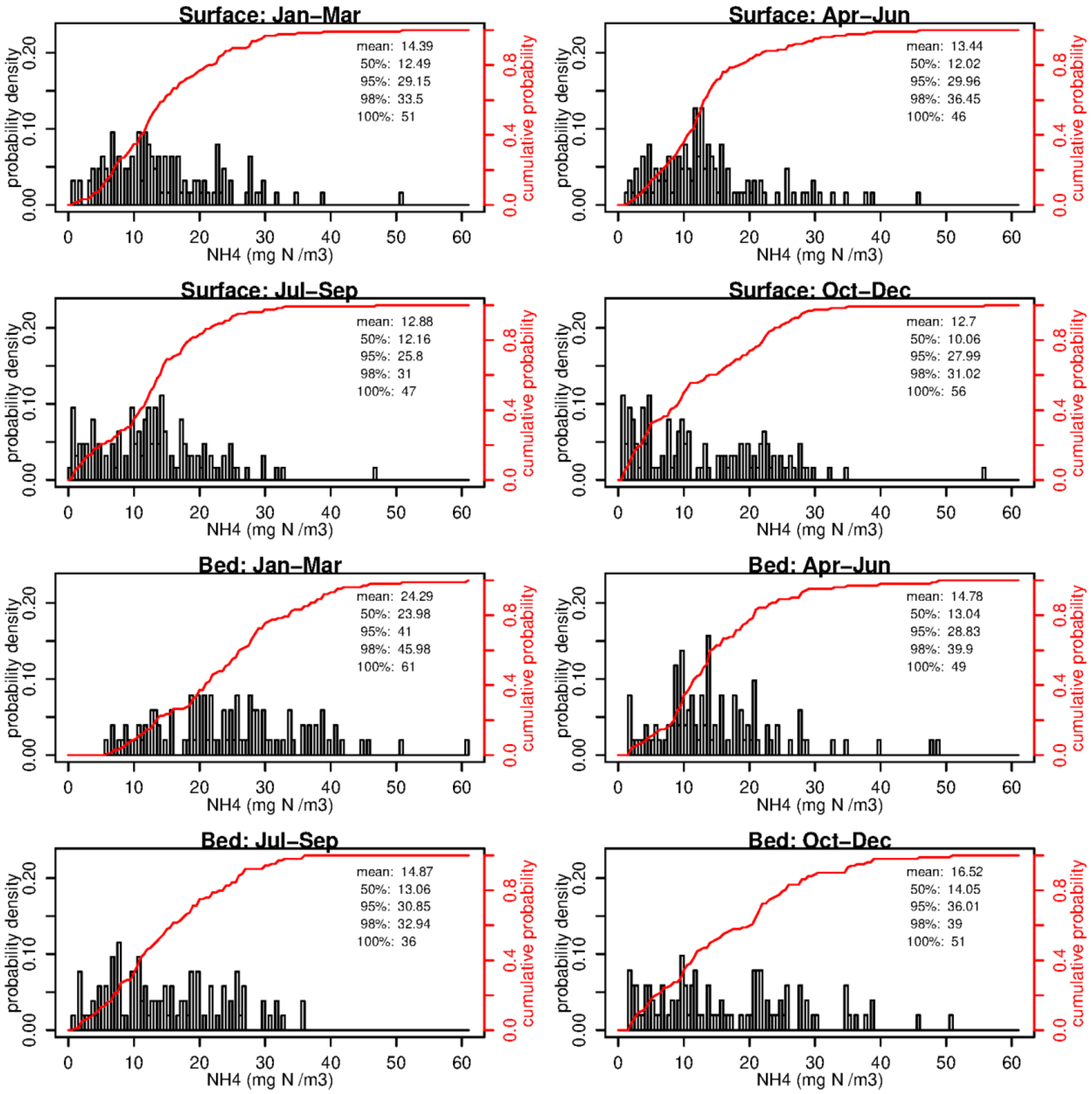


Figure D-9: Empirical probability density distributions for near-surface and near-bed ammoniacal nitrogen in Pelorus Sound.

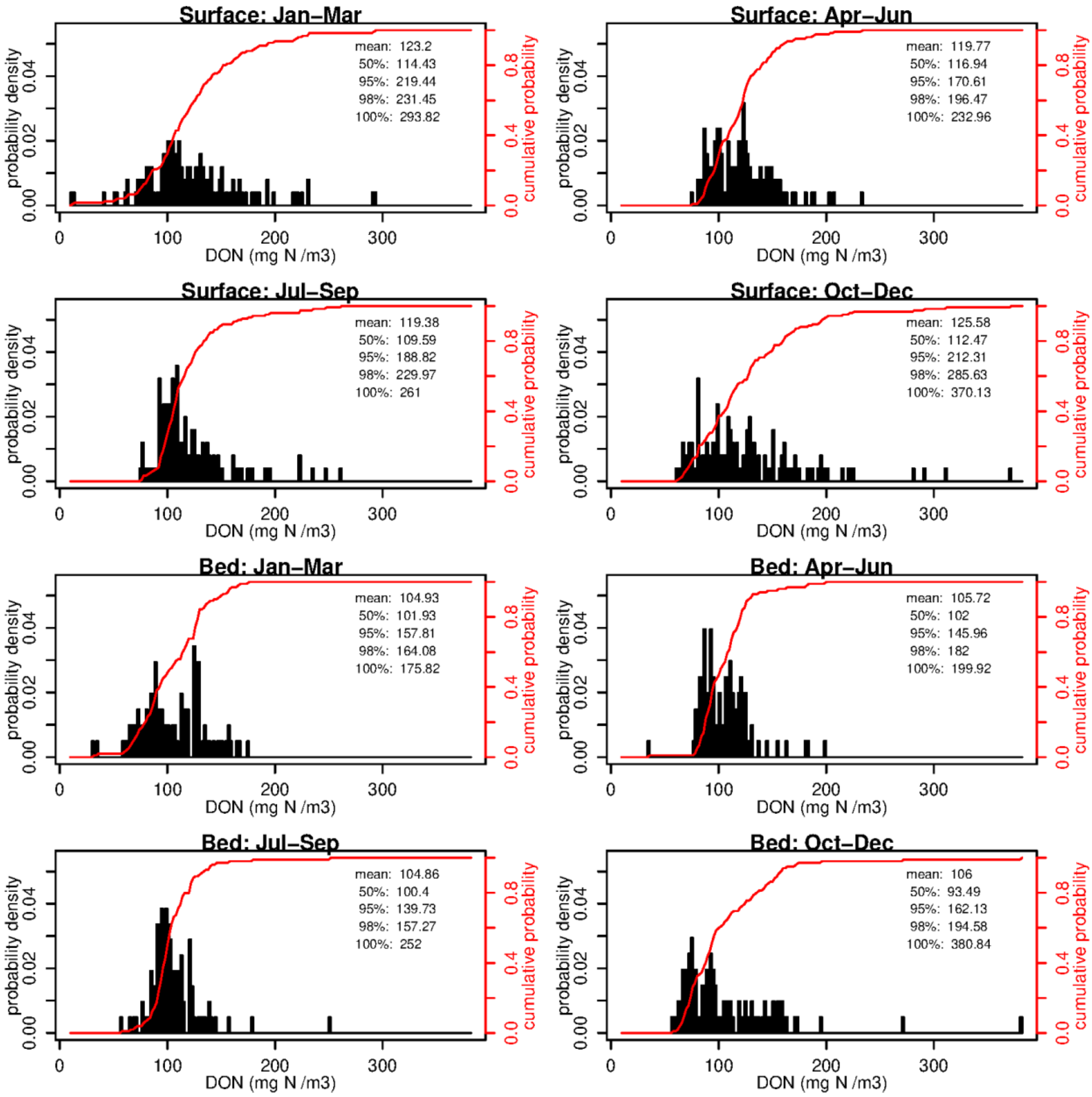


Figure D-10: Empirical probability density distributions for near-surface and near-bed dissolved organic nitrogen in Pelorus Sound.

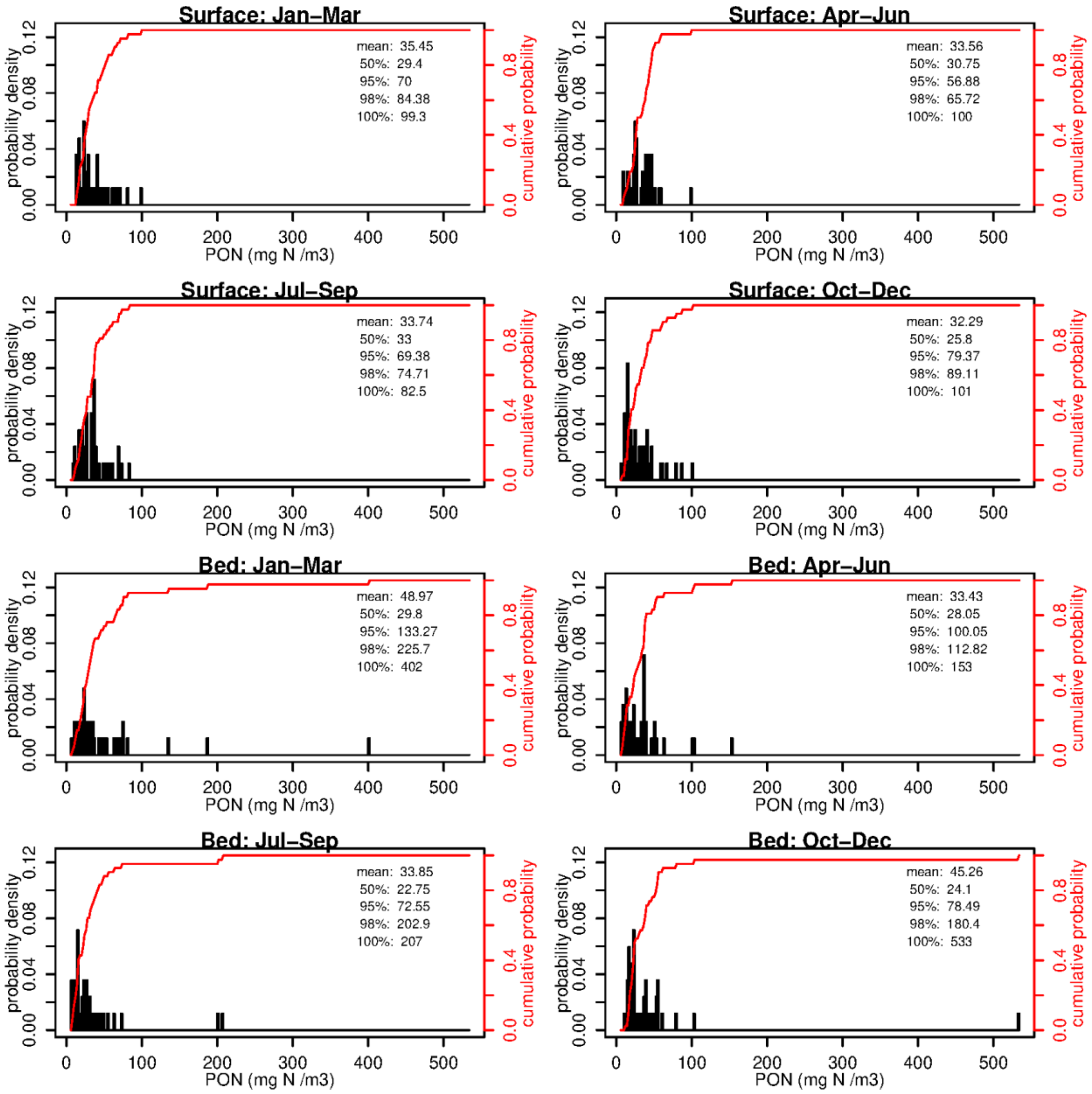


Figure D-11: Empirical probability density distributions for near-surface and near-bed particulate nitrogen (or particulate organic nitrogen in cases where that was measured instead) in Pelorus Sound.

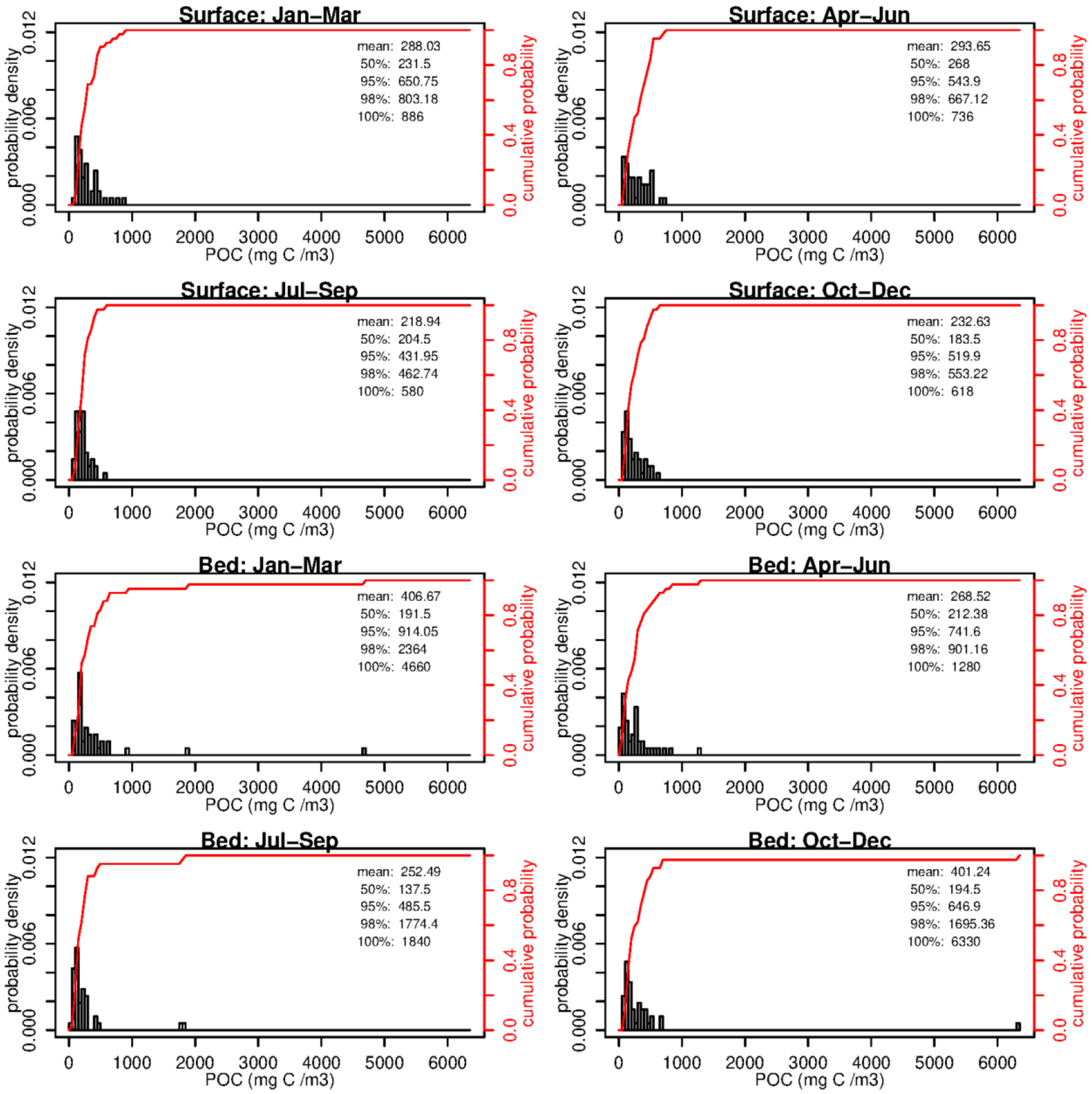


Figure D-12: Empirical probability density distributions for near-surface and near-bed particulate carbon (or particulate organic carbon where that was measured instead) in Pelorus Sound.

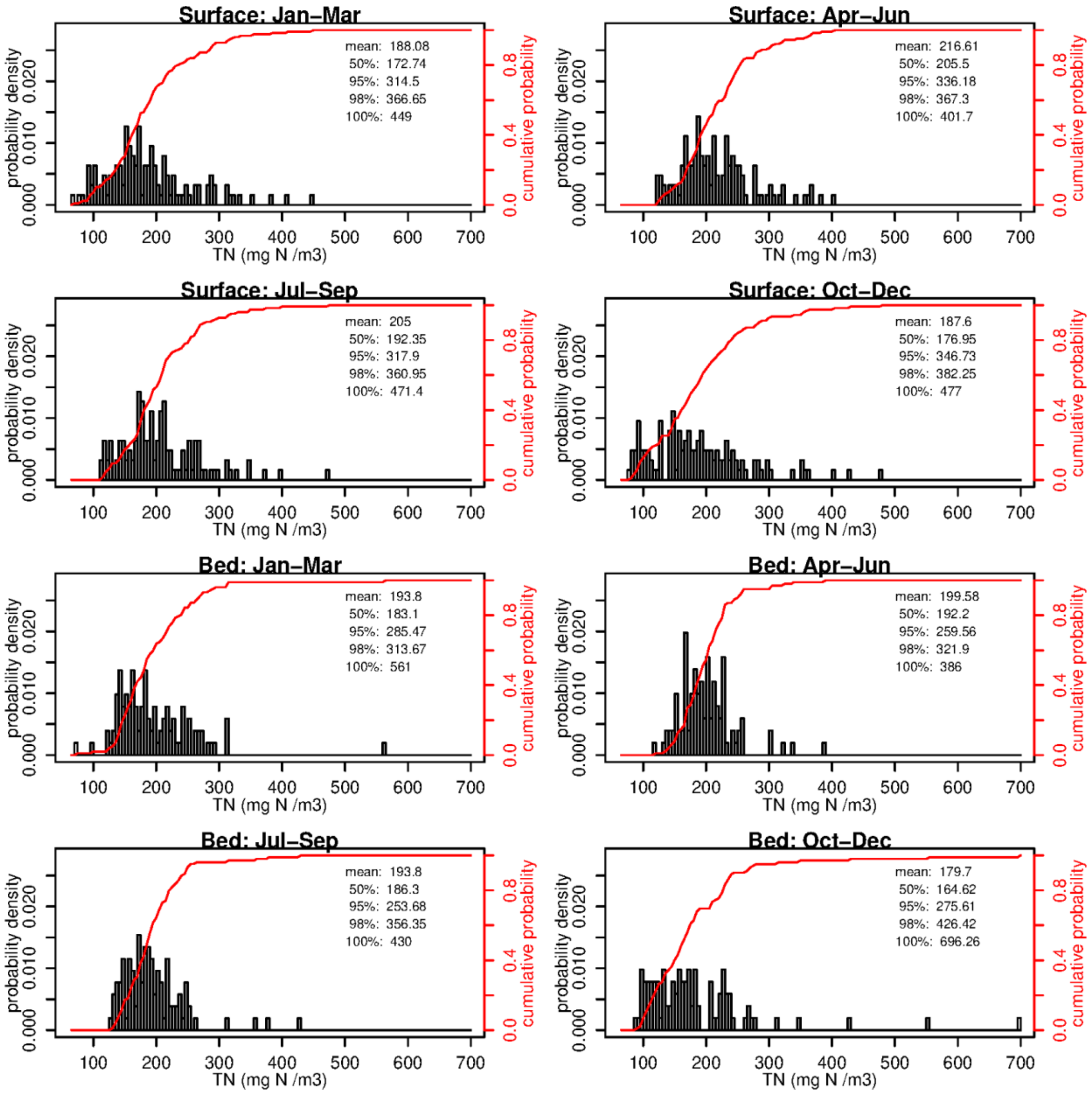


Figure D-13: Empirical probability density distributions for near-surface and near-bed total nitrogen in Pelorus Sound.

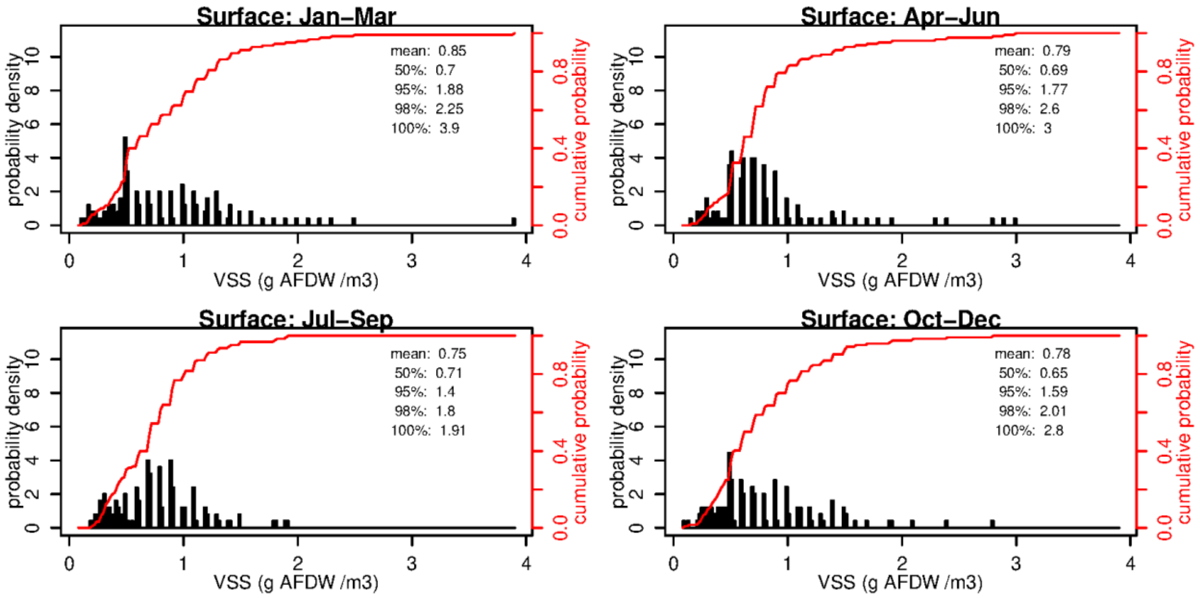


Figure D-14: Empirical probability density distributions for near-surface volatile suspended solids in Pelorus Sound.

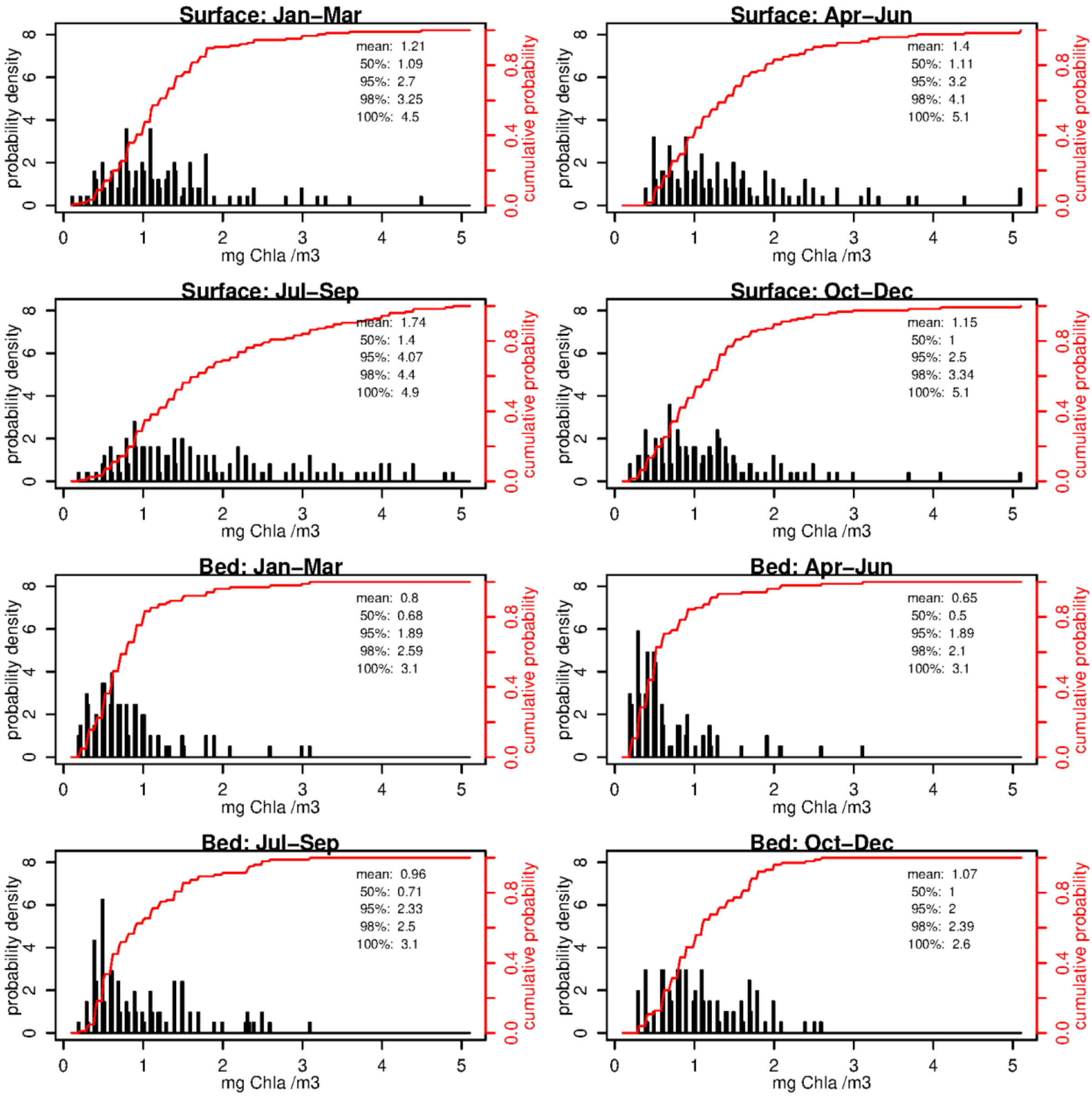


Figure D-15: Empirical probability density distributions for near-surface and near-bed chlorophyll concentration in Pelorus Sound.

Appendix E Re-calibration of CTD fluorometer data

Three different fluorometers have been used over the monitoring period. These fluorometers are sensitive to different wavelengths. To better compare CTD-fluorometer data over time, CHL-a concentrations from the water samples were compared to the CTD-fluorometer data. This comparison was used to recalibrate CTD-fluorometer data to better match the water samples and improve consistency between sensors over time. Water quality samples were available for 5 sites in Queen Charlotte Sound and 7 sites in Pelorus Sound. The 'near surface' samples were compared to fluorometer data averaged over the upper 15m, and 'near bed' samples compared to fluorometer data from 1-2m above the bed.

For each sensor, fluorometer and water sample data were plotted against each other, and a linear regression fitted. This was first done for each month. However, there was considerable scatter between fluorometer and water sample data such that it was not possible to determine if there was any significant trend or changes in the regressions over time for each sensor (other than for a two-month period for one sensor). Similarly, no difference could be detected in the regression fits for a sensor between Pelorus and Queen Charlotte Sound. Therefore, data from both sounds were combined, and a single regression developed for each sensor.

There was a discernible difference in calibration for the NIWA YSI exosonde for the period Jan-Feb 2014. A separate calibration adjusted was calculated for this period.

Plots of the CTD-derived and water sample CHL-*a*, and regressions between these, are plotted in figures E-1 to E-5.

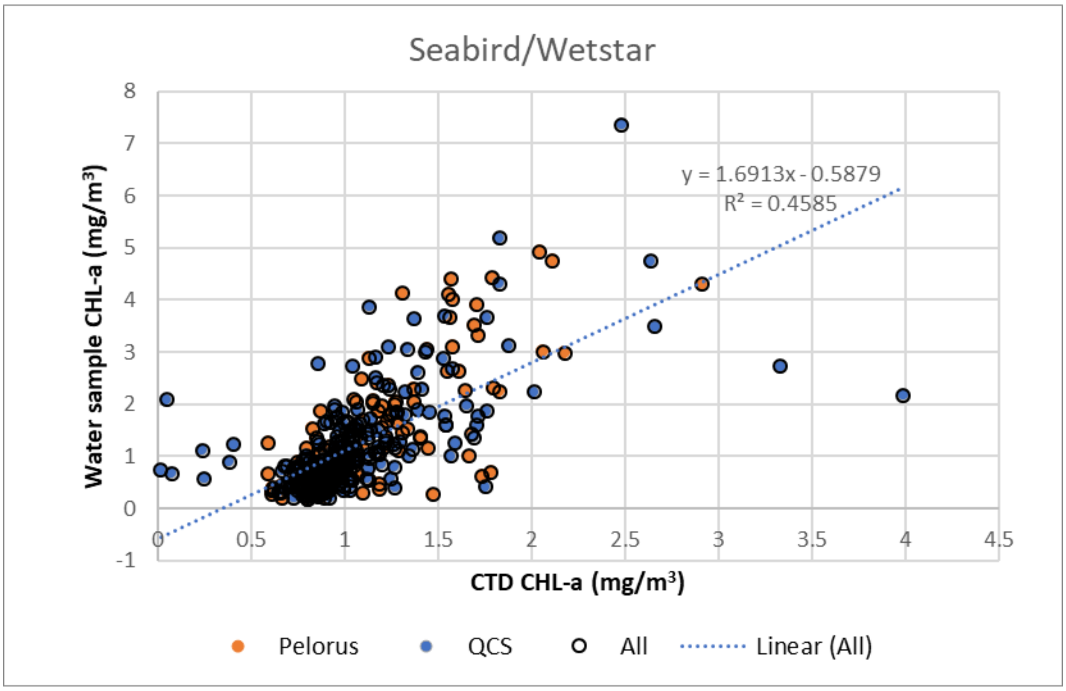


Figure E-1: Chl-a concentrations from the seabird CTD (Serial number 4248) and water samples. The regression shown was used to adjust CTD CHL-a measurements from July 2011 to July 2013, and April-May 2014.

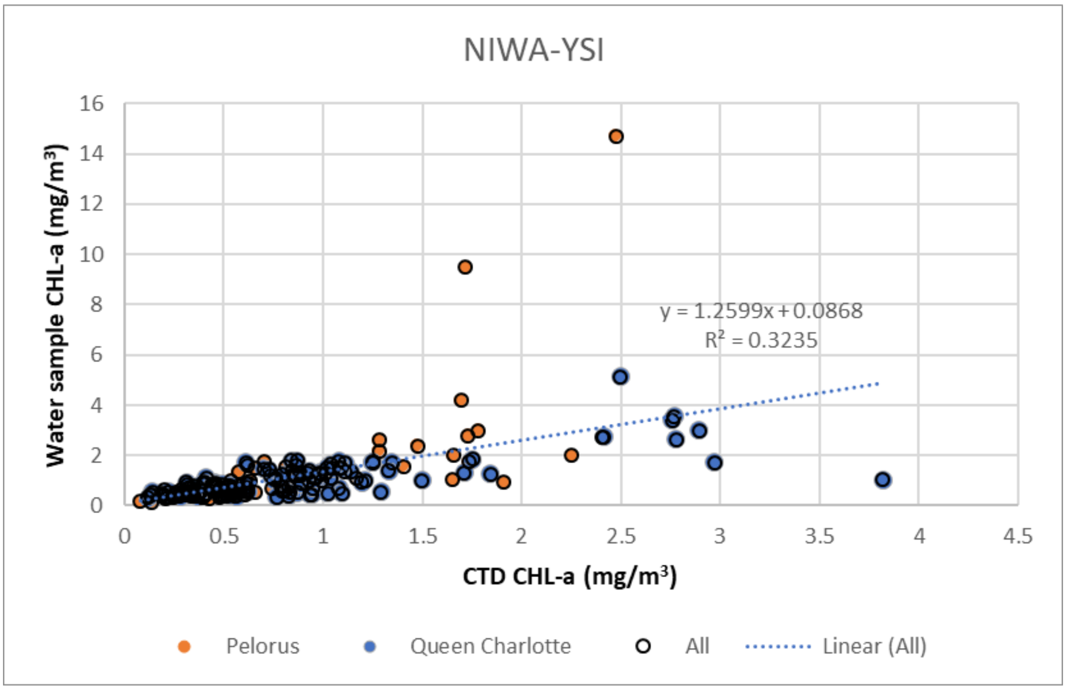


Figure E-2: Chl-a concentrations from NIWA's YSI Exosonde CTD (Serial number 13e101652) and water samples. This regression shown was used to adjust CTD CHL-a measurements for August – December 2013, March 2014, and June-July 2014.

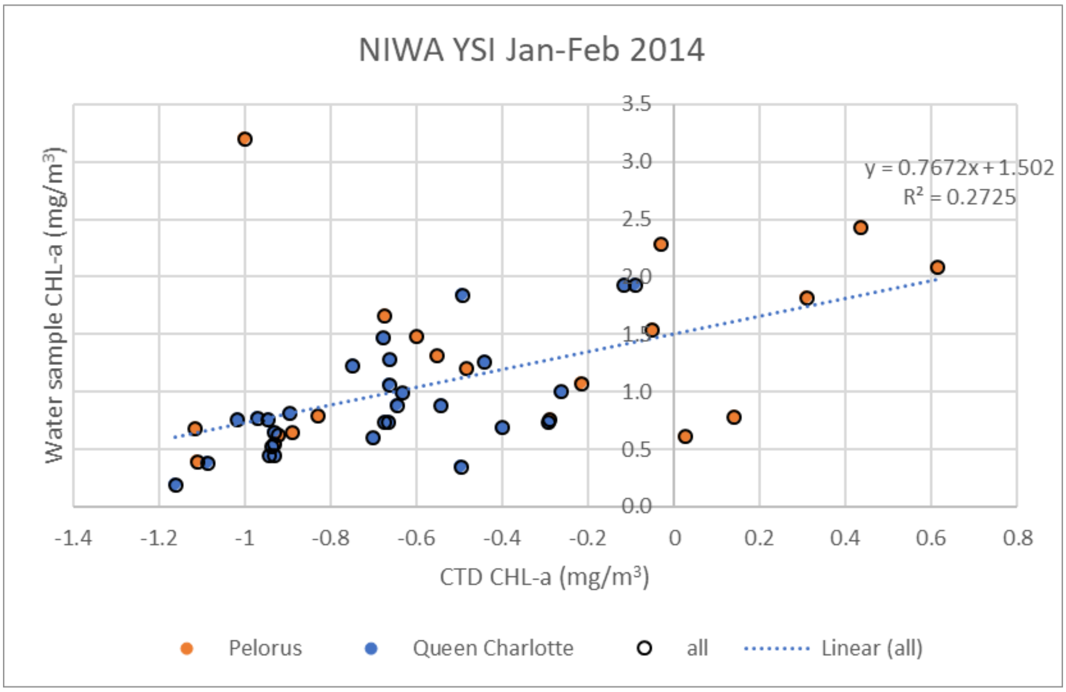


Figure E-3: Chl-a concentrations from NIWA's YSI Exosonde CTD (serial number 13e101652) and water samples for Jan-Feb 2014. The regression shown was used to adjust CTD CHL-a measurements for January – February 2014.

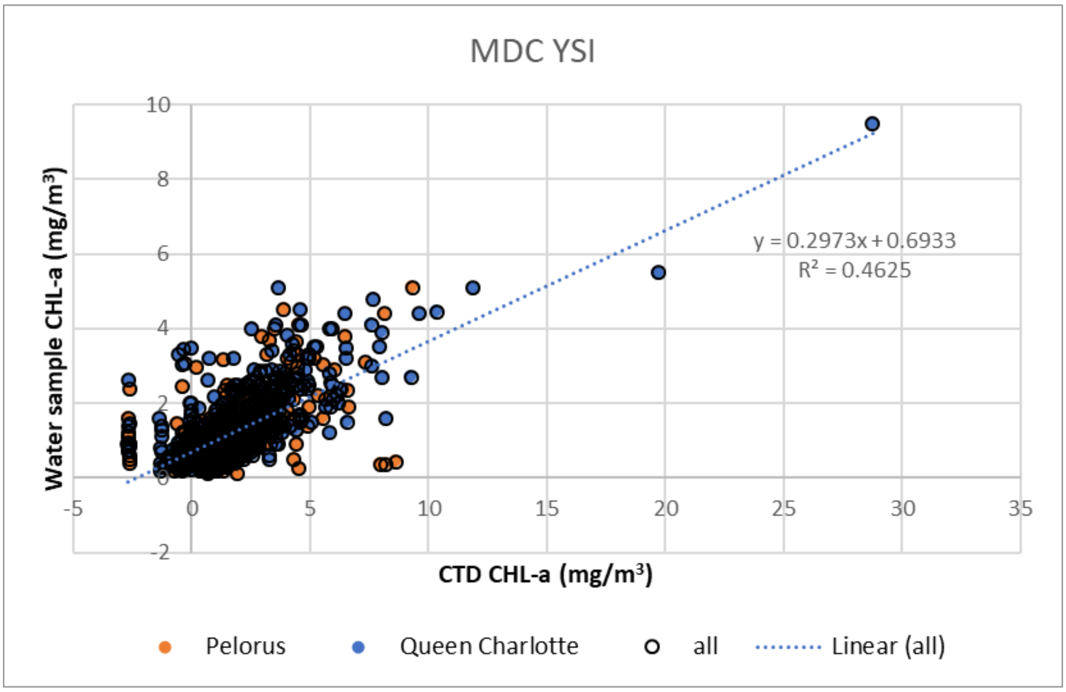


Figure E-4: Chl-a concentrations from Marlborough District Council's YSI Exosonde CTD (serial number 14g100211) and water samples. The regression shown was used to adjust CTD CHL-a measurements for August 2014 to June 2018.