Review of historical water-quality data from Pelorus Sound and Queen Charlotte Sound: long-term NIWA time-series and Marlborough District Council time-series

Prepared for New Zealand King Salmon

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Executive summary

The consent conditions governing the development of four new salmon farms by New Zealand King Salmon Co. Ltd. (NZKS) in the Marlborough Sounds region require a synthesis and data-review of all existing historical data related to water quality monitoring in the Marlborough Sounds. Our tender proposed that we review up to three data-sets: (a) the so-called Marlborough Shellfish Quality Program (MSQP) data-set, (b) an associated NIWA data-set, (c) Marlborough District Council data (MDC). We also offered to analyse two other data-sets during a later phase of the project. These were: (d) unpublished data from short-term, one-off NIWA studies at three sites (to be analysed only if the Review Panel request it), (e) unpublished Cawthron data (to be reviewed as a separate contract if requested by NZKS).

The MSQP data have not yet been made available to us. Thus, this review is restricted to NIWA's MSQP-related data and the MDC data (we have not been asked to review the Cawthron data). After the contract was signed, we became aware that a sixth data-set may also exist (through Mr Alan Johnson of MDC). NIWA has not seen those data.

NIWA's MSQP-related data-set includes water-quality data from eight stations in Pelorus Sound. Depth averaged (0-15 m depth) water samples were collected at all stations. At two (Outer Pelorus and Tawero Point), a further sample was collected at 40 m water depth. Some stations were occupied for only two-three years. Others were occupied for a decade or so. Sampling was fortnightly. The Marlborough District Council data comprises almost two years'-worth of monthly samples from five sites in Queen Charlotte Sound (incl. one in Tory Channel) and approximately one years'-worth of data from seven sites in Pelorus Sound. At each station, two samples were collected (4 m below sea-surface and a few metres above the seabed).

NIWA's Pelorus Sound data reveal:

- Marked annual cycles for nutrients. Dissolved reactive phosphorus (DRP), nitrate and dissolved silicon tend to be most abundant during the winter months and least abundant during the summer ones. In contrast, ammonium tends to be most abundant in summer/autumn.
- Dissolved inorganic nitrogen (the sum of nitrate and ammonium) is the limiting nutrient during the summer months.
- Chlorophyll concentration evolves in a much less regular manner than inorganic nutrients. Nonetheless, there is evidence of annual cycles – the nature of the cycle varies across stations. At some (e.g., Outer Pelorus), chlorophyll concentrations tend to be greatest in spring and/or late summer. At others (e.g., Beatrix Bay), they tend to be greatest during mid-winter.
- For most variables, there is substantial variability at fortnightly- and inter-annual time-scales. When grouped by calendar month, the coefficient of variation often exceeds 0.5 (but rarely exceeds 1.0) for many of the more biologically active water-properties (nutrients, chlorophyll, particulate organic matter).
- For most variables, the temporal variability exceeds the spatial variability.

Though comparisons are difficult (because the site locations differ and the time-series have differing lengths and sampling frequency, and do not overlap) the MDC and NIWA data from Pelorus Sound appear consistent with one another.

The most notable feature in MDC's Queen Charlotte data is that water-quality at the (sole) Tory Channel station is consistently different from that of the four stations in the main Queen Charlotte Channel. The Tory Channel station shows little/no evidence of vertical stratification whereas the other stations are stratified during spring, summer and autumn. Perhaps as a consequence, concentrations of chlorophyll and particulate organic matter are usually lower in Tory Channel than elsewhere. As in NIWA's Pelorus Sound data, DRP nitrate and DRSi tend to be most abundant in the winter months. Chlorophyll cycles less regularly than the nutrients (particularly in the inner Queen Charlotte Sound) and there is some evidence that the annual maximum reliably occurs in spring/summer at the seaward stations, but is less predictable at the inner/central stations.

1 Introduction

The consent conditions governing the development of four new salmon farms by New Zealand King Salmon Co. Ltd. (NZKS) in the Marlborough Sounds region require a synthesis and review of all existing historical data related to water quality monitoring in the Marlborough Sounds. The consent conditions also required that 'Baseline Monitoring' (prior to establishment of the new farms) be undertaken. The precise nature of this Baseline Monitoring was to be resolved through development of a Baseline Monitoring Plan (BMP) that is to be submitted to a review panel for approval prior to the onset of said monitoring. The data-review and BMP were to be submitted to the review panel in tandem by June 30 2013 – with an expectation that sampling would begin in late July 2013.

In our proposal for the data-review work we identified the following relevant data sets:

- Marlborough Shellfish Quality Program (MSQP) data (estimates of bacterial concentrations and species-specific counts of algae).
- NIWA MSQP-related time-series (estimates of nutrient concentrations, chlorophyll concentration and particulate concentrations).
- Marlborough District Council (MDC) monitoring data (similar to the NIWA-MSQP data).
- NIWA data-sets from Crail Bay and Waihinau Bay (several, relatively short-term data-sets for a variety of properties).
- Unpublished data held by the Cawthron Institute (details unknown).

The natures of each of these data-sets are described in section 2.

Our tender stipulated that the first three of these data-sets would be compiled and summarized in preparation for the baseline monitoring program design. The remaining NIWA data will be compiled and analysed at a later date (if requested by the review panel). Whilst our tender mentioned the Cawthron data, we specifically excluded analysis of those data from our tender price (with an offer to quote for their analysis if requested).

To date, we have not seen the MSQP data[1], but with the planned start-date for the Baseline Monitoring looming, it was deemed necessary to prepare a review of the NIWA-MSQP data and the MDC data. This report is that review.

[1] It is our understanding that NZKS are still negotiating with the owners of the MSQP data

2 Natures of the historical water-quality data-sets

The consent conditions require a synthesis and review of all existing historical data related to water quality monitoring in the Marlborough Sounds. In our proposal for this work we identified the following relevant data sets:

- Marlborough Shellfish Quality Program (MSQP) data (estimates of bacterial concentrations and species-specific counts of algae).
- NIWA MSQP-related time-series.
- Marlborough District Council monitoring data.
- NIWA data-sets from Crail Bay and Waihinau Bay.
- Unpublished data held by the Cawthron Institute.

2.1 Description of the MSQP data

This relevant part of the dataset comprises species-specific counts of phytoplankton abundance from more than 20 stations within Pelorus Sound, Port Gore and Queen Charlotte Sound. We understand that the data stretch back until the mid-1990s. We have not seen the data, we believe that they include weekly counts of toxic algal species. We are not sure whether they also include counts of non-toxic species.

The data are the property of the Marlborough Shellfish Industry. NIWA does not hold the data and I have not seen them. It is our understanding that NZKS are in negotiation with the Shellfish Industry to purchase a right to use the data, but until those negotiations are successfully completed, we cannot offer any analysis of the data. Accordingly, we will make no detailed mention of these data in this report.

2.2 Description of NIWA's MSQP-related time-series

For several years, NIWA funded the collection of additional water-quality data at eight of the MSQP sampling sites. Table 1 lists the station names. Four of the stations were sampled for only relatively short periods (one-four years), but the remaining four were sampled for a decade or more[2]. Six of the sampling stations were located in the inner/central Pelorus region (incl. side bays), but two ("Outer Pelorus" and "Cannon Hill") were in the outer Pelorus Sound – within a few km of the new NZKS fish farms at Richmond and Waitata (Figure 2-1). The Cannon Hill times-series are only about one year long, but the sampling at Outer Pelorus includes about six years' worth of samples from 40 m water depth and about five years' worth of samples from the upper 15 m of the water column. The deep-water and shallow water time-series from Outer Pelorus overlap one another for approximately one year.

[2] Albeit that the sampling at 'Outer Pelorus' consists of a six year record of sampling at 40 m water depth and four year record of sampling in the upper 15 m of the water column.

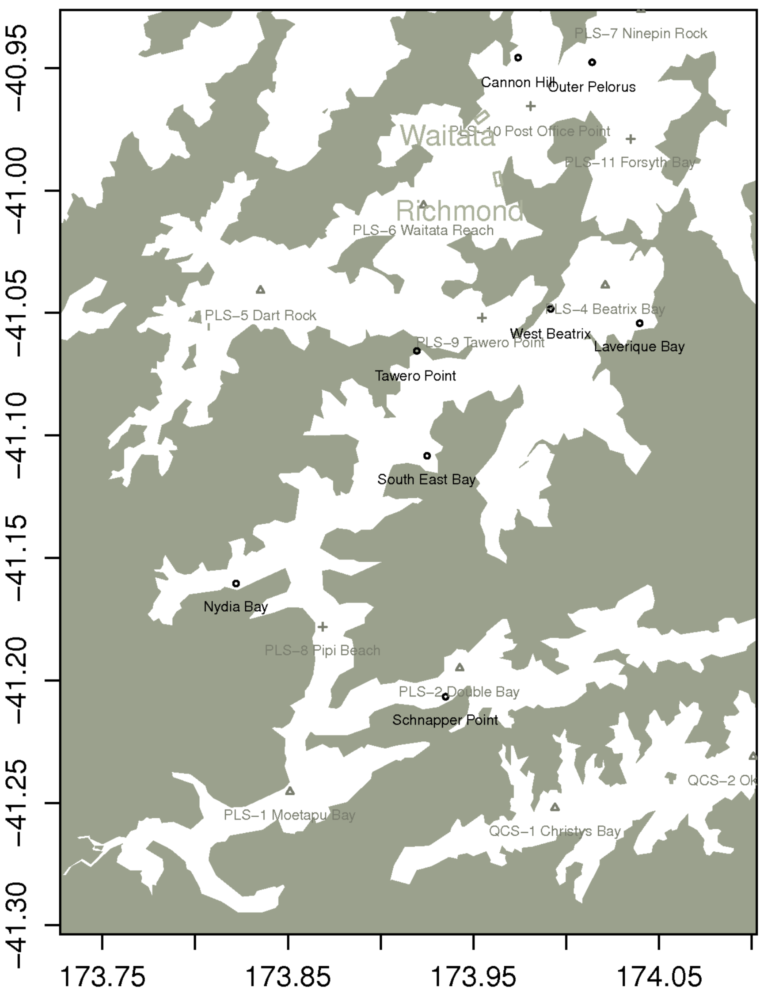


Figure 2-1: Map illustrating the locations of the stations sampled as part of NIWA's MSQP-related sampling (black, circles) and Marlborough District Council's monitoring (grey, triangles and crosses) The perimeters of the Richmond and Waitata fish farming zones are also shown (small rectangles). The circles and triangles are sites at which water samples were collected (for nutrient etc., sampling). The crosses are sites where CTD drops were made (measuring vertical profiles of temperature and salinity). The CTD data are not discussed in this report.

Table 2 lists the water-quality characteristics that were measured. This suite covers many of the quantities which the Consent Conditions require NZKS to monitor for (Condition 80 c). Quantities which NZKS must monitor, but which were not measured in NIWA's sampling program include: silicon, phytoplankton concentration 'biomass' (which we infer to be carbon biomass or ash-free dry weight rather than chlorophyll), phytoplankton species composition and dissolved oxygen.

Table 1: **Details of stations sampled in NIWA's MSQP-related sampling program.** "Surface station" samples were collected using a weighted hose-pipe that was dropped to a depth of 15 m and then sealed before being recovered. Thus, they represent depth average values over the upper 15 m. The 40 m samples were collected using a bottle-sampling device**.**

Site	Approximate time-span (at some sites, some of the variables were not sampled over the entire period described)	Comment
Outer Pelorus	40 m depth station: 2002-2008 Surface Station: 2007-2011	NIWA made some of the data available to the Cawthron Institute for the purpose of preparing evidence for the NZKS hearings
Cannon Hill	2007-2008	
West Beatrix	1997-2011	Some of these data are summarized in Zeldis (2008) and Zeldis, J.R., Hadfield et al. (2013)
Laverique Bay	1997-2007	
Tawero Point	40 m depth station: 2002-2007 Surface station: 1997-2007	
South East Bay	2007-2008	
Nydia Bay	2007-2008	
Schnapper Point	2007-2011	

Table 2: **Water quality variables measured in NIWA's MSQP-related sampling program.** At some stations only a sub-set of the variables was measured, or the time-series does not extend throughout the whole period. Sampling was fortnightly.

Characteristics measured in NIWA's MSQP-related water-quality sampling
Chlorophyll
Ammoniacal nitrogen, nitrate/nitrite-nitrogen, dissolved organic nitrogen (collectively: Total Dissolved nitrogen, TDN)
Dissolved Reactive Phosphorus, Total Dissolved Phosphorus
Particulate Carbon, Particulate Nitrogen (PN; PN+TDN=Total Nitrogen)
Particulate Organic Carbon, Particulate Organic Nitrogen
Suspended Inorganic Solids, Total Suspended Solids, Volatile Suspended Solids
Turbidity

2.3 Marlborough District Council Water Quality data

Marlborough District Council has been gathering water quality data at five sites within Queen Charlotte Sound since July 2011. They began a similar water quality monitoring programme at seven sites in Pelorus Sound in July 2012. In both cases, sampling is at monthly intervals. Figure 2-1 shows the locations of the MDC sampling sites within Pelorus Sound. Figure 2-2 shows the locations of their stations within Queen Charlotte Sound.

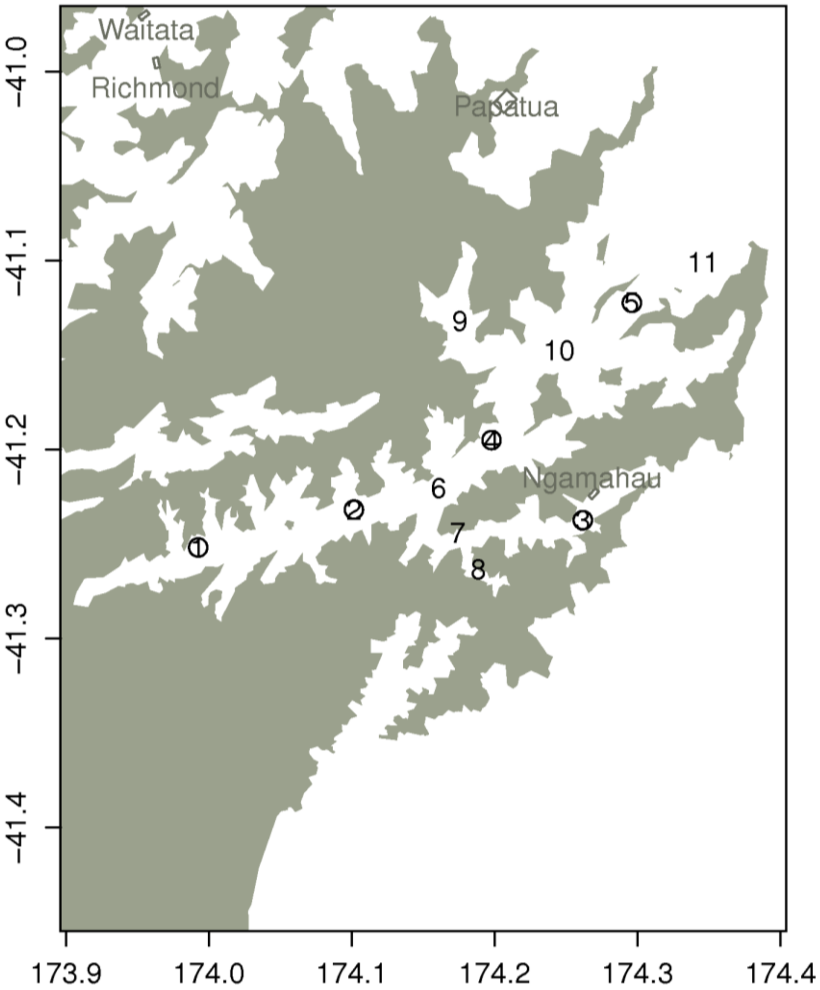


Figure 2-2: Map illustrating the sampling stations of the Marlborough District Council programme. Water quality stations are enclosed with a circle. CTD sampling was undertaken at all stations (these data are not reported in this report). The NZKS fish farming zone perimeters are shown in grey.

Table 3 lists the characteristics measured by Marlborough District Council. They are very similar to those measured in NIWA's MSQP-related sampling, but also include dissolved oxygen, dissolved reactive silicate and plankton species composition.

Table 3: Characteristics measured in the Marlborough District Council Sampling programs for Queen Charlotte and Pelorus Sounds. Samples are gathered at monthly intervals.

Characteristics measured in the Marlborough District Council water-quality sampling
Chlorophyll
Ammoniacal nitrogen, nitrate/nitrite-nitrogen, dissolved organic nitrogen (collectively: Total Dissolved nitrogen, TDN)
Dissolved Reactive Phosphorus, Total Dissolved Phosphorus
Particulate Carbon, Particulate Nitrogen (PN; PN+TDN=Total Nitrogen)
Dissolved Reactive Silicate

Characteristics measured in the Marlborough District Council water-quality sampling
Particulate Organic Carbon, Particulate Organic Nitrogen
Suspended Inorganic Solids, Total Suspended Solids, Volatile Suspended Solids
Turbidity
CTD drops to establish the depth profiles of temperature and salinity

2.4 NIWA's Crail Bay, Waihinau Bay & Port Ligar data

These data are not presented in this report, however, I describe their nature briefly in order to help the Review Panel decide upon their relevance to the issue of establishing the natural scales of variability within Marlborough Sounds.

NIWA deployed its PSmart monitoring buoy in Crail Bay for approximately six months from July 2011. This yielded measurements of chlorophyll concentration, backscatter, coloured dissolved organic matter, temperature and salinity. Whilst the data span less than one year, and are from a region that is somewhat distant from the proposed farming sites, they were collected at very high frequency (circa hourly). Thus, they provide a means of estimating short-term variability. Quantifying this short-term variability will help to define the uncertainty which one should attach to individual data-points from a more traditional (e.g., fortnightly or monthly water-quality monitoring program). In turn, this will help to inform decisions regarding the number of sequential 'outlying' data points (from a standard monitoring program), or magnitude of outlying extent that should be required before an exceedance threshold is deemed to have been crossed.

During 2007/2008 NIWA made surveys (one incoming tide and one outgoing tide, once every three months) along transects within Waihinau and Port Ligar Bays. Characteristics measured are listed in Table 4. Whilst the time-series consist of few points, they are directly relevant to the proposed Waitata Bay farm and will complement NIWA's MSQP-related Cannon Hill data set. Since sampling was along a transect and repeated on both phases of the tide, they provide some information about variability at relatively fine spatial and temporal scales.

Table 4: Characteristics measured in NIWA's 2007/2008 sampling of Waihinau and Port Ligar Bays.

Characteristics measured in Waihinau and Port Ligar Bays 2007/2008
Chlorophyll (size fractionated)
Ammoniacal nitrogen, nitrate/nitrite nitrogen
Dissolved reactive phosphorus
Particulate carbon, Particulate nitrogen
Particulate organic carbon, Particulate organic nitrogen
Total suspended solids, Volatile suspended solids
Bacteria & zooplankton
Sediment trap data

2.5 Unpublished data of the Cawthron Institute

These data are not presented within this report (I have not seen them). The little that I know about them stems from a brief description of them in the evidence presented to the board of Inquiry by the Cawthron Institute.

Knight (2012, page 2) mentions the existence of a time-series of water quality data collected by Mr Lincoln MacKenzie at Wedge Point (Queen Charlotte Sound) over the period 1996-2000. I do not know the details of this data-set, and NIWA has not sought access to it.

In our tender for this data-synthesis, we did offer to prepare an additional proposal/quote to summarize the Cawthron data for NZKS (if Cawthron agreed to make it available). That offer was not taken up by NZKS. It is possible that NZKS have asked the Cawthron Institute to prepare a summary, but if not, the Review Panel might wish to consider whether one is required (esp. given the comparative scarcity of historical data from Queen Charlotte Sound).

2.6 Other unpublished data

After our tender was accepted, Mr Alan Johnson (Marlborough District Council) brought this newspaper article to our attention http://www.stuff.co.nz/marlborough-express/news/8795822/Lobbyist-thrown-out-of-forum. The article implies that there are approximately three years' worth of unpublished measurements of some water-quality and plankton characteristics (temperature, salinity, dissolved oxygen, water clarity and microscope counts of individuals) at three sites within Queen Charlotte Sound. We were not aware of this data-set when we prepared our tender. I have not sought access to these data and I present no analysis of them in this report. I do not know the details of sampling (frequency, depth resolution and precise horizontal locations).

3 Summary of NIWA's Pelorus Sound data

For the purposes of this synthesis and summary, I have chosen to take the raw time-series for each water-quality variable and group them by site and calendar month. For each variable, at each site, I present a boxplot that illustrates the statistical distribution of the variable's values in the calendar month (across all years) in question. By analysing the data in this way, we are able to illustrate the annual dynamical cycle (by reading across the sequential, monthly, box-plots), whilst also revealing the natural scale of variability that can occur at each time of year (illustrated by the individual, month-specific boxplots). This variability comprises two parts: fortnightly-scale and inter-annual.

In this section of the report, I present the results for each water quality variable on a page of (up to) ten images (one per sampling station). Each image contains (up to) 12 box-plots (one per calendar month). Arranging the boxplots in this manner makes it relatively easy to spot seasonal variations at each site, but inhibits between-site comparisons. Each image also lists the calendar-period over which the underlying data were gathered, and the total number of data-points contributing to the group of box-plots. In addition, the coefficients of variation (a measure of relative variability=standard deviation of the time-series/mean of the time-series) for each calendar month are also listed in the images). Broadly speaking, the longer the calendar period (the larger the number of data points), the more likely it is that the box-plots provide statistically robust illustrations of the true nature of any seasonal cycle and of the true magnitude of within-calendar month (but across years) variation.

The same data are reproduced in Appendix 1, but in that case each image contains (up to) 10 box-plots (one per sampling station). There are (up to) 12 images on a page (one image per calendar month). Arranging the data in this way facilitates between-site comparisons.

3.1 Dissolved reactive phosphorus and nitrate

The dynamics of dissolved reactive phosphorus (henceforth, 'DRP'; Figure 3-1) and nitrite+nitrate (henceforth, 'nitrate'; Figure 3-2) are qualitatively similar to one another across all stations. These nutrients tend to be most abundant in early/mid-winter and least abundant in late spring/early summer. The ratio (annual maximum average monthly concentration/annual minimum average monthly concentration) is greater for nitrate than it is for DRP. Similarly, within any given month, nitrate concentrations are much more variable (absolute and relative to the average) than the DRP concentrations. At the "Outer Pelorus" and "Tawero Point" stations, we have samples from the upper 15 m of the water column (henceforth, "surface") and from 40 m water depth. The monthly median concentrations are similar in both depth strata at both stations. The monthly coefficients of variation (a measure or relative variability=standard deviation/mean) for DRP and nitrate are all moderately large, but those for nitrate tend to be larger (frequently, > 0.5).

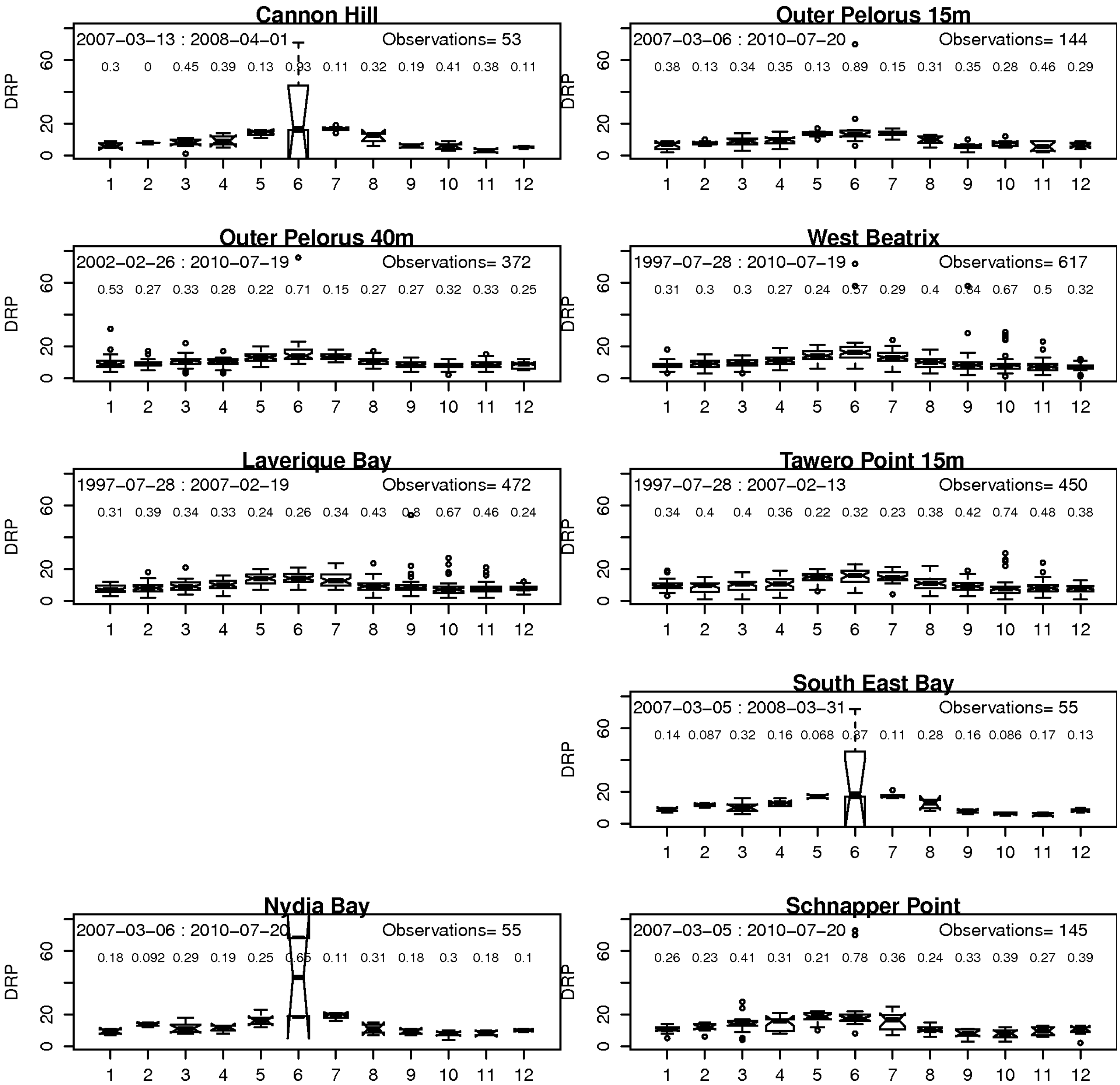


Figure 3-1: Boxplots illustrating the statistical distribution of dissolved reactive phosphorus concentration (mg P m^{-3}) by calendar month at each site. The ‘waist’ of each boxplot denotes the median. The two ‘hinges’ indicate the approximate positions of the first and third quartiles of the data. The notches extend to +/-1.58 interquartile range/sqrt(n). The notches approximate the 95% confidence region for the estimate of the median. The whiskers extend to the most extreme datapoint that is no more than 1.5 interquartile ranges from the box. The large-font inset text states the calendar period spanned by each dataset and how many observations are in the data-set. The small-font text above each month’s boxplot lists the coefficient of variation (standard-deviation of all data for the month/mean of all data for the month) for each month of the year. One year’s-worth of data equates to 26 data points. The panels bearing the titles “Outer Pelorus 40m” and “Tawero Point 40m” show data from 40 m water depth. The remaining panels show data from the upper 15 m of the water column.

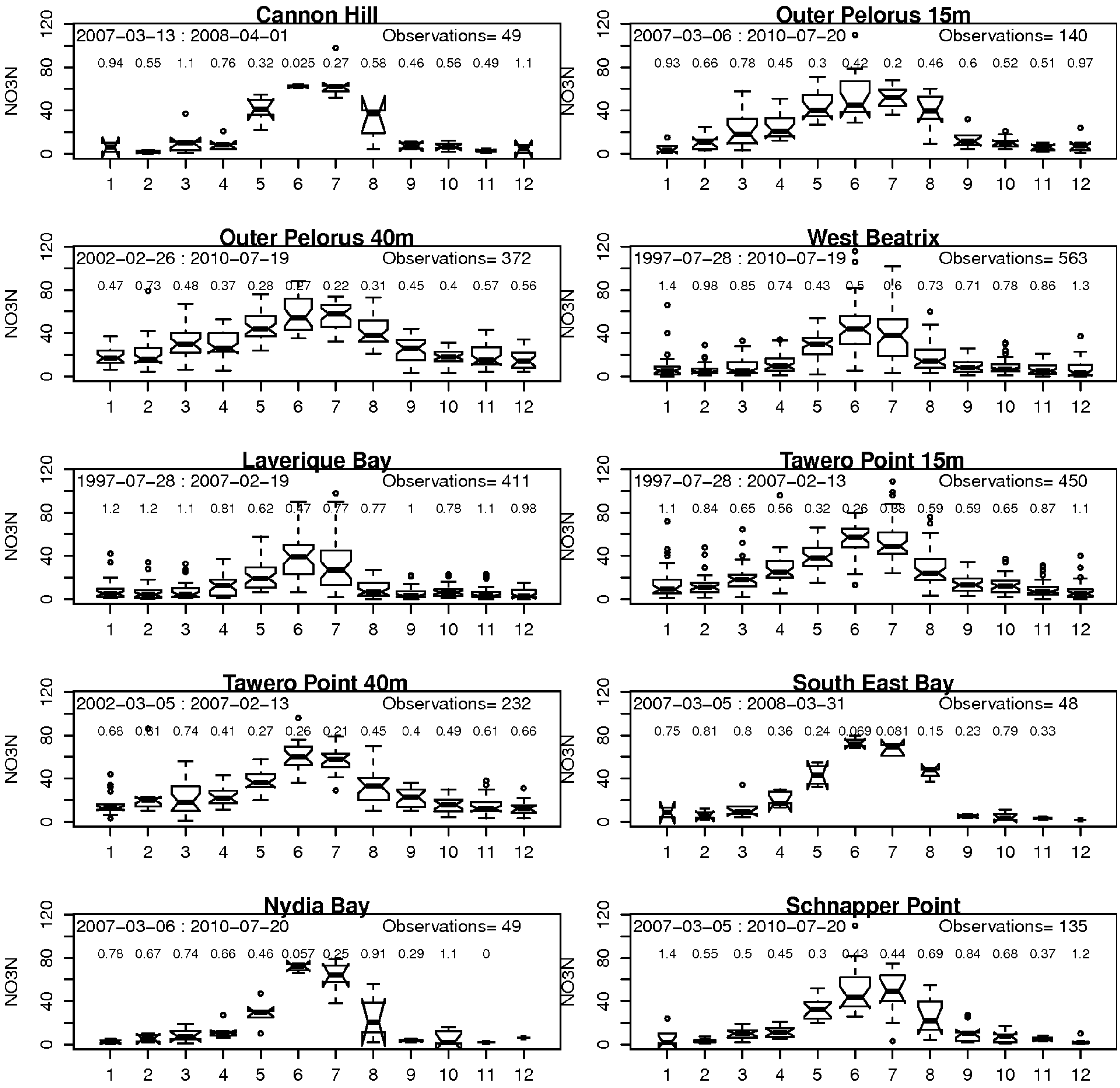


Figure 3-2: Boxplots illustrating the statistical distribution of dissolved (nitrate+nitrite)-nitrogen concentration (mg N m^{-3}) by calendar month at each site.

3.2 Ammoniacal nitrogen

The seasonal dynamics of ammoniacal nitrogen (Figure 3-3) differ from those of DRP and nitrate. Ammoniacal nitrogen concentrations tend to be greatest in late summer/early autumn. It might appear that some stations (Cannon Hill, Nydia Bay, South East Bay) exhibit greater calendar-month to calendar-month variability than others (Pelorus, West Beatrix, Laverique, Tawero). Unfortunately, it is not clear whether this is a genuine feature or an artefact associated with the fact that those showing the greatest variability happen to be the shorter time-series (such that the medians are most likely to be biased). The coefficients of variation for monthly ammonium are usually larger than those for DRP and nitrate (frequently, >0.75).

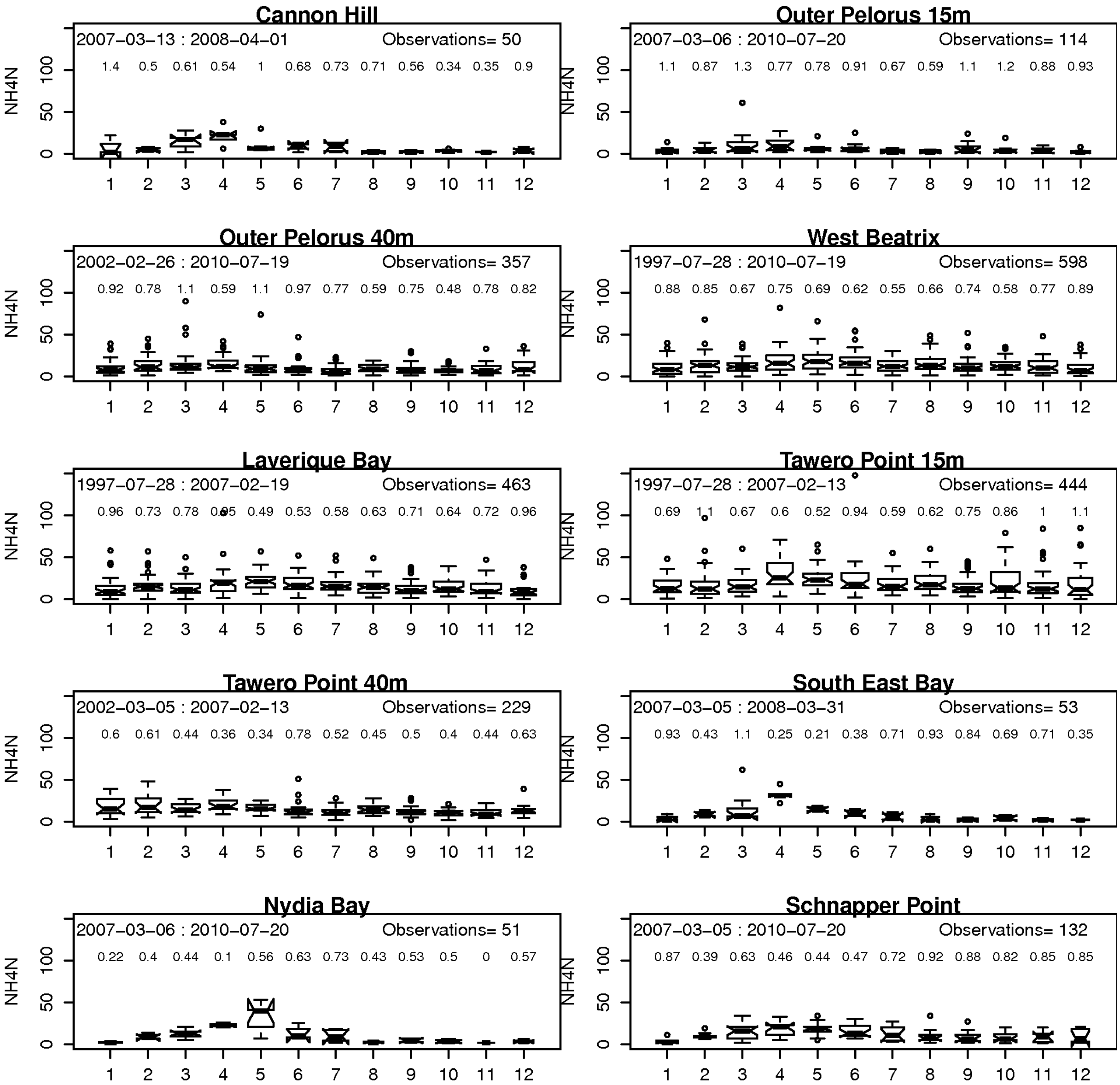


Figure 3-3: Boxplots illustrating the statistical distribution of ammoniacal nitrogen concentration (mg N m^{-3}) by calendar month at each site.

Comparison of the measured concentrations of inorganic nutrient with published half-saturation nutrient concentrations for phytoplankton growth suggest that dissolved inorganic nitrogen (nitrate+ammonium) will usually be more limiting than phosphorus (or silicon, see the MDC data). The fact that the nitrogen is more seasonally variable than phosphorus is further evidence of this – DIN (particularly NO_3) becomes very depleted in much of the non-winter period (i.e., outside the light-limited period), whereas phosphorus is more seasonally stable.

3.3 Dissolved organic nitrogen

Dissolved organic nitrogen concentrations do not show a clear annual cycle at any station. Arguably, the within-month variability is greater at the two stations in the outer part of Pelorus, but median concentrations are similar across all stations and across all months (Figure 3-4). The DON concentrations are markedly greater than the total concentrations of inorganic nitrogen. The coefficients of variation are small relative to those for inorganic nutrients. Whilst some phytoplankton are able to consume simple forms of dissolved organic nitrogen, the majority of the DON that is measured is likely to be inaccessible to phytoplankton. This implies that the majority of the DON cannot be readily utilised in primary production – hence it shows less seasonal (and month-to-month) variation than inorganic nitrogen which is readily taken up by phytoplankton.

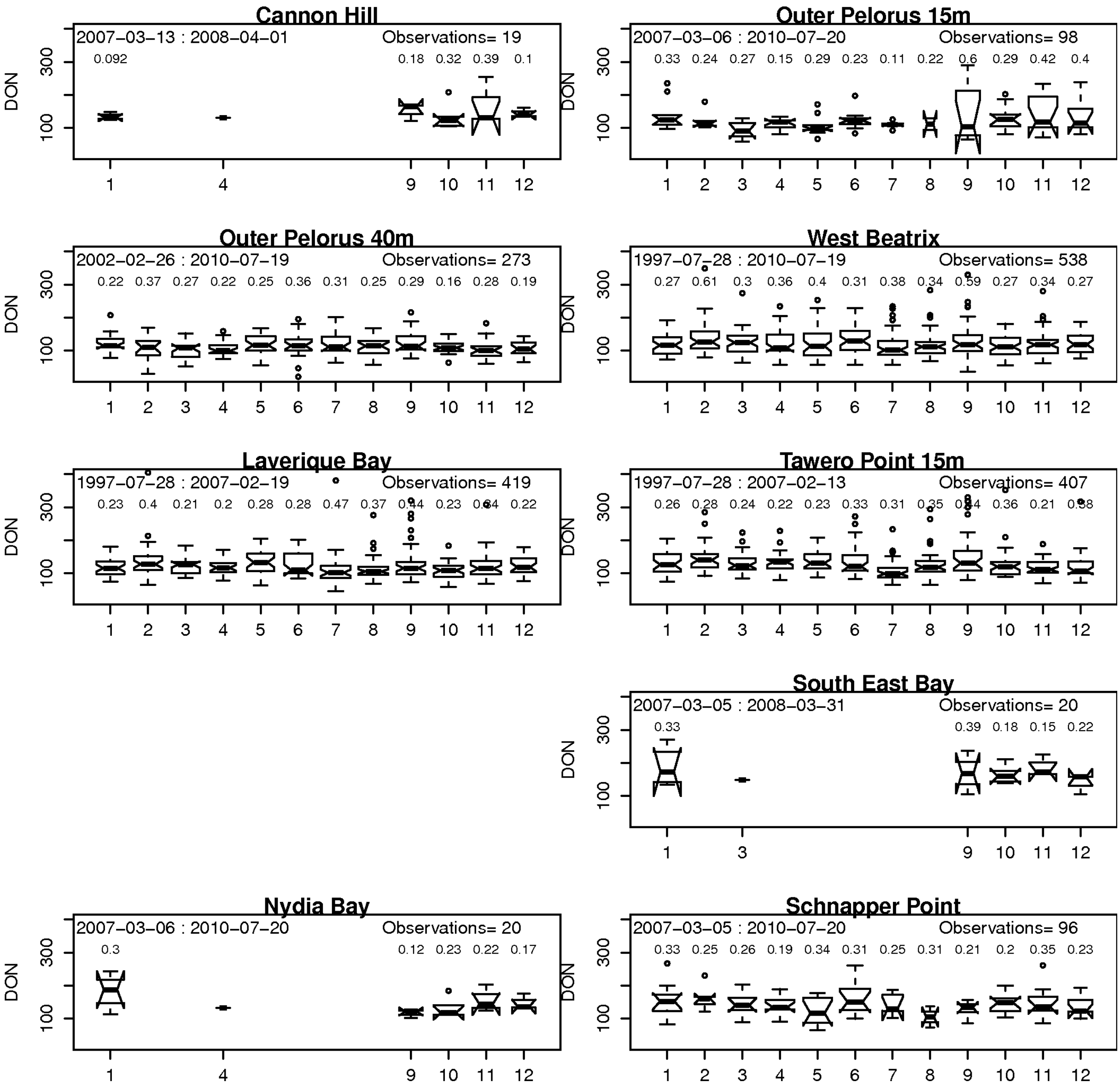


Figure 3-4: Boxplots illustrating the statistical distribution of dissolved organic nitrogen concentration (mg N m^{-3}) by calendar month at each site.

3.4 Total dissolved phosphorus & total dissolved nitrogen

Total dissolved phosphorus concentration is somewhat greater than the concentration of DRP – indicating the presence of a significant (but not overwhelming) quantity of dissolved organic phosphorus (Figure 3-5). There is some evidence of an annual cycle in the TDP concentrations – presumably driven by the cycle of DRP. Interestingly, the coefficients of variation for TDP tend to be somewhat smaller than those of DRP – despite the fact that DRP is the dominant component of TDP. This may indicate that DRP and dissolved organic phosphorus are tightly coupled such that when one is relatively scarce, the other tends to be more abundant.

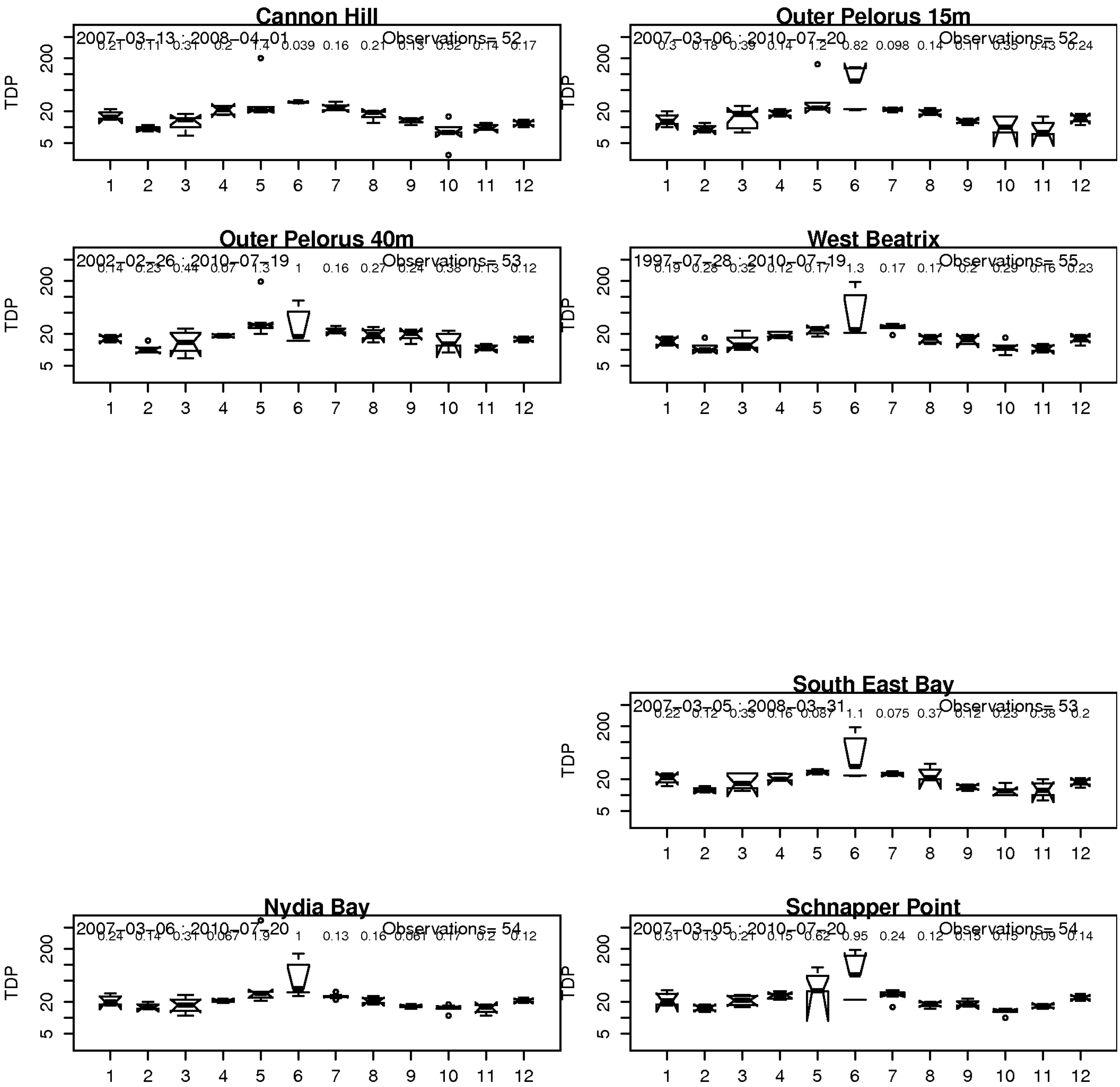


Figure 3-5: Boxplots illustrating the statistical distribution of total dissolved phosphorus concentration (mg P m^{-3}) by calendar month at each site.

The dynamics of total dissolved nitrogen are dominated by those of the dissolved organic nitrogen component. Nonetheless, the annual cycles of nitrate and ammonium are large enough to drive a small amplitude cycle in TDN (Figure 3-6). The coefficients of variation tend to be small because the majority of DON is not readily bio-available.

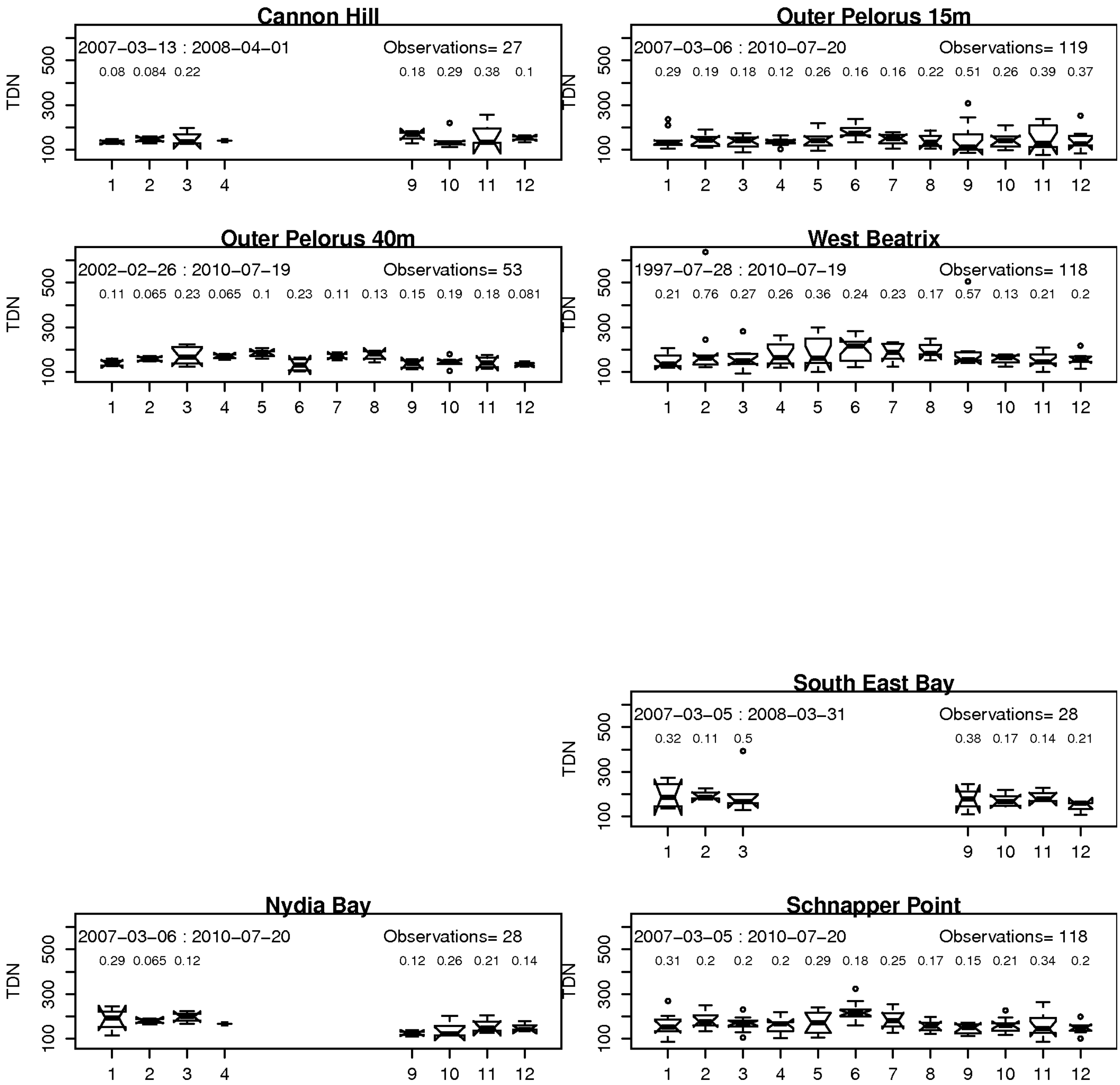


Figure 3-6: Boxplots illustrating the statistical distribution of total dissolved nitrogen concentration (mg N m^{-3}) by calendar month at each site.

3.5 Chlorophyll

At the two stations in the outer Pelorus (Cannon Hill and Outer Pelorus), chlorophyll concentrations are at their lowest during early/mid-winter and at their greatest in early spring and/or mid/late summer (Figure 3-7). A similar pattern is evident at Tawero Point and South East Bay. This is a typical seasonal pattern for coastal waters around New Zealand. In contrast, at West Beatrix and Laverique (also in Beatrix Bay), chlorophyll concentrations tend to be greatest in mid-winter. This is may indicate an increasing influence of riverine effects on productivity at these sites. River water adds buoyance and nutrients, both of which will enhance productivity in winter when light and nutrients can become co-limiting. The within calendar-month scatter frequently exceeds the amplitude of the annual cycle. Therefore, it should come as no surprise that the coefficients of variation tend to be moderately large (usually larger than those for nitrate, but smaller than those for ammonium).

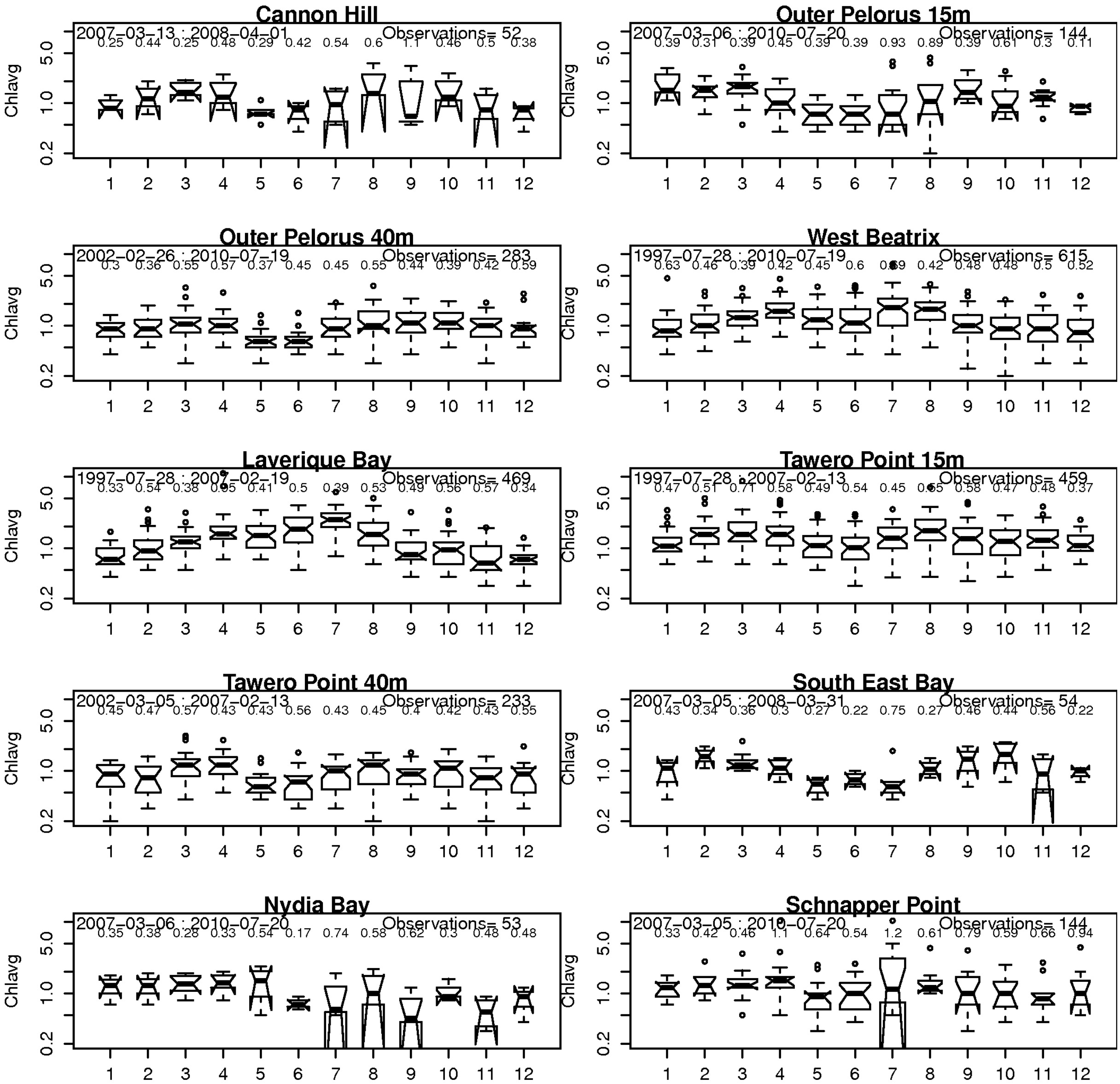


Figure 3-7: Boxplots illustrating the statistical distribution of chlorophyll concentration (mg Chla m^{-3}) by calendar month at each site.

3.6 Particulate carbon and nitrogen

Particulate carbon (Figure 3-8), particulate nitrogen (Figure 3-9), particulate organic carbon (Figure 3-10) and particulate organic nitrogen (Figure 3-11) all show qualitatively similar dynamics – if there is any annual cycle, it is of very small amplitude relative to the mean (and to the scatter in any one calendar month).

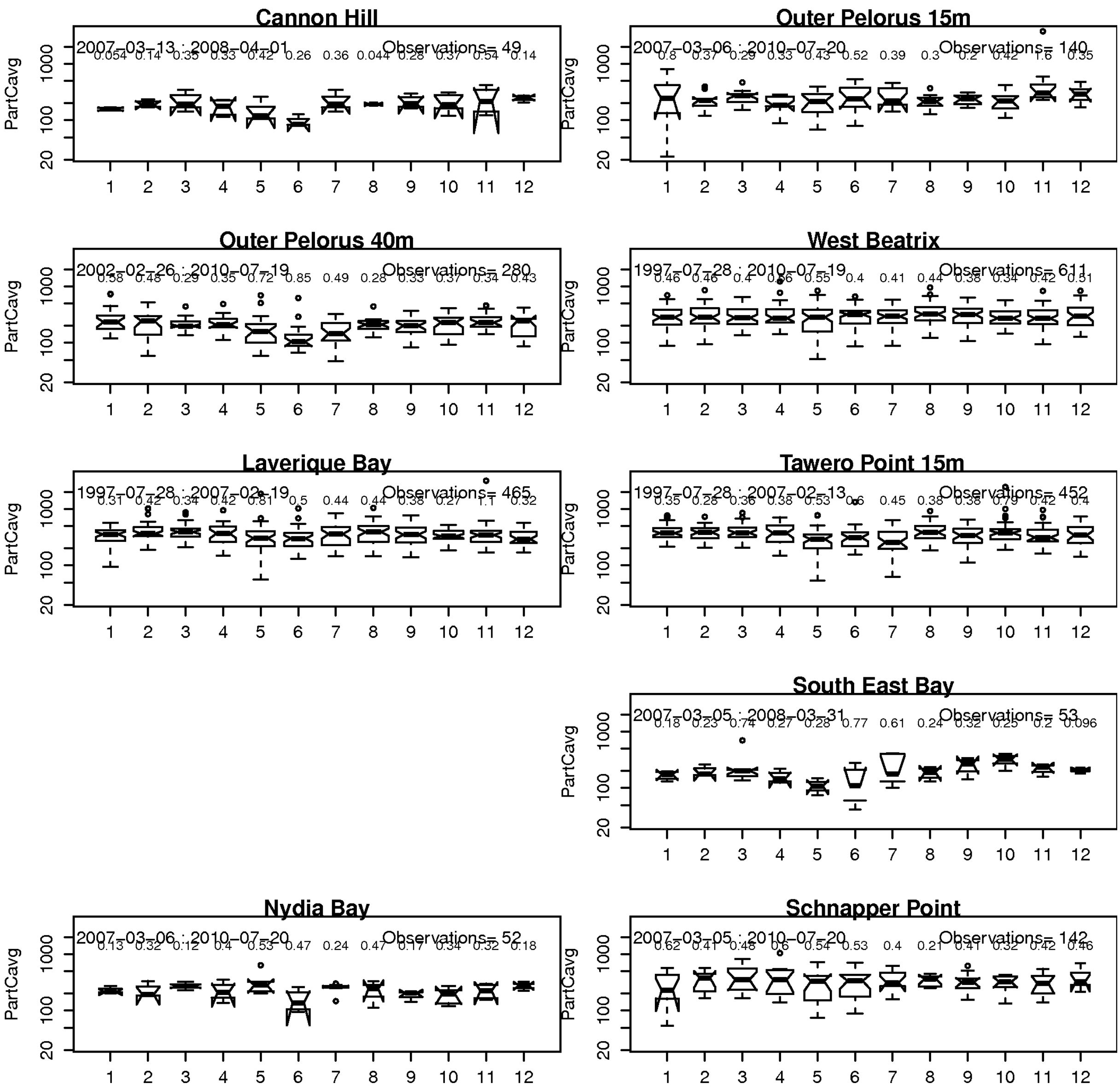


Figure 3-8: Boxplots illustrating the statistical distribution of particulate carbon concentration (mg C m^{-3}) by calendar month at each site.

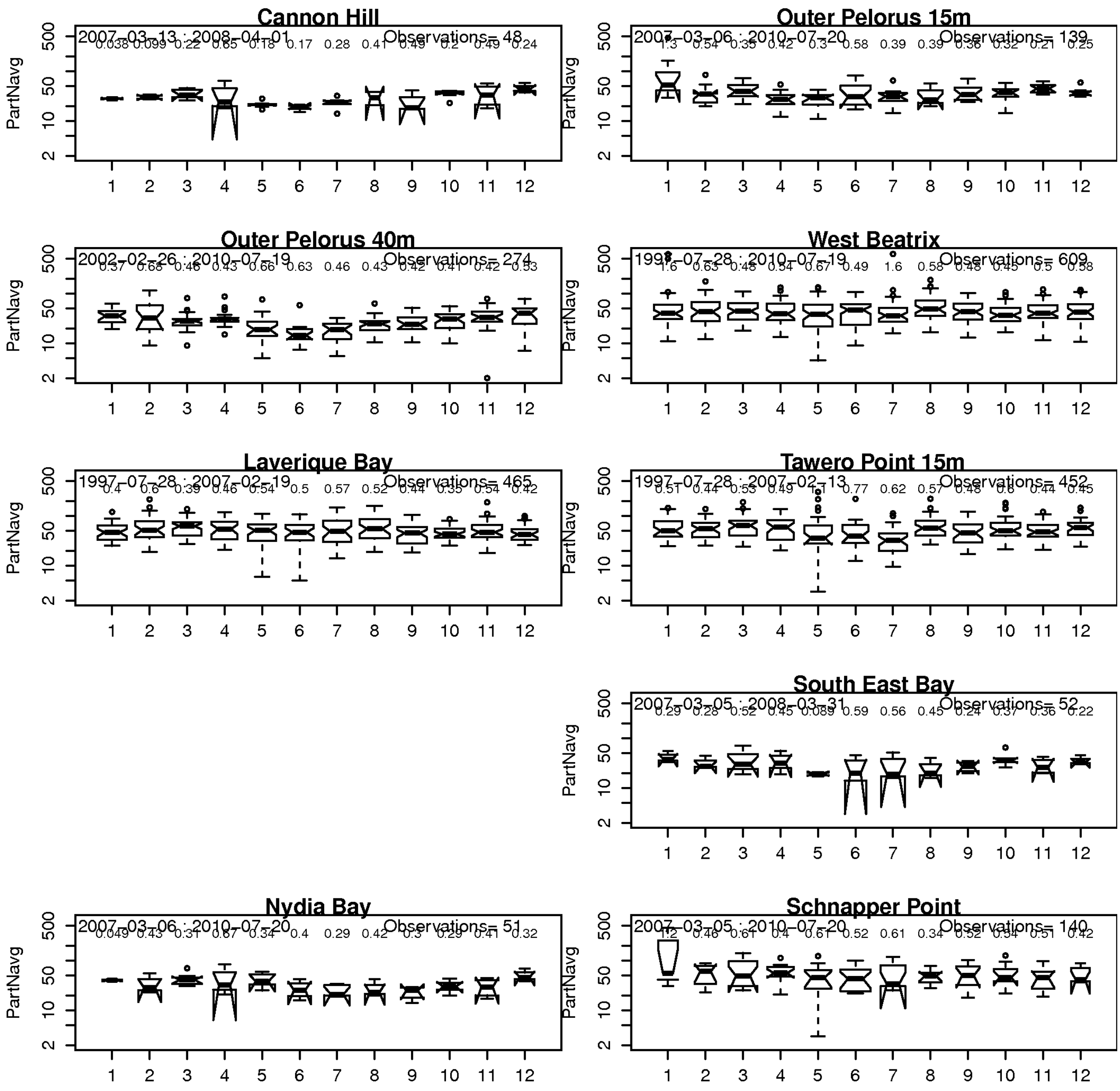


Figure 3-9: Boxplots illustrating the statistical distribution of particulate nitrogen concentration (mg N m^{-3}) by calendar month at each site.

3.7 Particulate organic carbon and particulate organic nitrogen

The chemical analyses for particulate organic carbon and particulate organic nitrogen differ from those for particulate carbon and particulate nitrogen. In theory, particulate carbon will include inorganic particulate carbon (e.g., carbonate etc.,) as well as the organic forms. Thus, PC>=POC. The distinction is less clear cut for PN vs PON. Nonetheless, it transpires that the medians of the ratios of PC/POC and PN/PON are both in the range 1.15-1.20. This implies that most of the particulate carbon and nitrogen is organic material[3]. Inevitably, POC and PON share very similar dynamics. The within-month variabilities in POC and PC are similar but the across-month variations of POC appear a little greater. This is probably a

[3] It does not necessarily imply that most of the particulate matter is organic (see the ensuing sections on suspended solids)

reflection of seasonally changing phytoplankton abundance (with knock-on effects for detrital abundance).

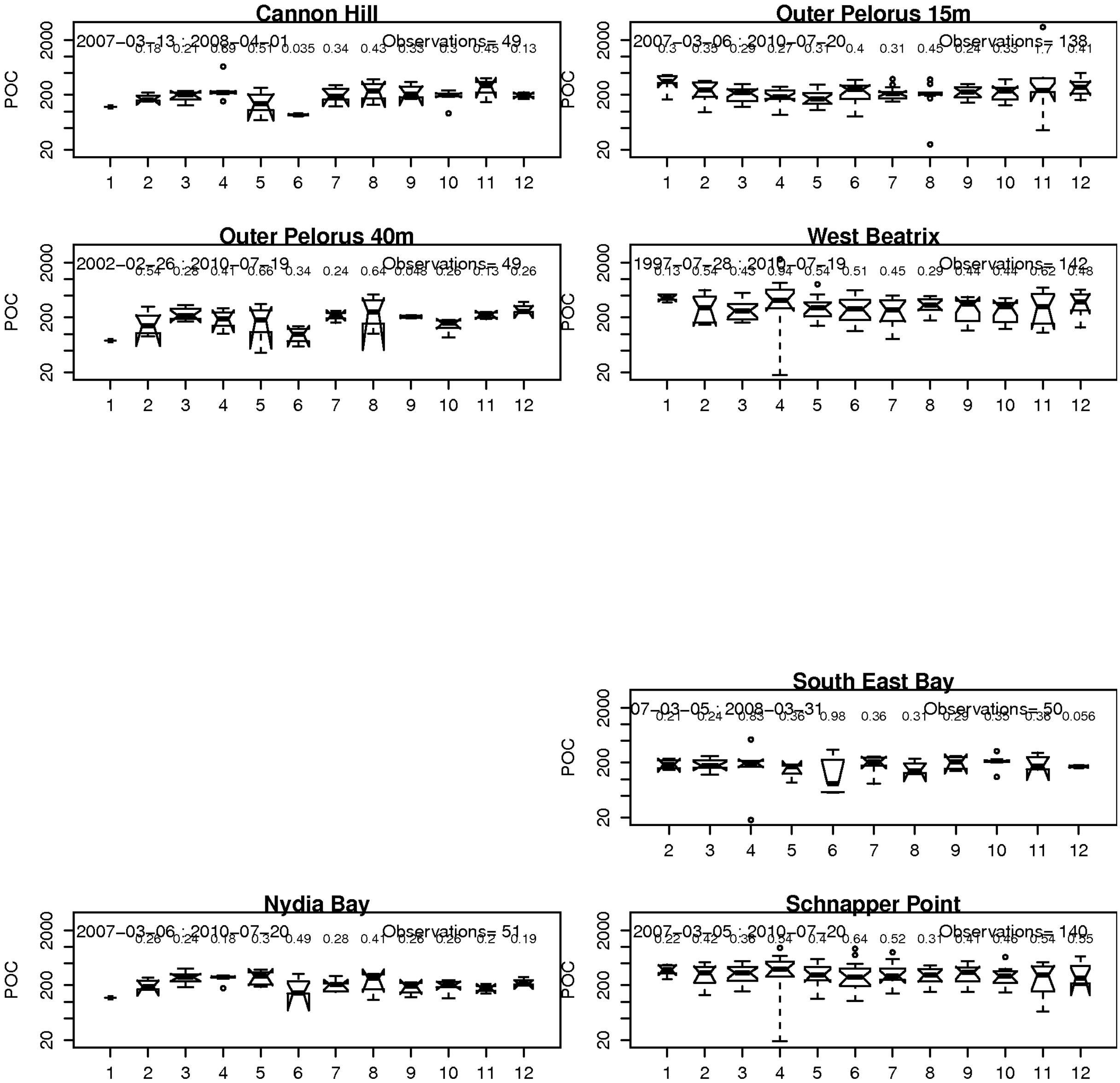


Figure 3-10:Boxplots illustrating the statistical distribution of particulate organic carbon concentration (mg N m^{-3}) by calendar month at each site.

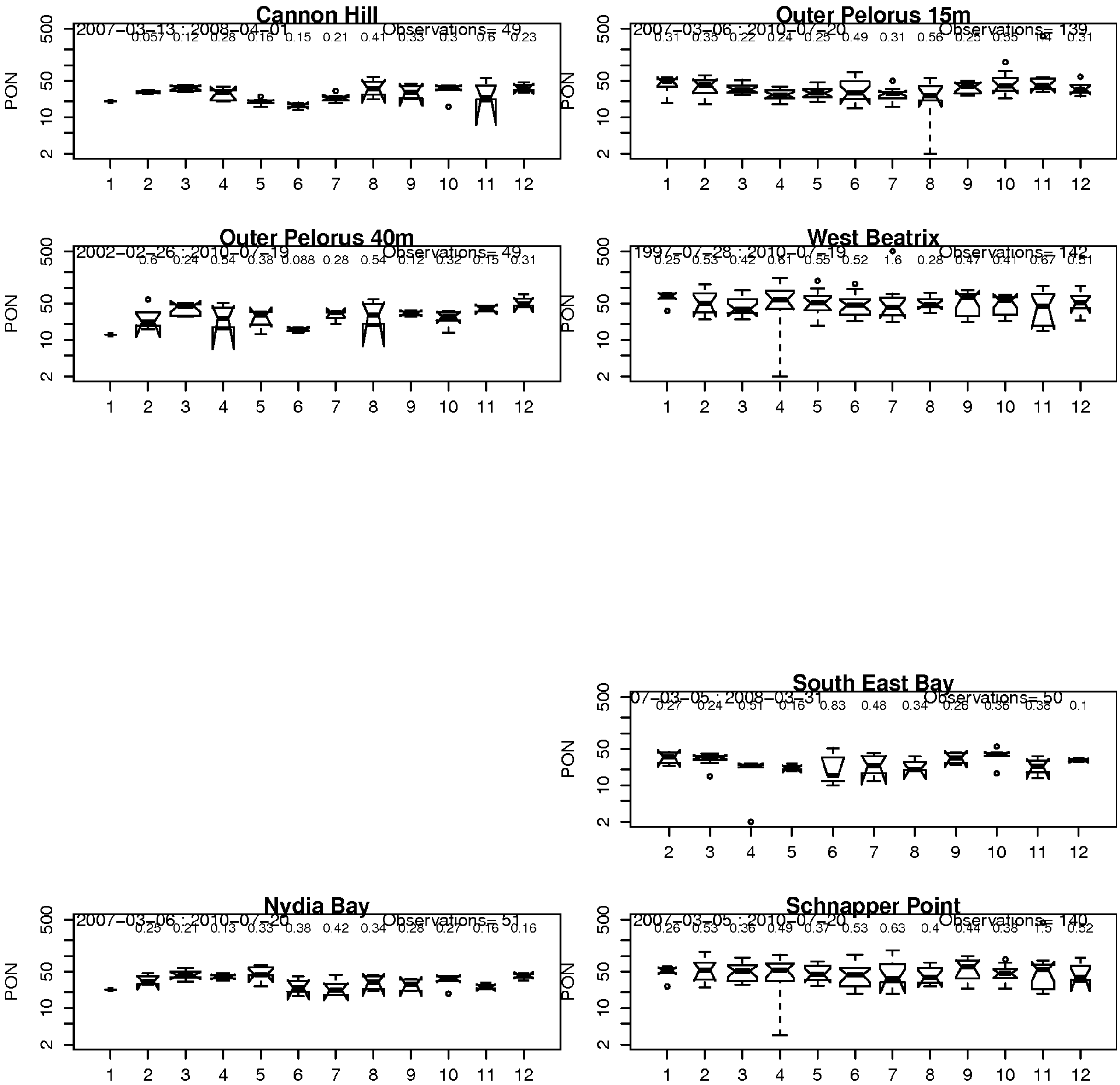


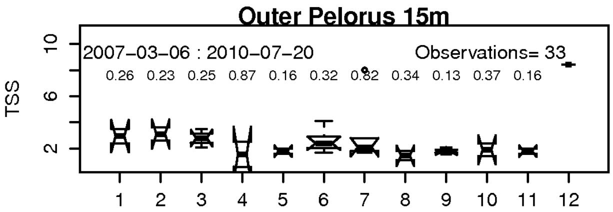
Figure 3-11:Boxplots illustrating the statistical distribution of particulate organic nitrogen concentration (mg N m^{-3}) by calendar month at each site.

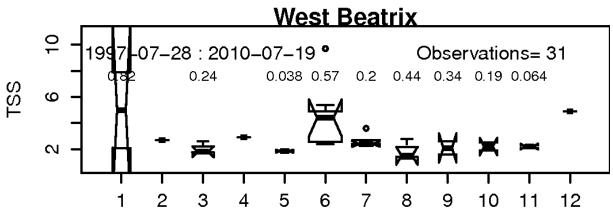
3.8 Suspended Solids & turbidity

The dynamics of total suspended solids (TSS, Figure 3-12), suspended inorganic solids (SIS, Figure 3-13) and volatile suspended solids (VSS, Figure 3-14) are intertwined (TSS=SIS+VSS). Volatile suspended solids are those that are lost ('burnt off') when the total solids are 'cooked' at high temperature for about 24 hours. VSS is a proxy for mass of organic matter (measured as gram ash free dry weight) whereas TSS (measured as g dry weight) represents the total dry mass of suspended solids (incl. SIS – the inorganic particulates).

As one might hope, TSS exceeds VSS. The median ratio (across all sites) is approximately 0.3 (range 0.06-0.6). Thus, organic particulates are typically approximately half as abundant as inorganic ones (by dry mass concentration). None of the measures show a clear annual cycle. Turbidity is strongly influenced by the concentration of suspended solids. Thus, it is no surprise to find that turbidity also shows little evidence of an annual cycle (Figure 3-15). VSS and TSS both seem to exhibit greater within-month and across month variability than does SIS; however, there are comparatively few measurements of TSS and VSS at any of the sites. That may imply that seston concentrations are more variable than inorganic particulate concentrations. However, there are many fewer observations of TSS and VSS than of SIS and I suspect the (seeming) differing variabilities are also influenced by a small-sample-size (ie sampling-error) effect.

One might expect that VSS and POC should be tightly correlated (carbon typically represents 30-50% of the ash-free dry weight of organic matter. Indeed, the median ratio of POC / VSS in our data is approximately 0.3 – however, the slope of the correlation relationship is much less than one (though significantly greater than zero). This surprising result arises because the VSS concentrations are frequently below the detection limit of the method (0.5 g m^{-3}). For the purposes of the correlation analysis, these were treated as equal to 0.5 g m^{-3}. The net result that the correlation is seriously biased at low VSS concentrations. One might question whether there is value in endeavouring to measure VSS in the Sounds (unless a more sensitive method can be found).





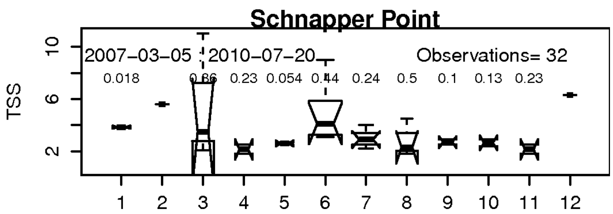


Figure 3-12:Boxplots illustrating the statistical distribution of total suspended solids concentration (g m^{-3}) by calendar month at each site.

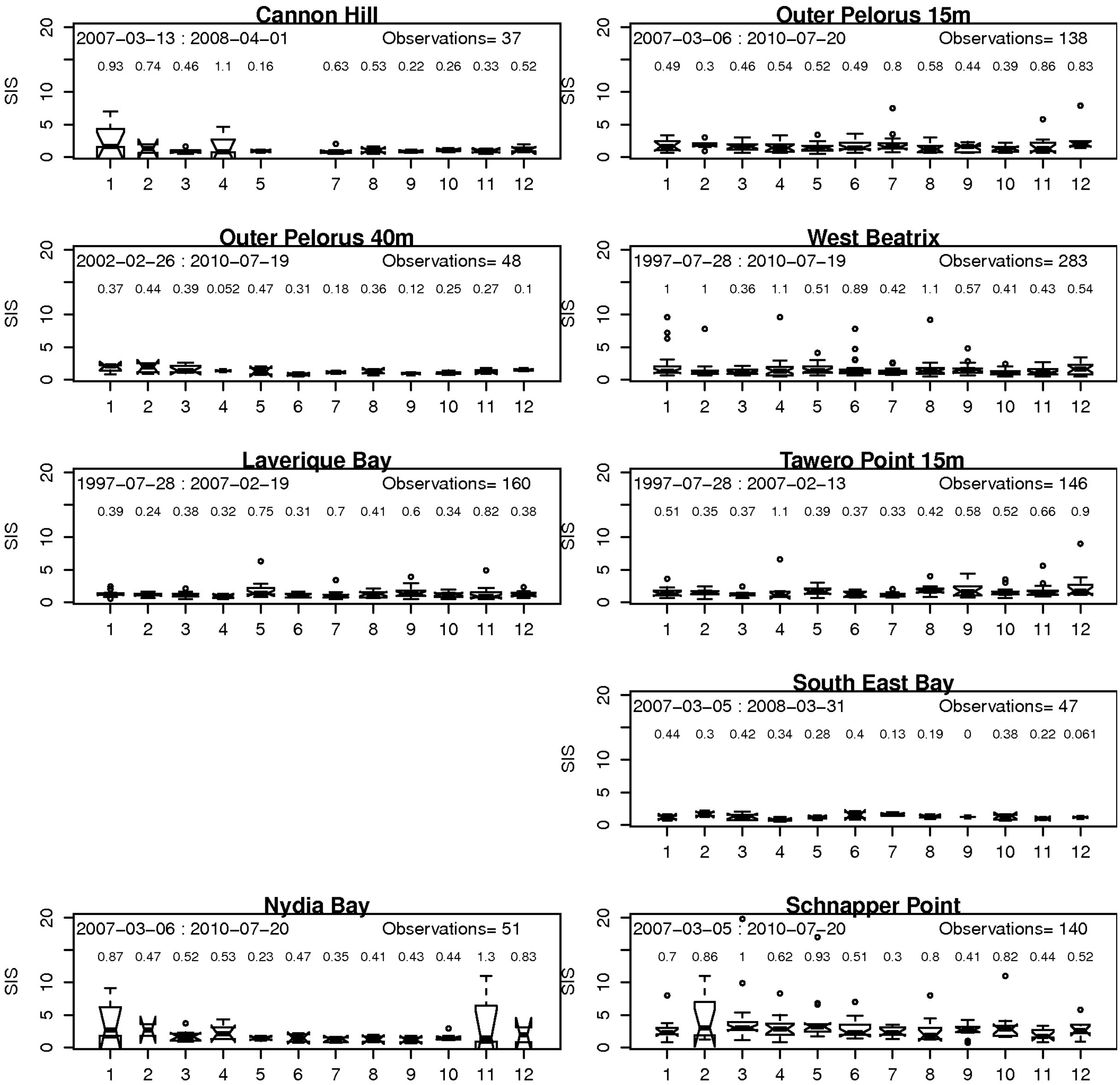
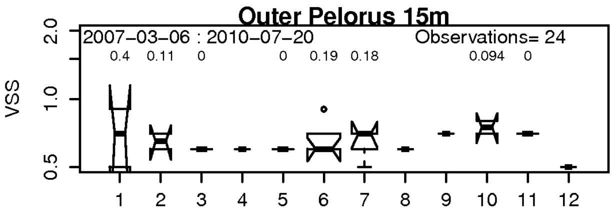
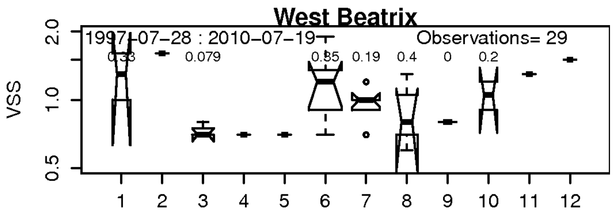


Figure 3-13:Boxplots illustrating the statistical distribution of suspended inorganic solids concentration (g (DW-AFDW) m^{-3}) by calendar month at each site.





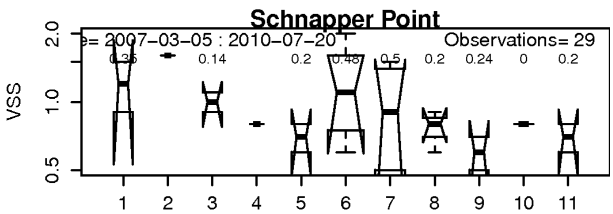


Figure 3-14:Boxplots illustrating the statistical distribution of volatile suspended solids concentration (g AFDW m^{-3}) by calendar month at each site.

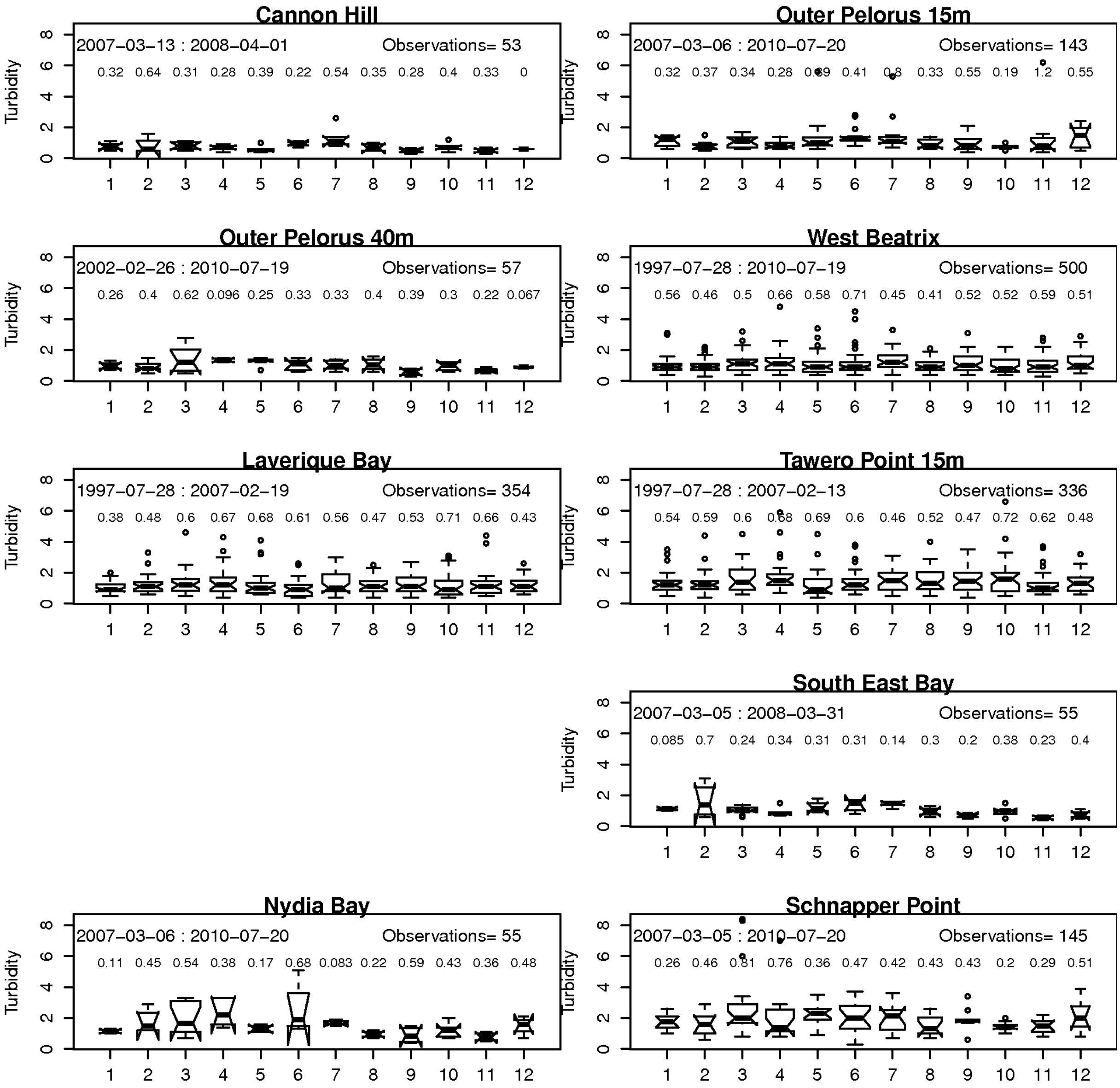


Figure 3-15:Boxplots illustrating the statistical distribution of turbidity (NTU) by calendar month at each site.

3.9 Inter-annual variability

Whilst much of the within-month variability is high frequency (ie fortnight to fortnight variation), there is also substantial inter-annual variability (see Appendix 2). For some variables (notably, inorganic nutrients, chlorophyll and particulate organic carbon/nitrogen), the average concentration in a given calendar month can vary by >50% across years. This aspect has been analysed by Zeldis et al. (2008, 2013) and has been found to be a strong driver of mussel farm productivity, because PN concentration is a good index of mussel food abundance.

4 Summary of Marlborough District Council's Pelorus Sound Data

The MDC data extend back only to July 2012. Thus, they span less than one year at present. The raw time-series are presented in (Figure 4-1 - Figure 4-13). Given the short span of these time-series, we do not devote much space to describing / interpreting the individual times-series. We restrict ourselves to showing the raw time-series (section 4.1) and presenting box-plots (section 4.2) that compare the MDC- and NIWA- Pelorus Sound time-series. In all cases, the box-plots are based upon the entire MDC or NIWA) time-series.

Whilst MDC sampling sites are not coincident (time or space) with any of the historical NIWA sites, we believe that NIWA's historical data and the MDC data reveal qualitatively similar patterns. Where there is evidence of annual cycles in the NIWA data, there are hints of similar cycles in the MDC data. Furthermore, for the most part, the measured concentrations span similar ranges in both data-sets (Figure 4-14 - Figure 4-26).

There are hints that the MDC sampling is consistently yielding lower average DOC concentrations than were recorded in NIWA's historical sampling. This is also true of several of the nitrogen components (PON, TDN, and perhaps NH_4). We know of no changes in laboratory practice that might drive such differences. There are some differences in the nature of the sampling devices etc., but we do not believe that those would drive the (possible) differences. Thus, we are inclined to believe that the (apparent) differences reflect the fact that NIWA's data span several years whereas MDC's data span less than one year. The implications are: (a) that MDC's data may present a biased picture of (what will prove to be) the 'true distribution of property concentrations during the 2012/2013 year (once a full year's worth of data are accrued), (b) even if unbiased for the 2012/2013 year, they may be biased relative to the multi-annual distribution of property values (which is what NIWA's data sample from).

Many of the particulate properties (POC, PON, TSS, VSS) measured at the innermost Pelorus Station (PLS-1) were present in unusually high concentrations on one occasion during March 2013. It is tempting to ascribe this to import of terrigenous material during a river-flood – but the salinities measured during this sampling trip were not unusually low.

Figure 4-14 - Figure 4-26 (and Appendix 1) also provide a means of readily comparing conditions across sites within Pelorus (cf comparing NIWA and MDC data). The indications are that biological activity is greatest in the central regions of the Sound. Chlorophyll, POC, PON and VSS concentrations tend to be greatest there. Similarly, ammonium concentrations (indicative of high organic matter breakdown rates) also tend to be greatest whilst nitrate concentrations (inversely indicative of high primary production rates) tend to be the smallest. That said, the between site variability (of site means) is usually less than the within-site temporal variability around the site-specific mean.

There are data from two depth strata (near surface and 40 m below surface) in NIWA's data for the Outer Pelorus and Tawera Point stations. The differences between corresponding median concentrations are usually small relative to the range of variability across individual observations. Nonetheless, corresponding medians are significantly different in several cases (Figure 4-14 - Figure 4-26). This suggests that the water-columns at these stations may stratify (at least weakly) at a depth between approximately 15 m and 40 m for at least some of the year. The water depth in the vicinity of the Outer Pelorus station is approximately 70 m but shallows rapidly towards about 40 m to the east and west (M. Gibbs pers. com., also compare Figure 6 of Knight and Beamsley 2012 with the site location map in this report). Boat drift during sampling combined with the steep bathymetry implies that the 40 m sample will not always have been at the same height above the seabed. Nonetheless, at Outer Pelorus it is probable that the seabed was several tens of metres below the 40 m sampling depth. Stronger stratification may have been present across this (unsampled) deeper stratum (M. Gibbs, pers. comm.).

The MDC data also provide hints that (genuinely) near-bed and near-surface concentrations can differ in Pelorus (more so in the stations from central Pelorus than those of outer Pelorus), but with so few data to date, it is difficult to know whether this is a genuine feature or an artefact of sampling ‘noise’.

4.1 MDC Pelorus data: time-series plots

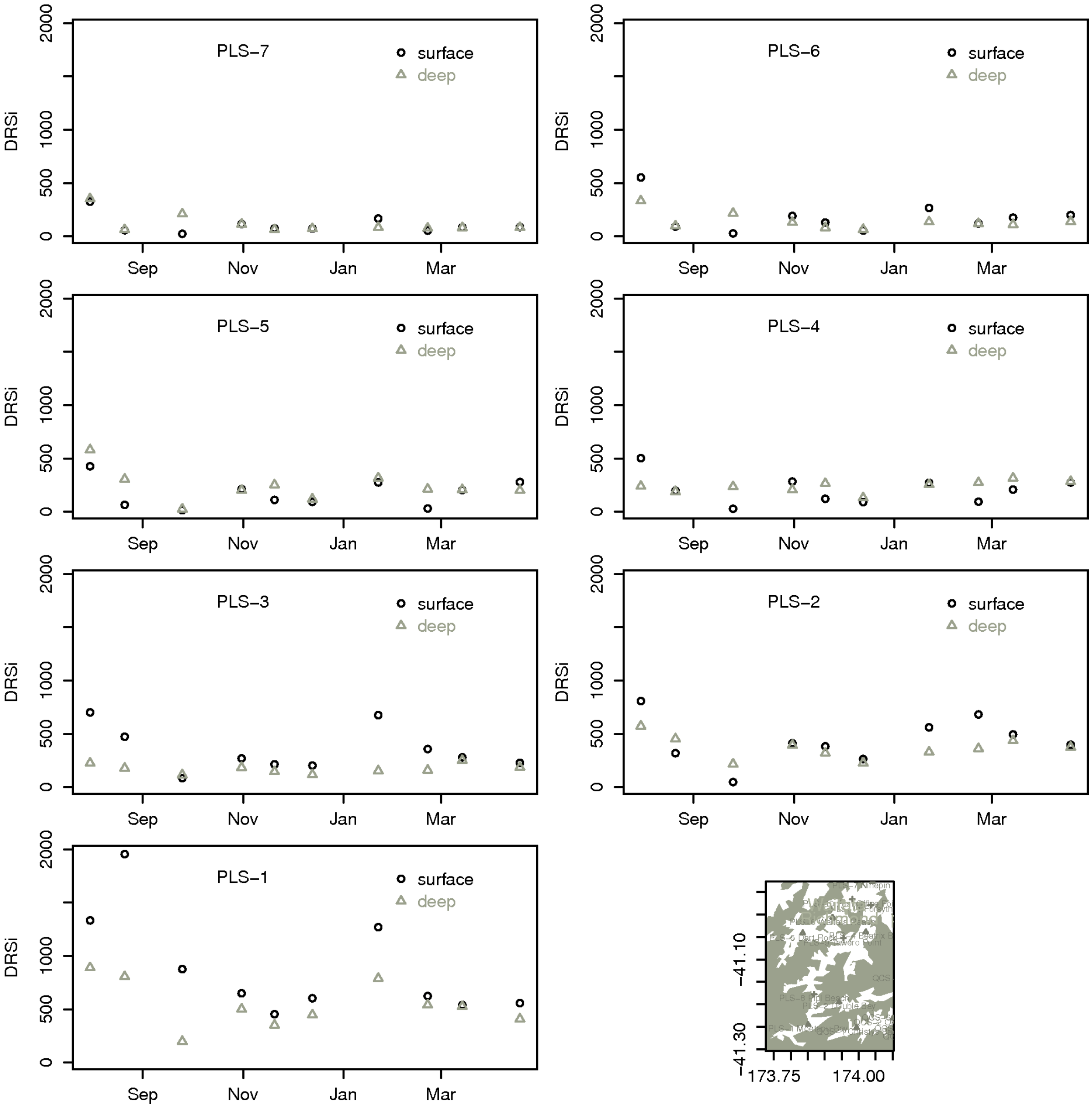


Figure 4-1: Time-series of dissolved reactive silicon (mg Si m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

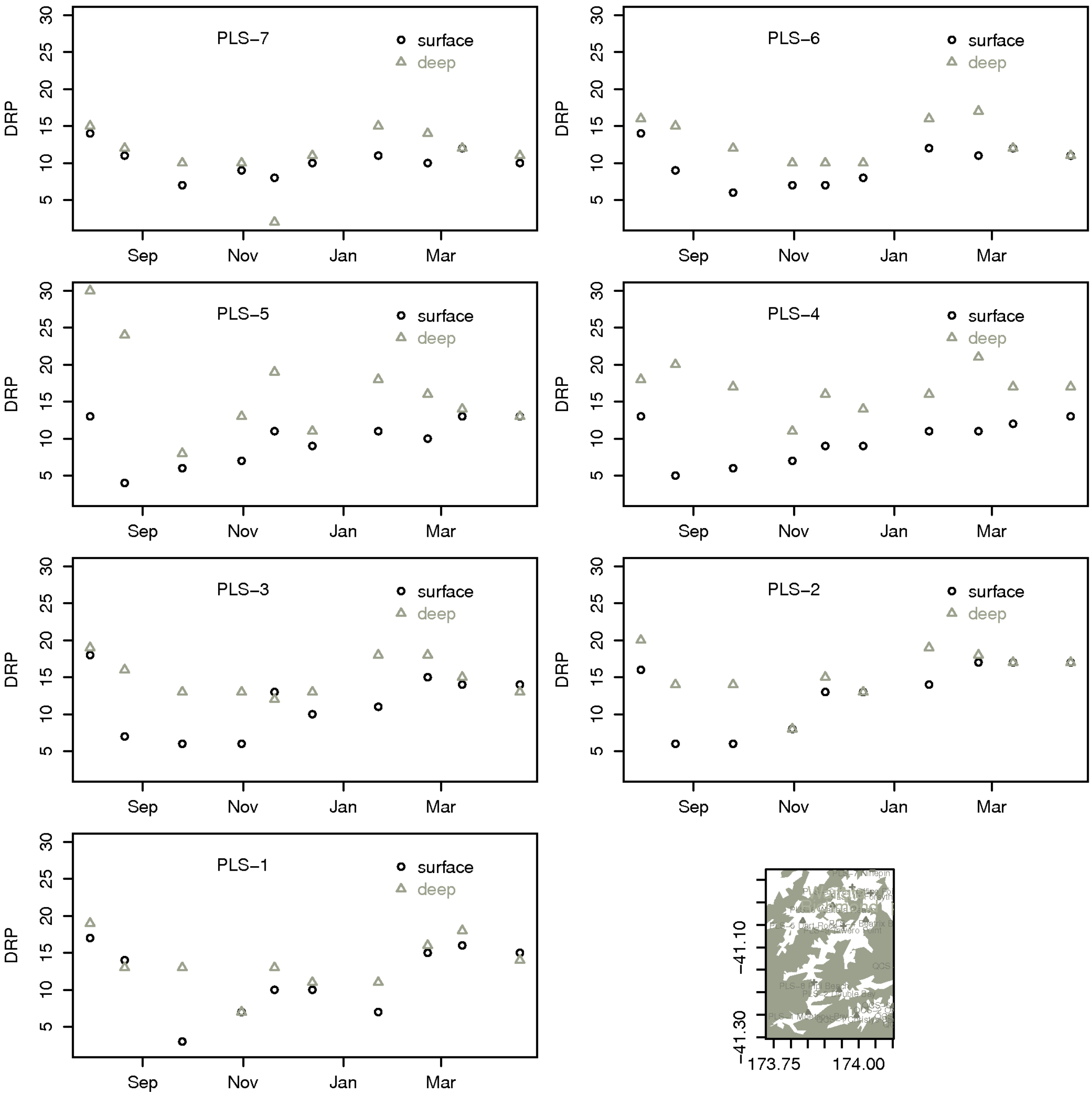


Figure 4-2: Time-series of dissolved reactive phosphorus (mg P m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

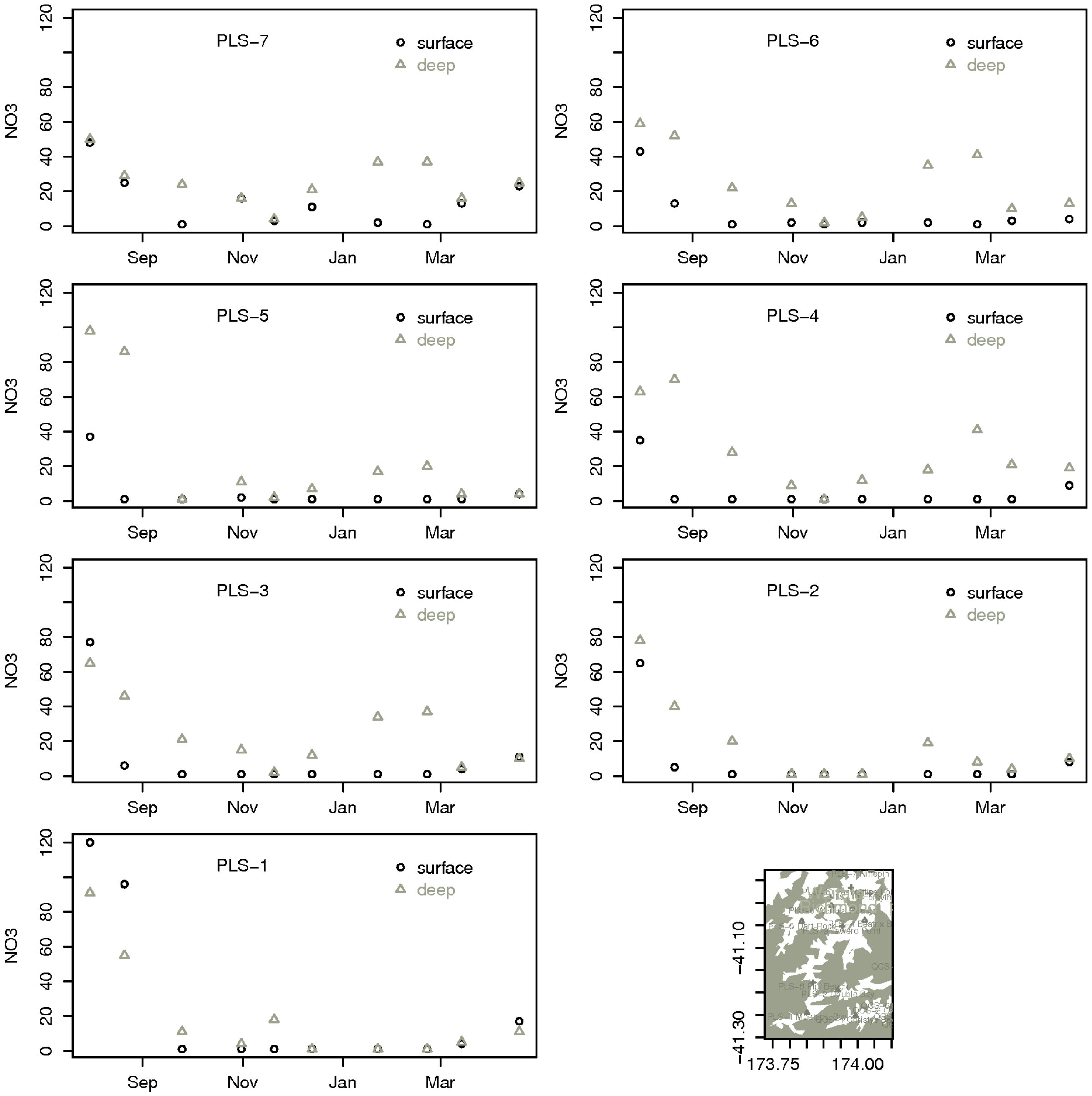


Figure 4-3: Time-series of nitrite+nitrate (mg N m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

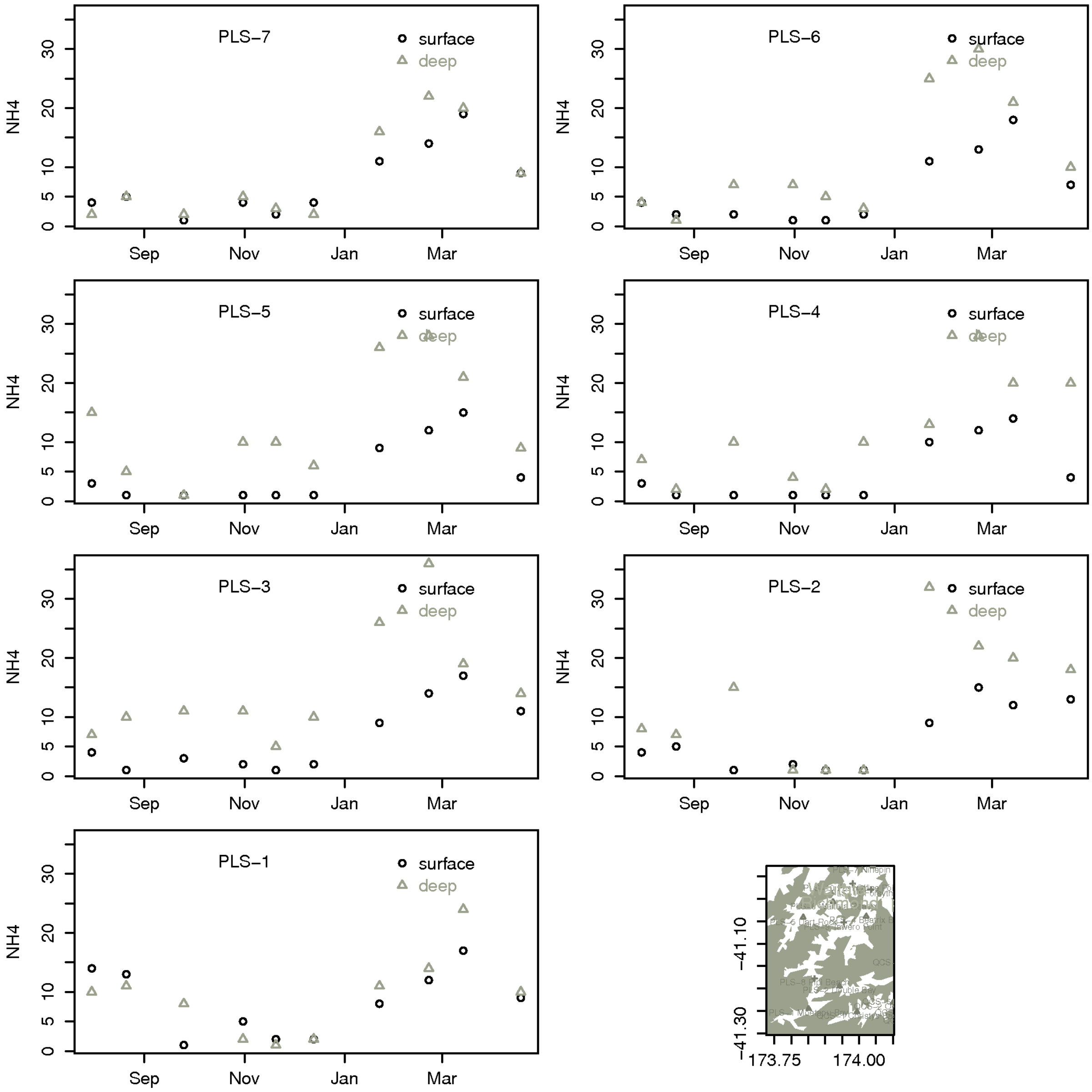


Figure 4-4: Time-series of ammoniacal nitrogen (mg N m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

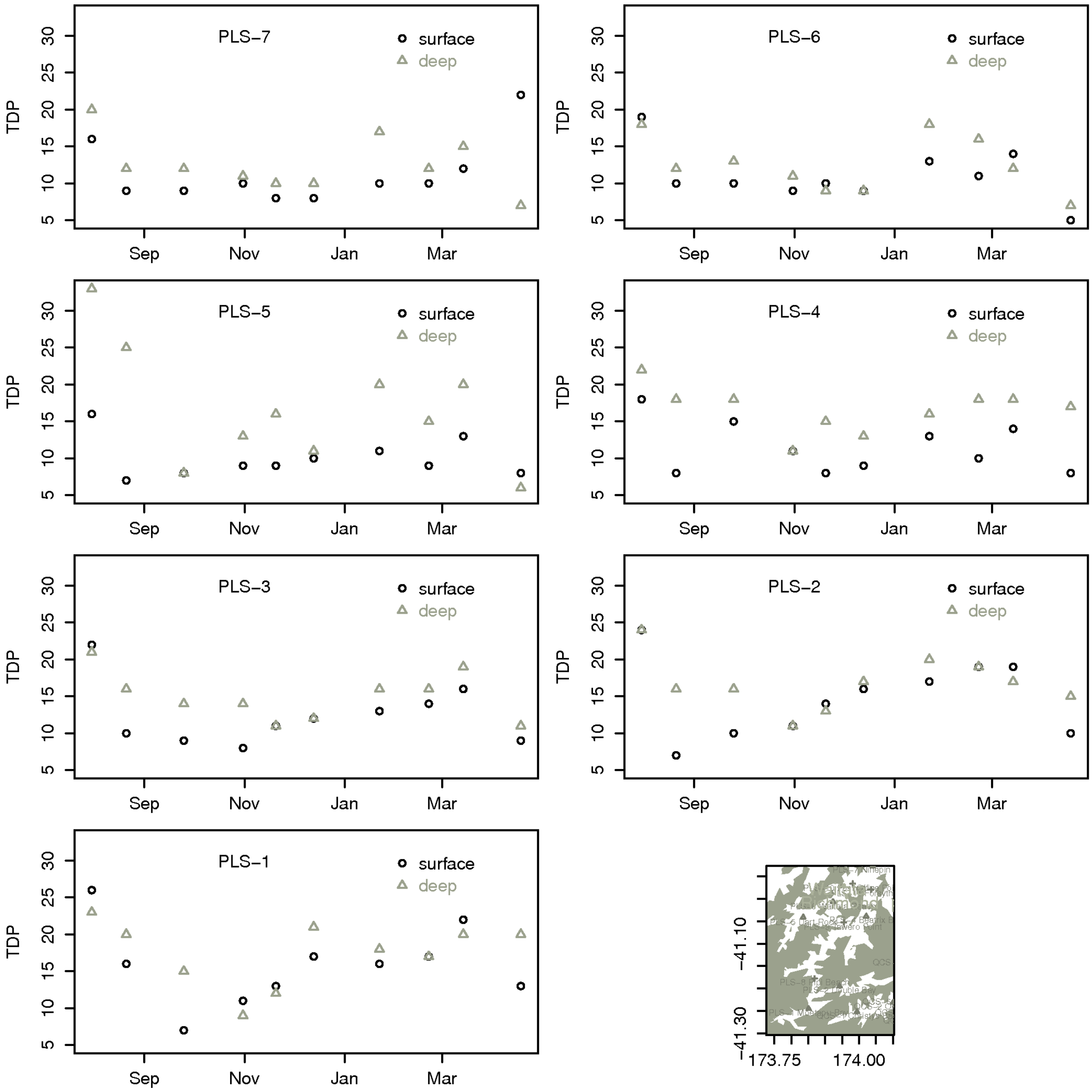


Figure 4-5: Time-series of total dissolved phosphorus (mg P m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

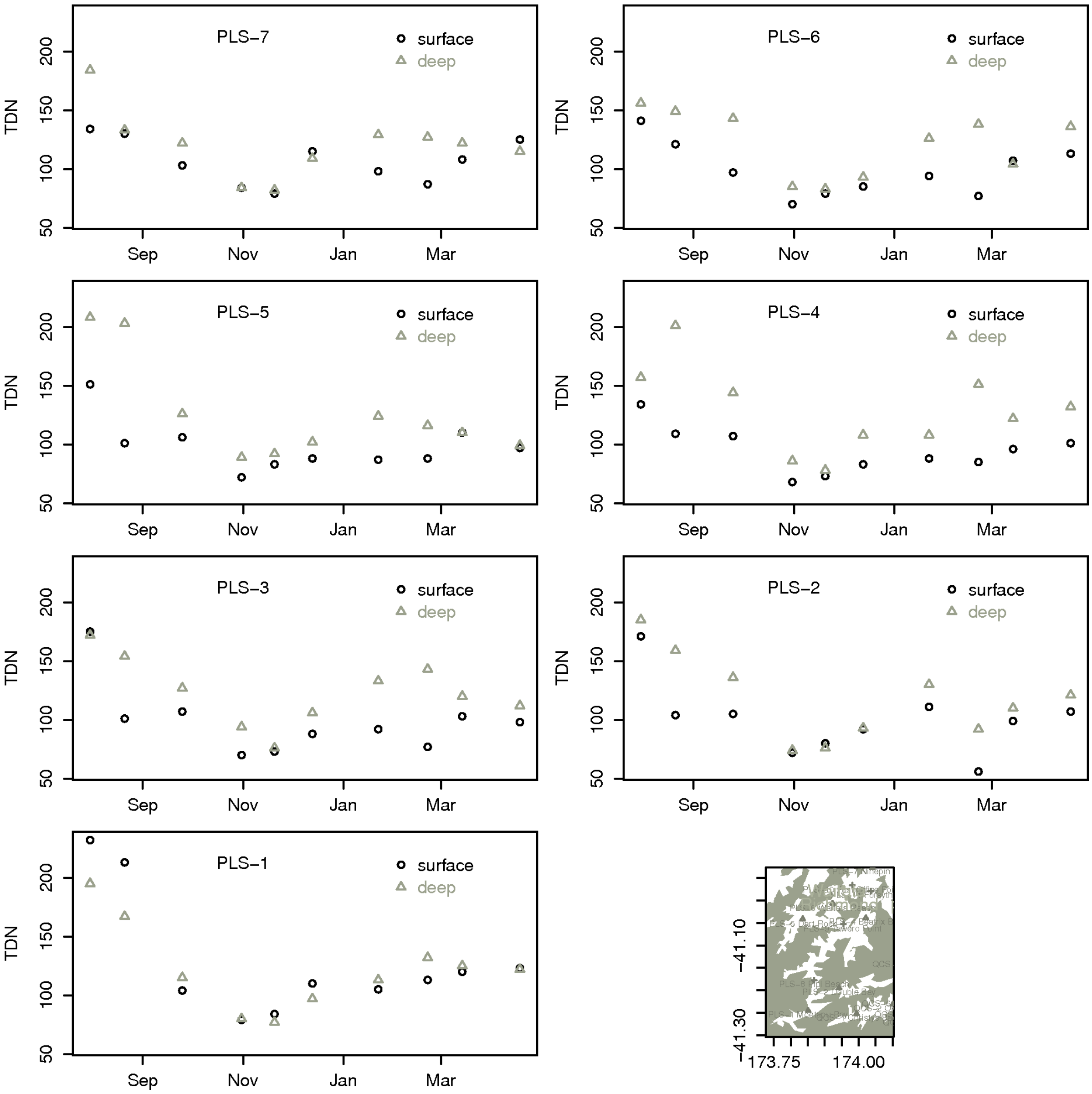


Figure 4-6: Time-series of total dissolved nitrogen (mg N m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

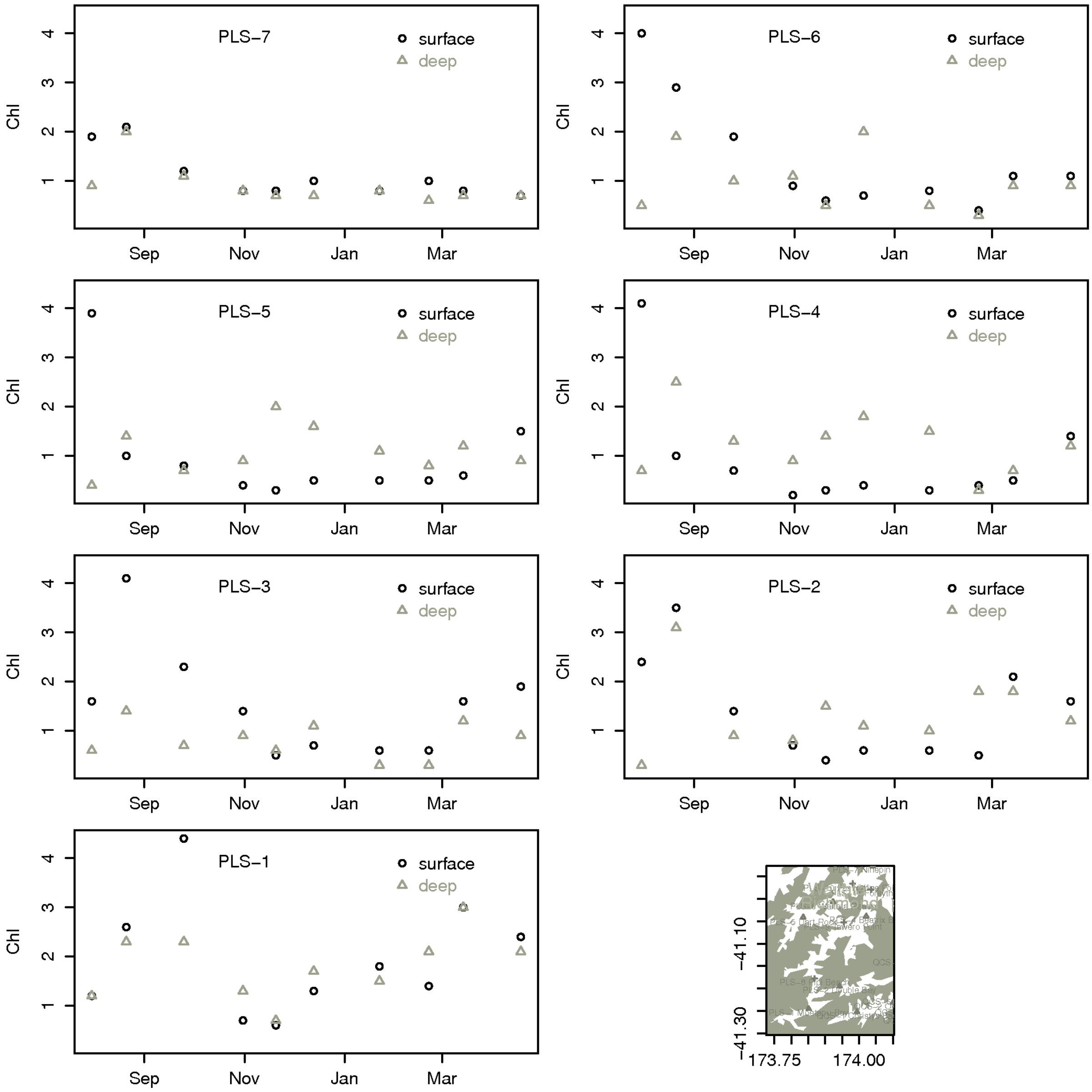


Figure 4-7: Time-series of chlorophyll-a concentration (mg Chl-a m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

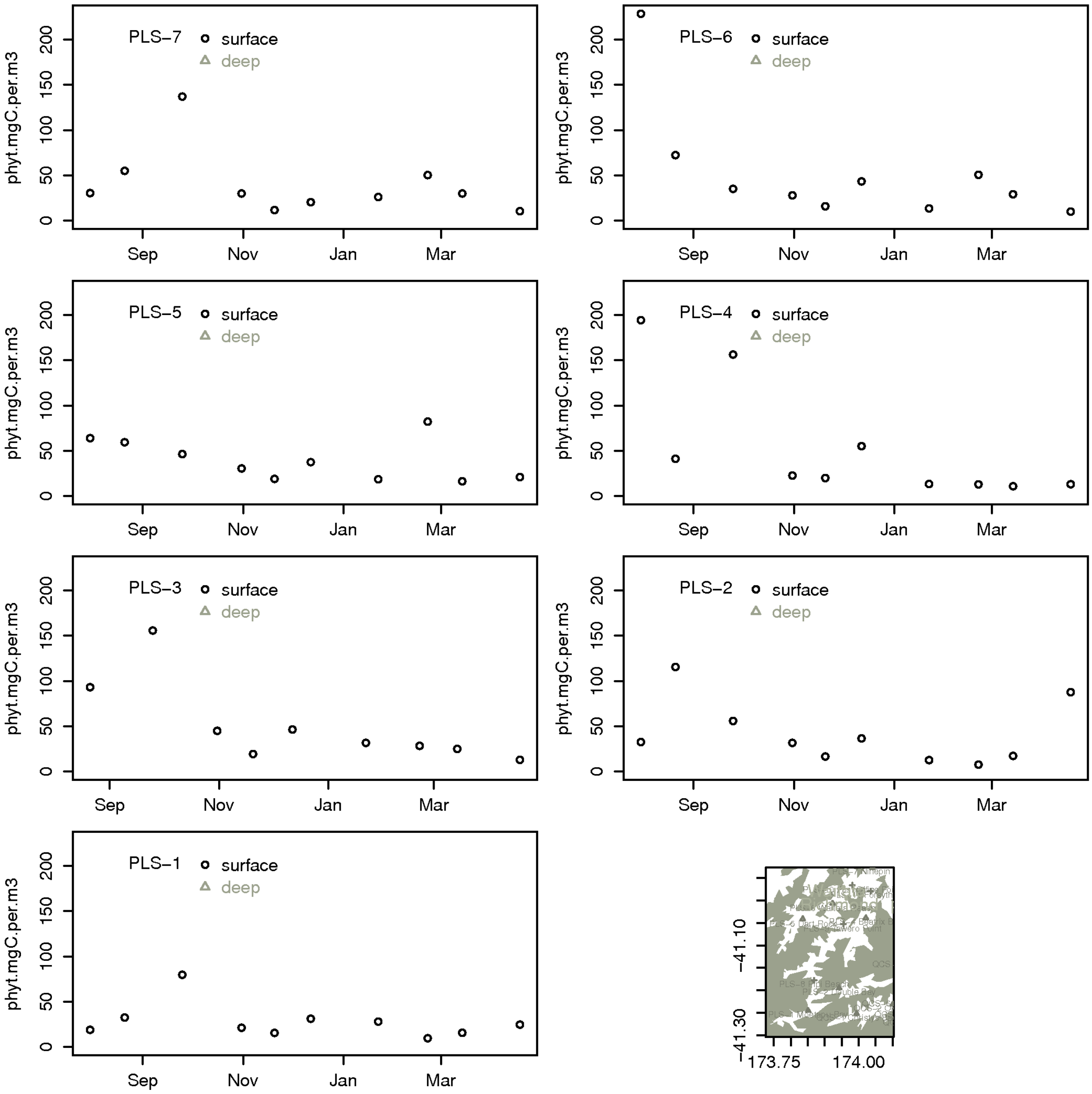


Figure 4-8: Time-series of phytoplankton carbon concentration (mg C m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013). Carbon concentration was calculated from cell-counts, and empirical cell-carbon-cell-biovolume relationships.

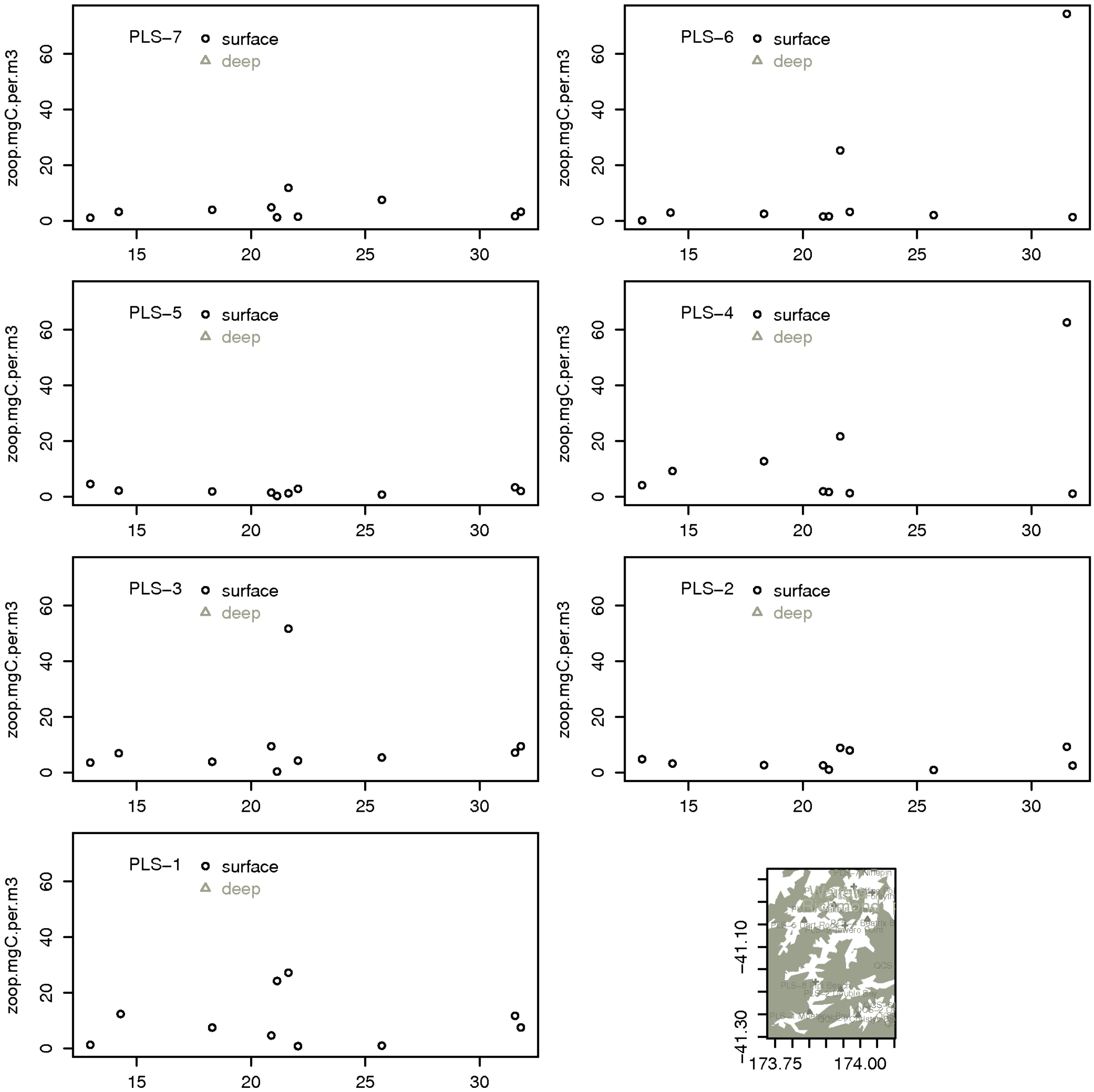


Figure 4-9: Time-series of inferred zooplankton carbon concentration (mg C m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013). Carbon concentration was estimated from counts of individuals and published estimates of individual weights for the taxa.

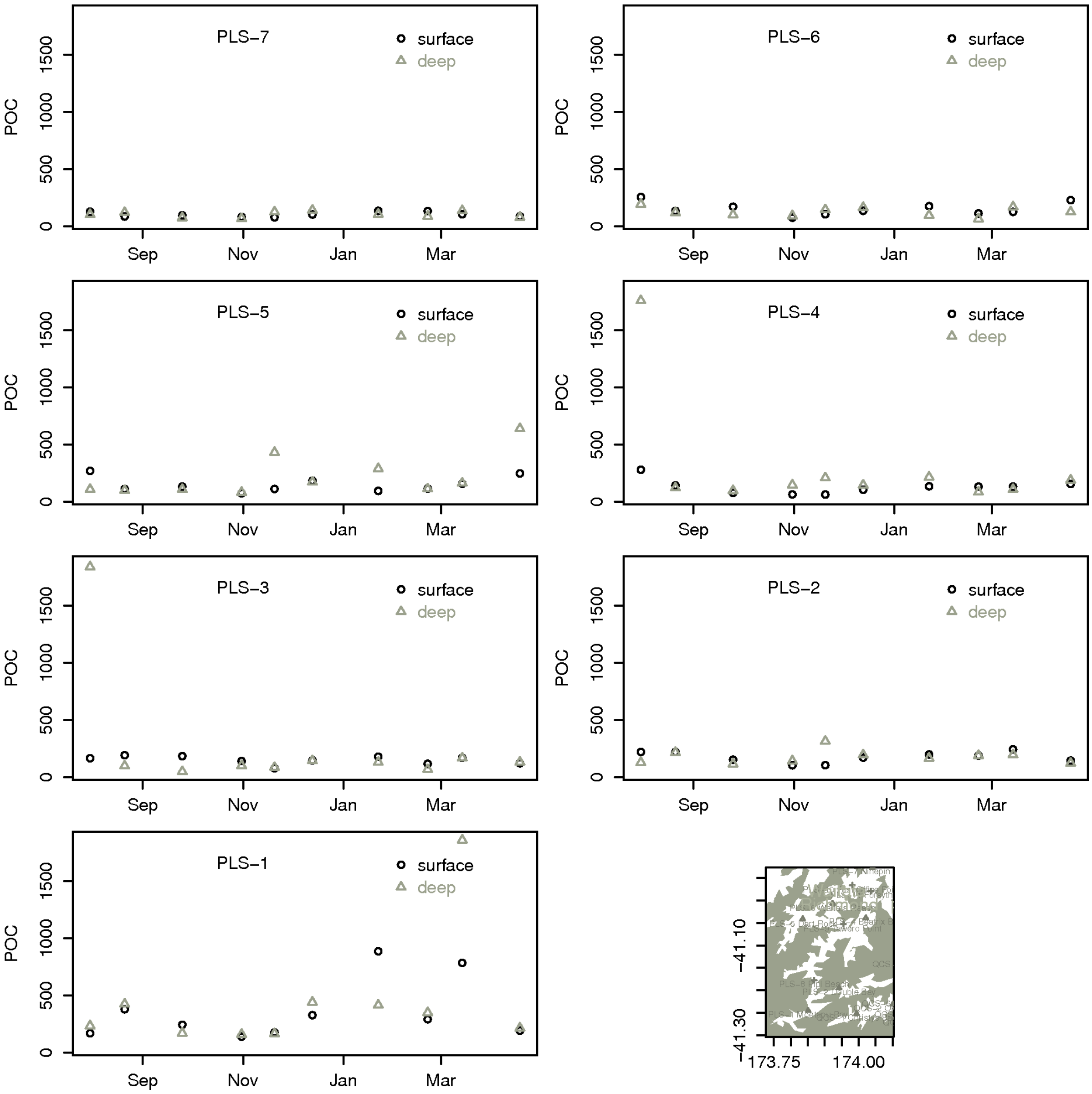


Figure 4-10: Time-series of particulate organic carbon concentration (mg C m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

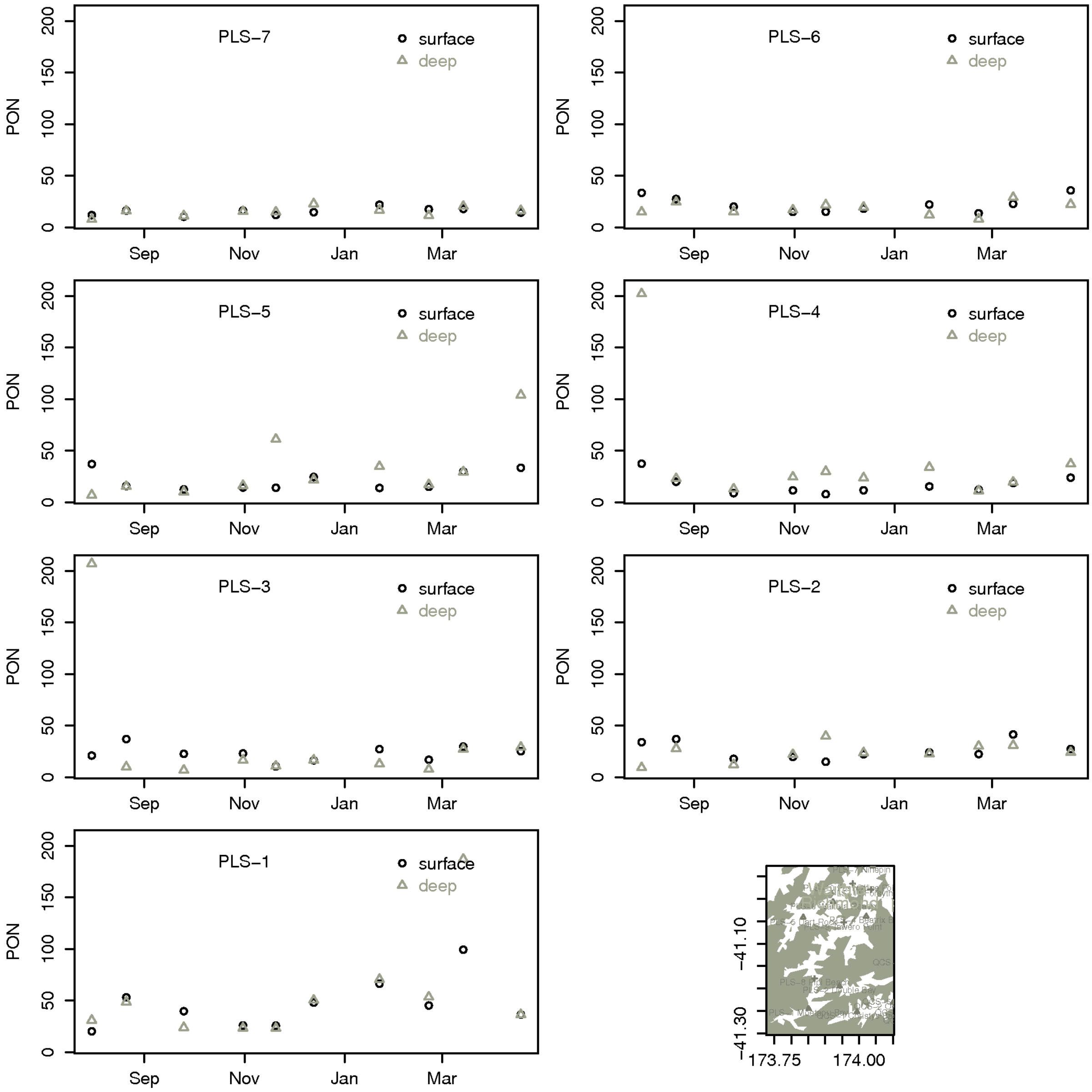


Figure 4-11: Time-series of particulate organic nitrogen concentration (mg N m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

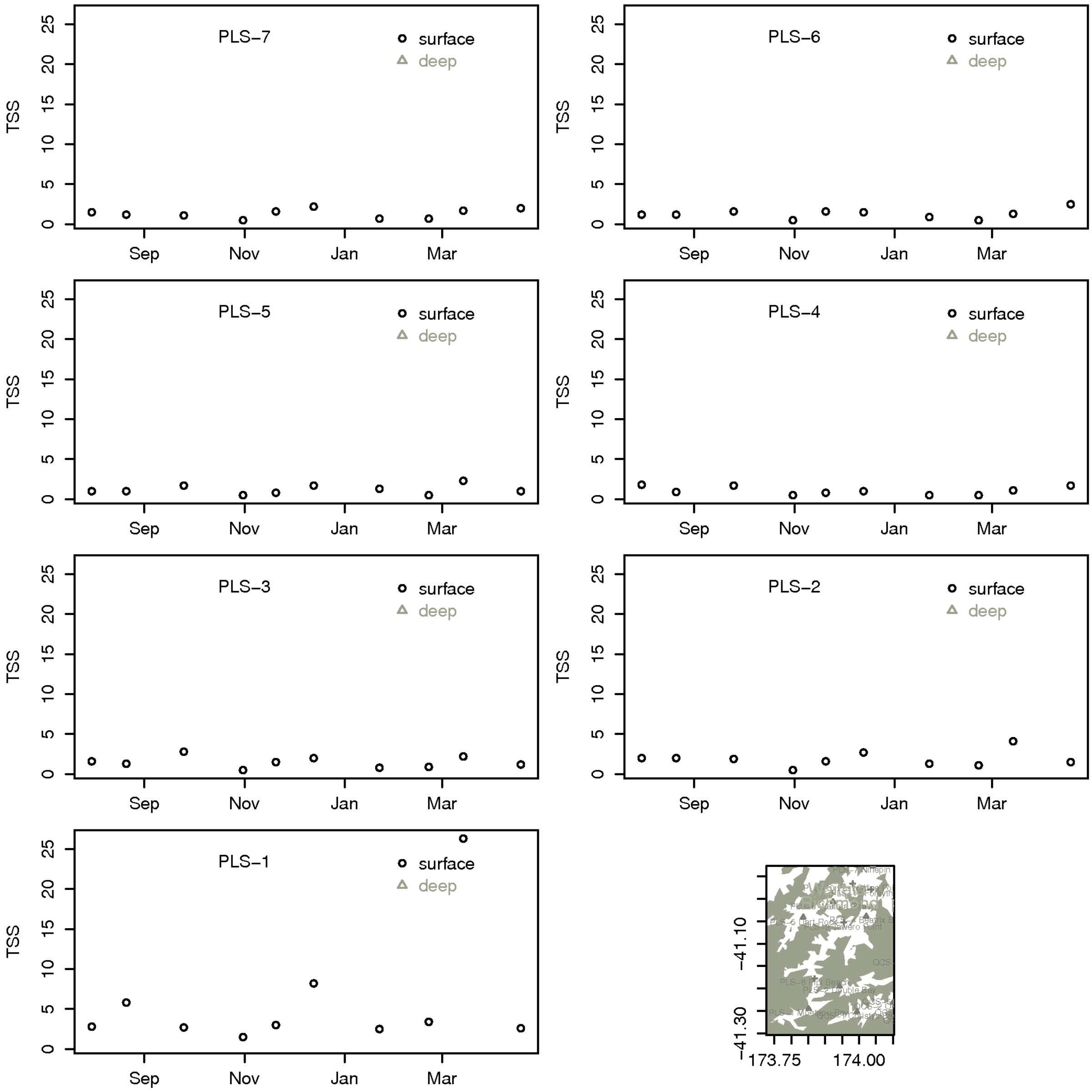


Figure 4-12: Time-series of total suspended solids (g DW m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013).

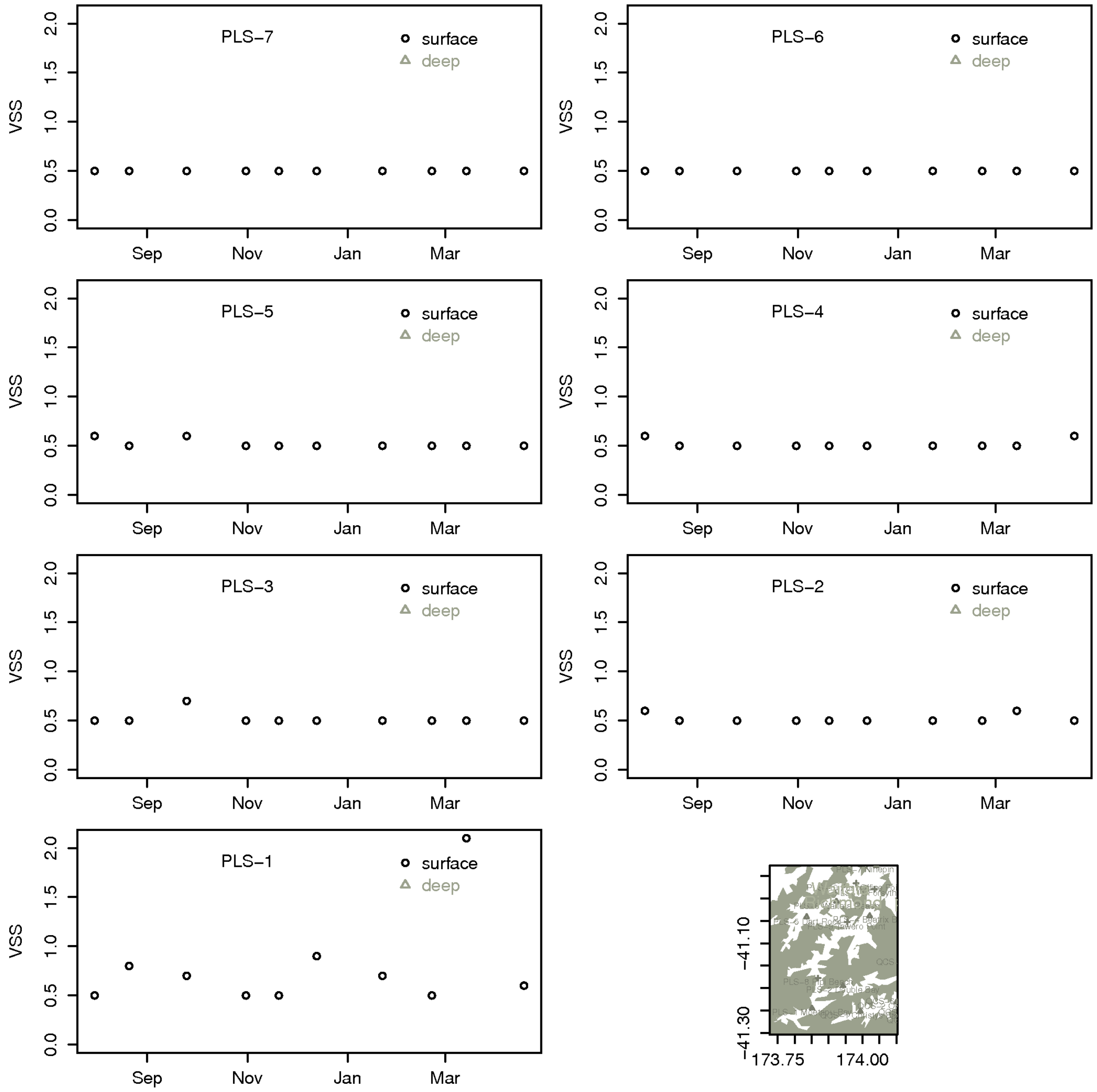


Figure 4-13: Time-series of volatile suspended solids (mg AFDW m^{-3}) measured at seven sites in Pelorus Sound in the Marlborough District Council sampling program (2012-2013). Values showing as 0.5 on the graphs are recorded as <0.5 in the laboratory reports. Thus, the points on the graphs are over-estimates of the true concentrations.

4.2 Comparison of MDC data and NIWA data

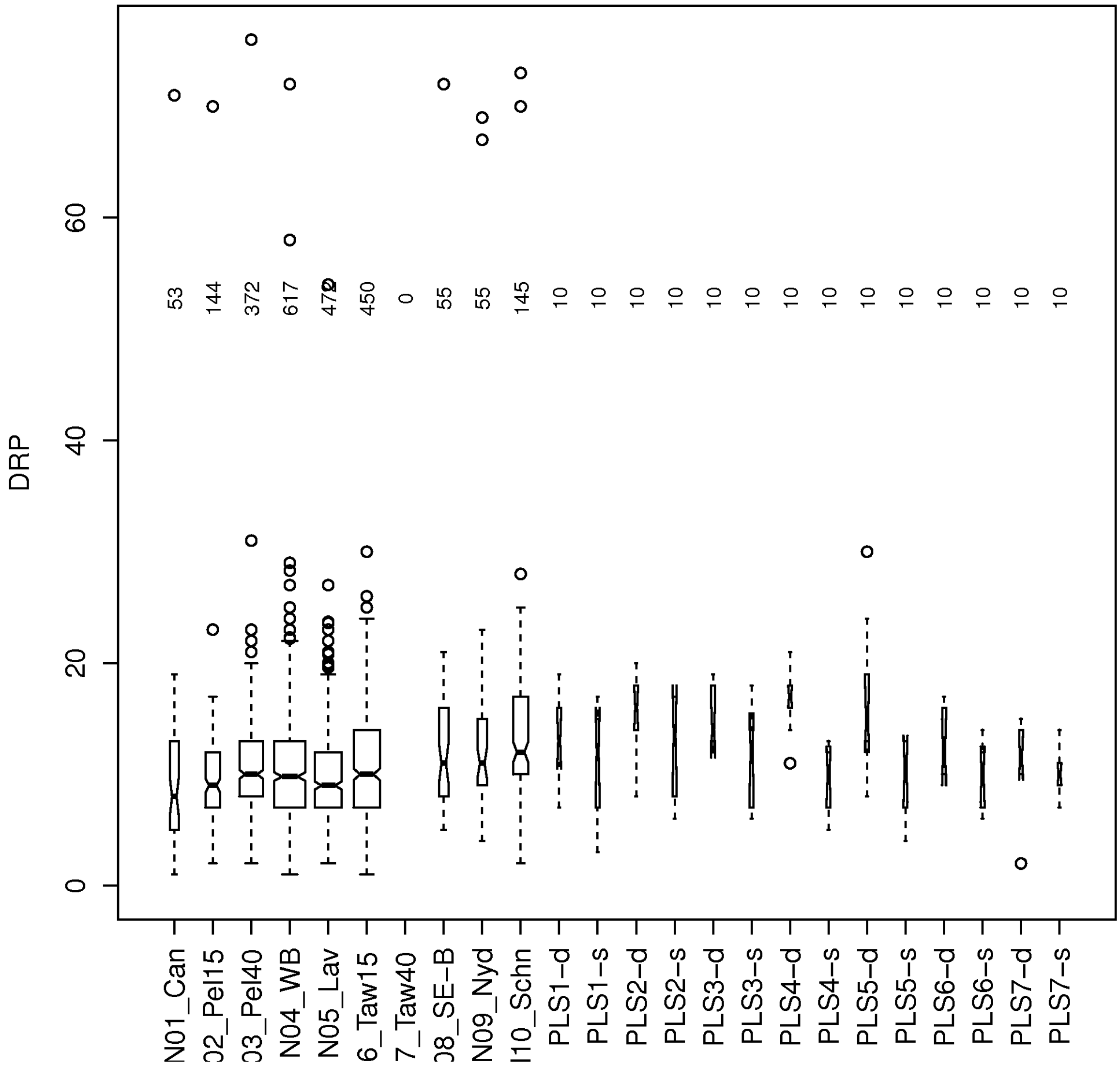


Figure 4-14: Boxplots illustrating the distributions of all DRP concentrations (mg P m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1 – PLS-7) Pelorus Sounds data. The number above each boxplot indicate the number of data-points in the time-series. The width of each box-plot is proportional to the square-root of this number. N01-Can: Cannonhill;NO2-Pel15: outer Pelorus surface layer sample; N03-Pel40: outer Pelorus 40 m sample; N04-WB: west Beatrix; N05-Lav: Laverique Bay; NO6-Taw15: surface layer Tawero sample; NO7-Taw40: Tawero 40 m sample; NO8-SE-B: Southeast Bay; NO9-Nyd: Nydia Bay; N10-Schn: Schnapper Bay; PLS<1-7>-<s,d> MDC's stations 1-7 surface and deep samples.

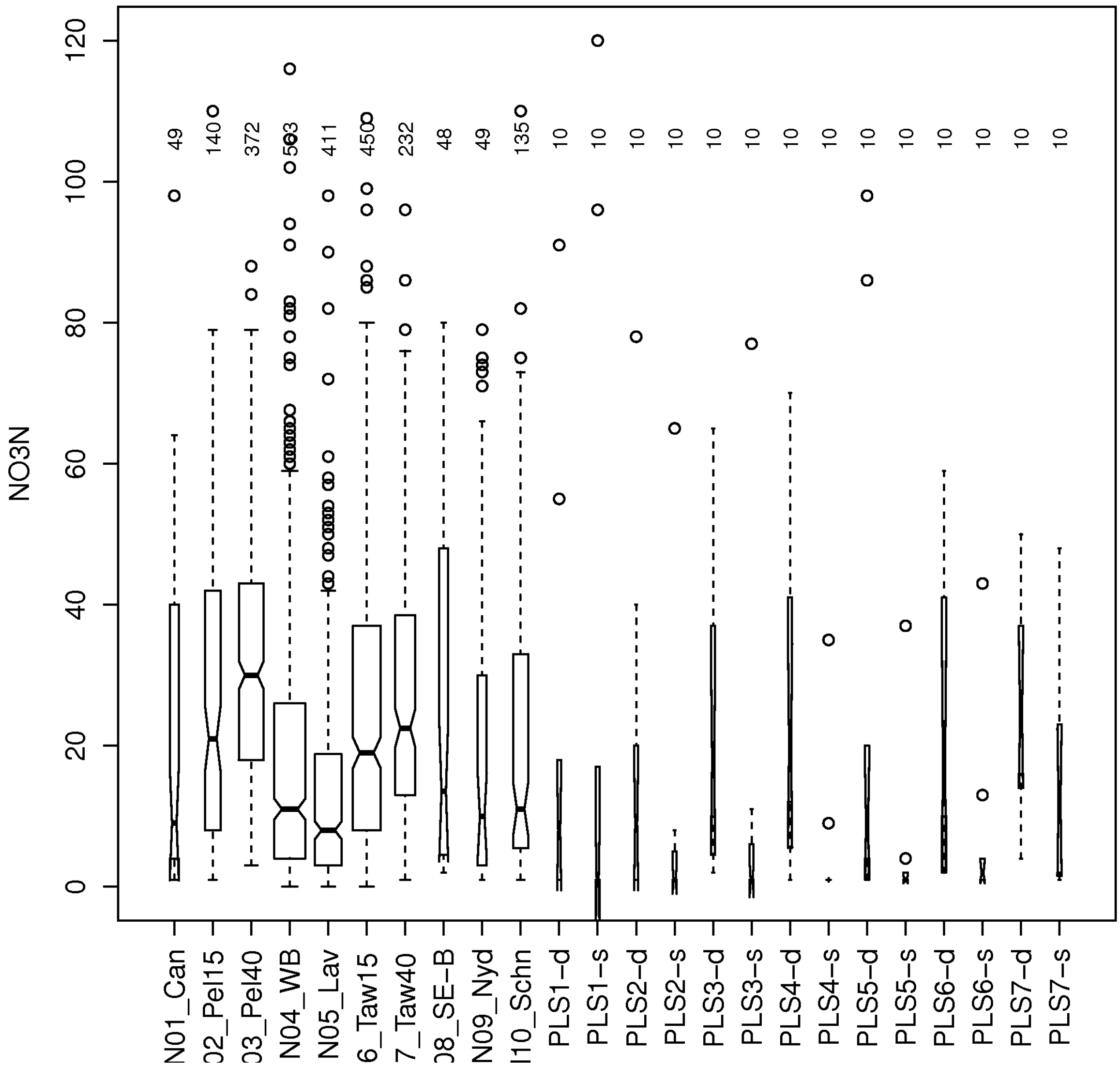


Figure 4-15: Boxplots illustrating the distributions of all (nitrate+nitrite) concentrations (mg N m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

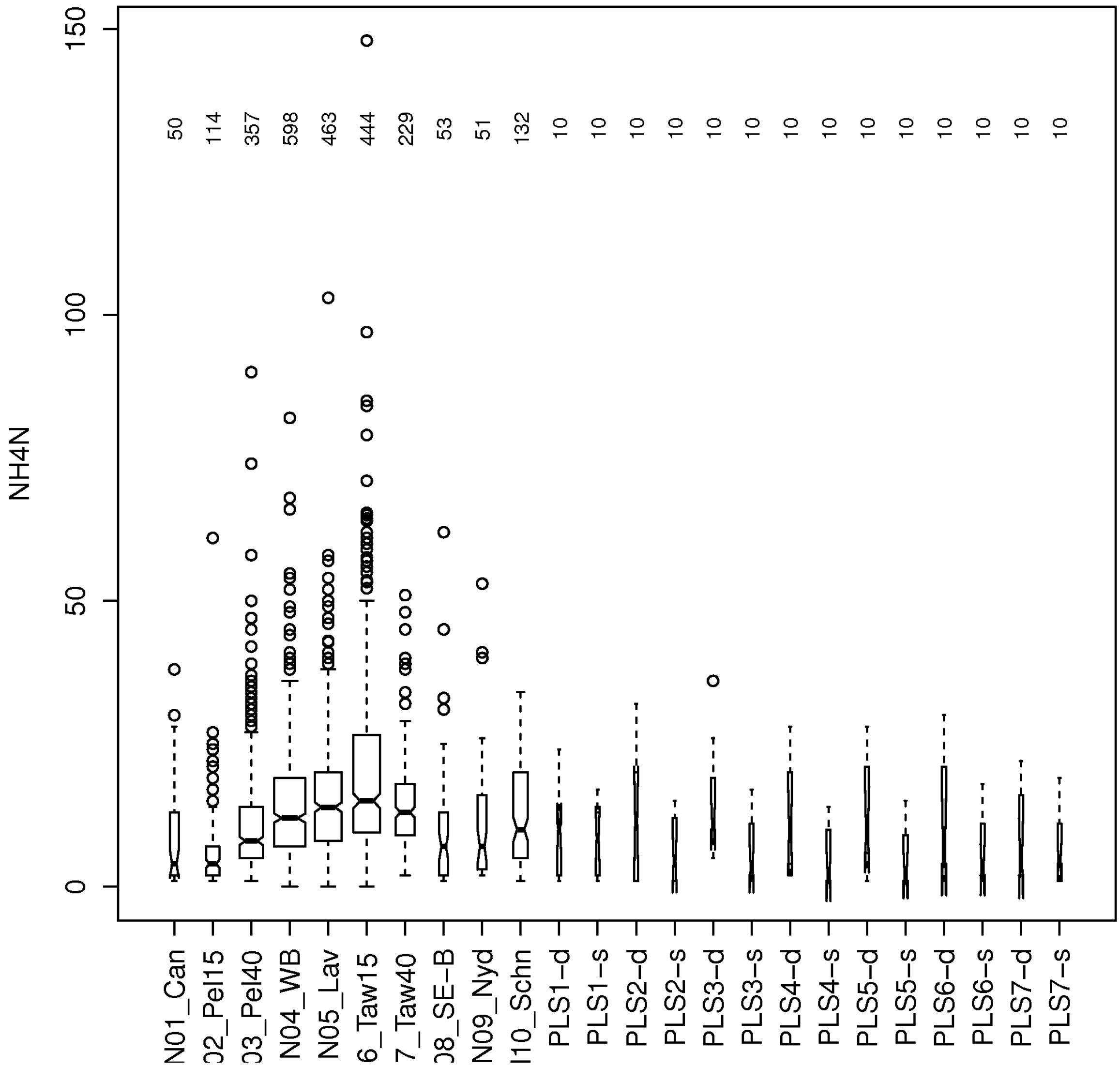


Figure 4-16: Boxplots illustrating the distributions of all ammoniacal nitrogen concentrations (mg N m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

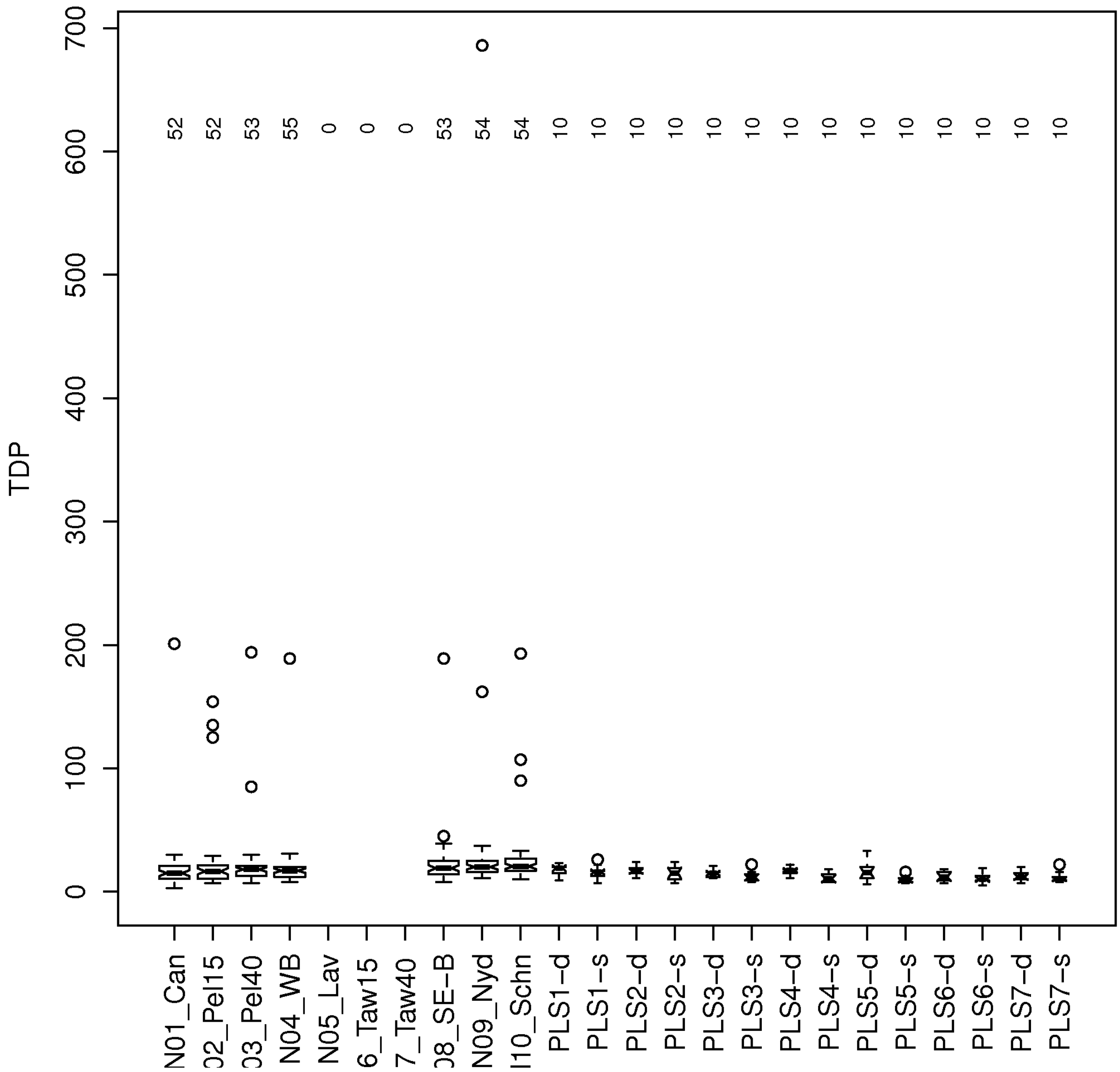


Figure 4-17: Boxplots illustrating the distributions of all total dissolved phosphorus concentrations (mg P m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

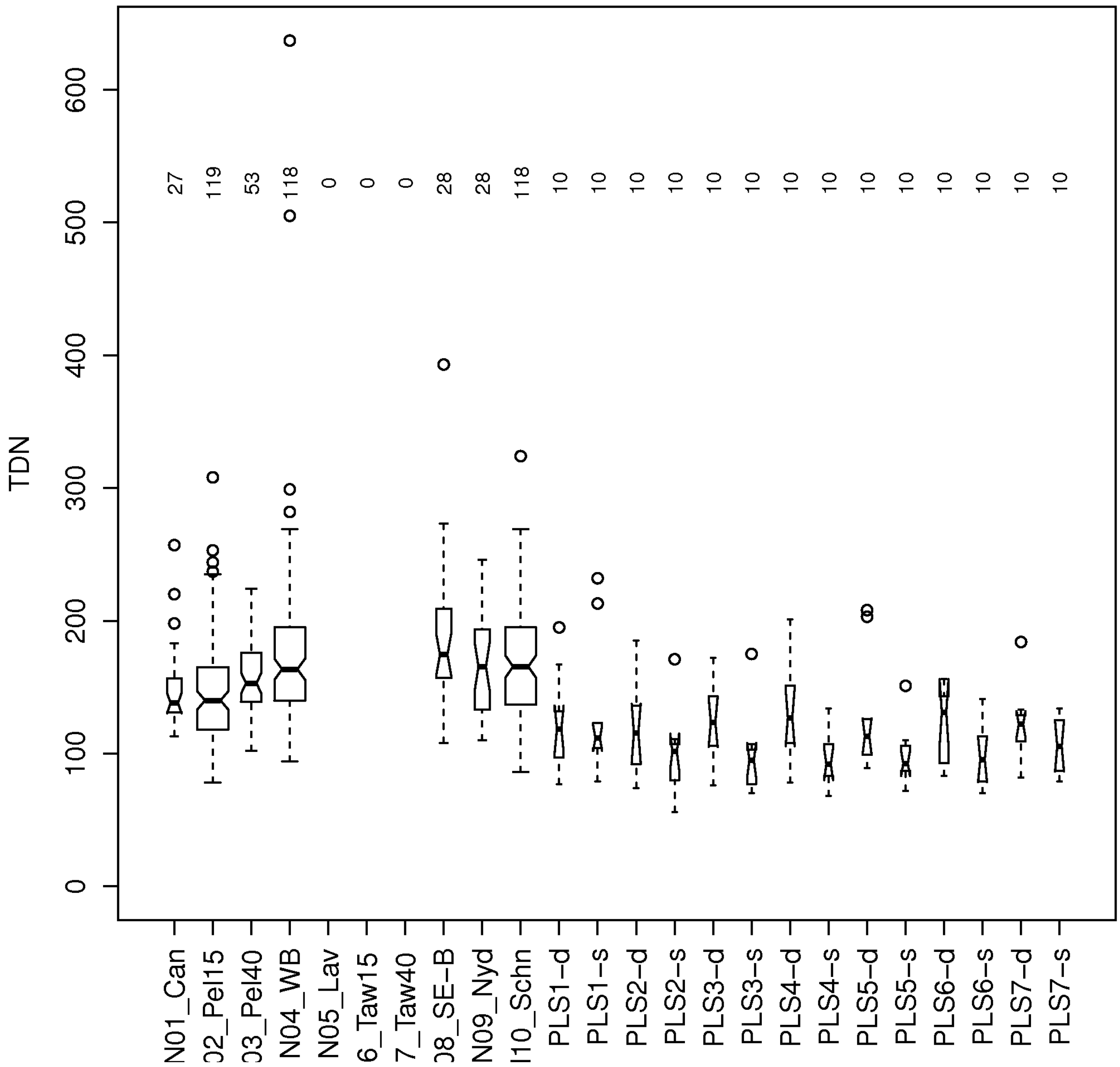


Figure 4-18: Boxplots illustrating the distributions of all total dissolved nitrogen concentrations (mg N m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

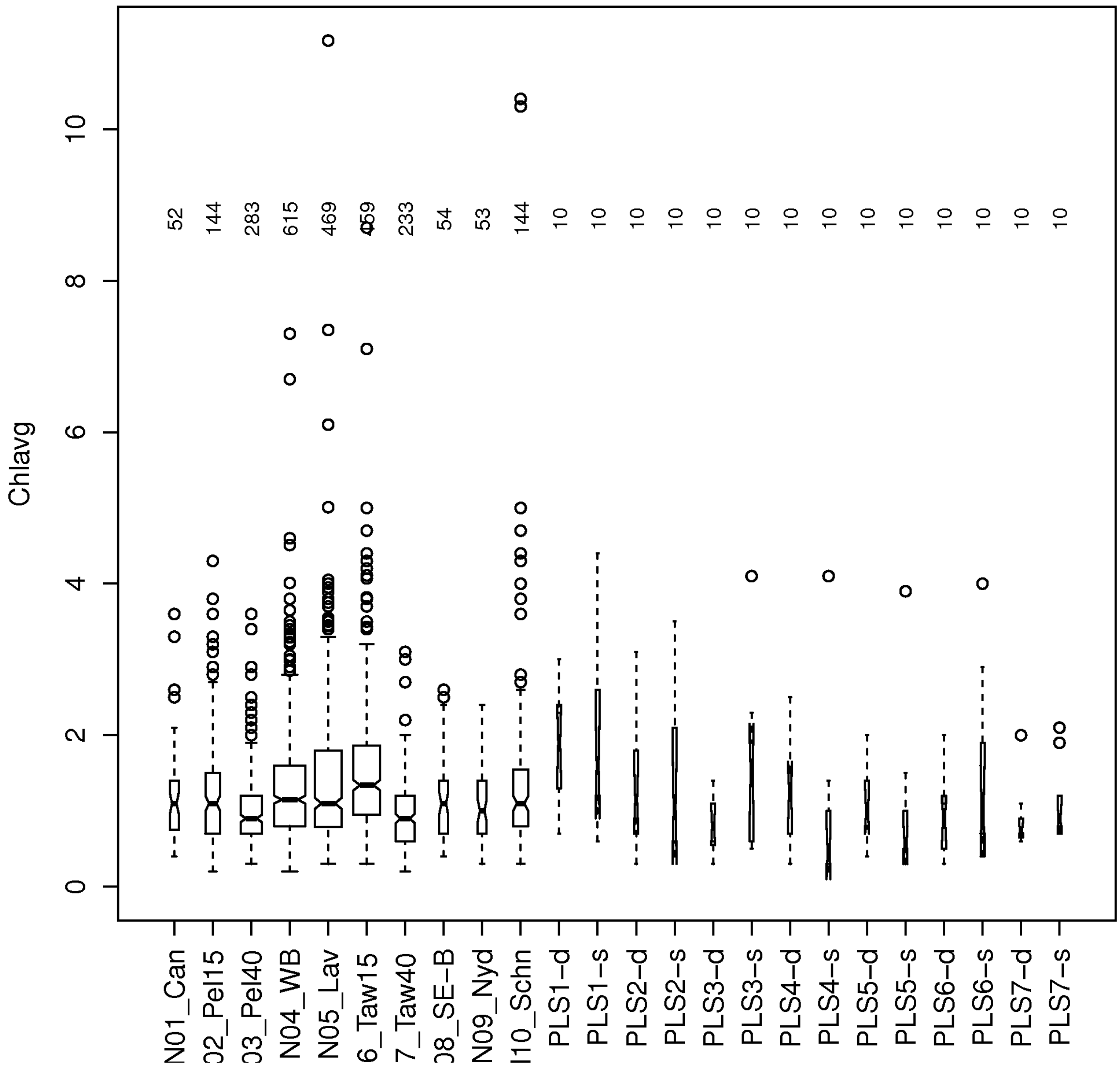


Figure 4-19: Boxplots illustrating the distributions of all chlorophyll-a concentrations (mg Chl-a m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

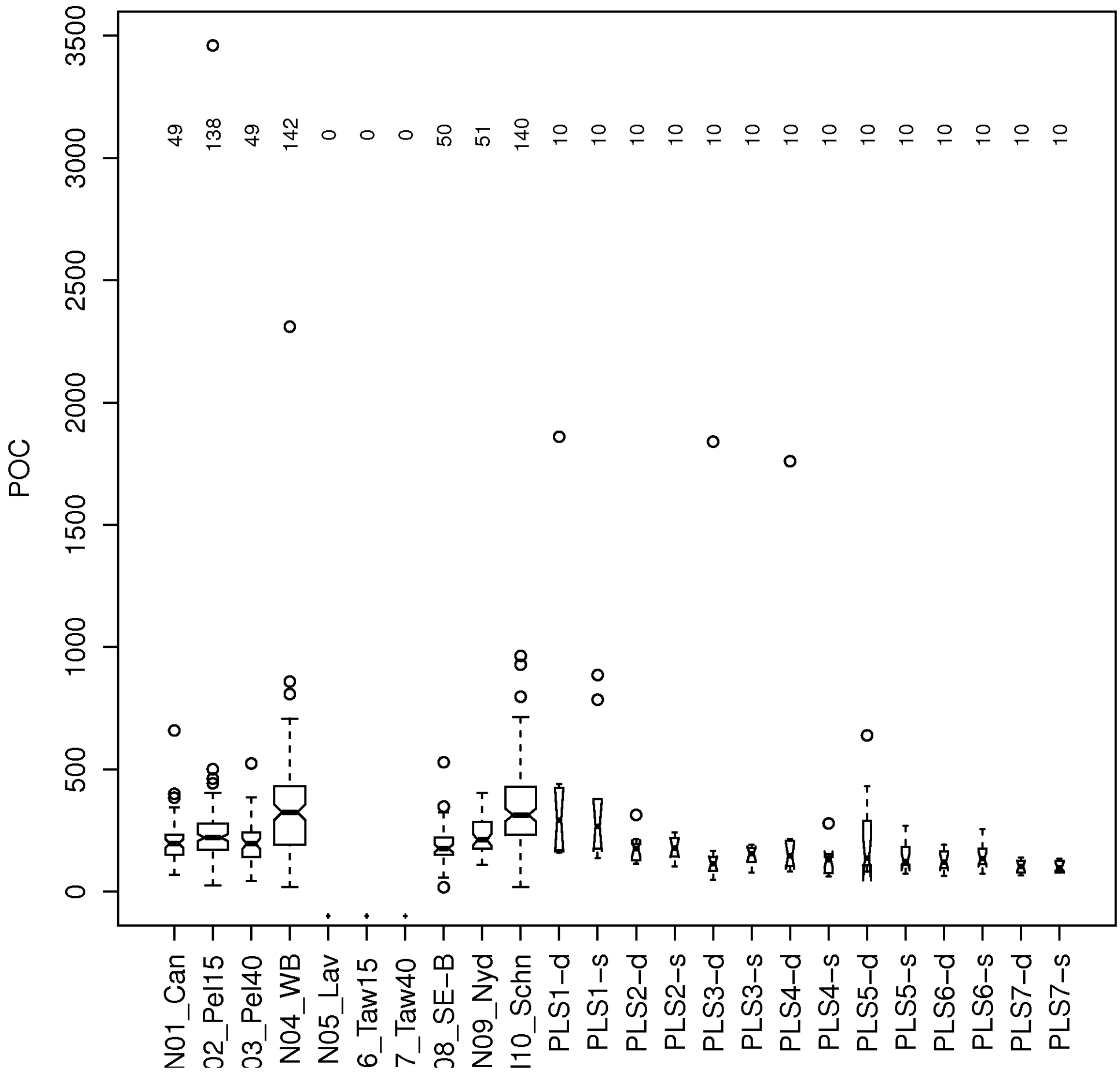


Figure 4-20: Boxplots illustrating the distributions of all particulate organic carbon concentrations (mg C m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

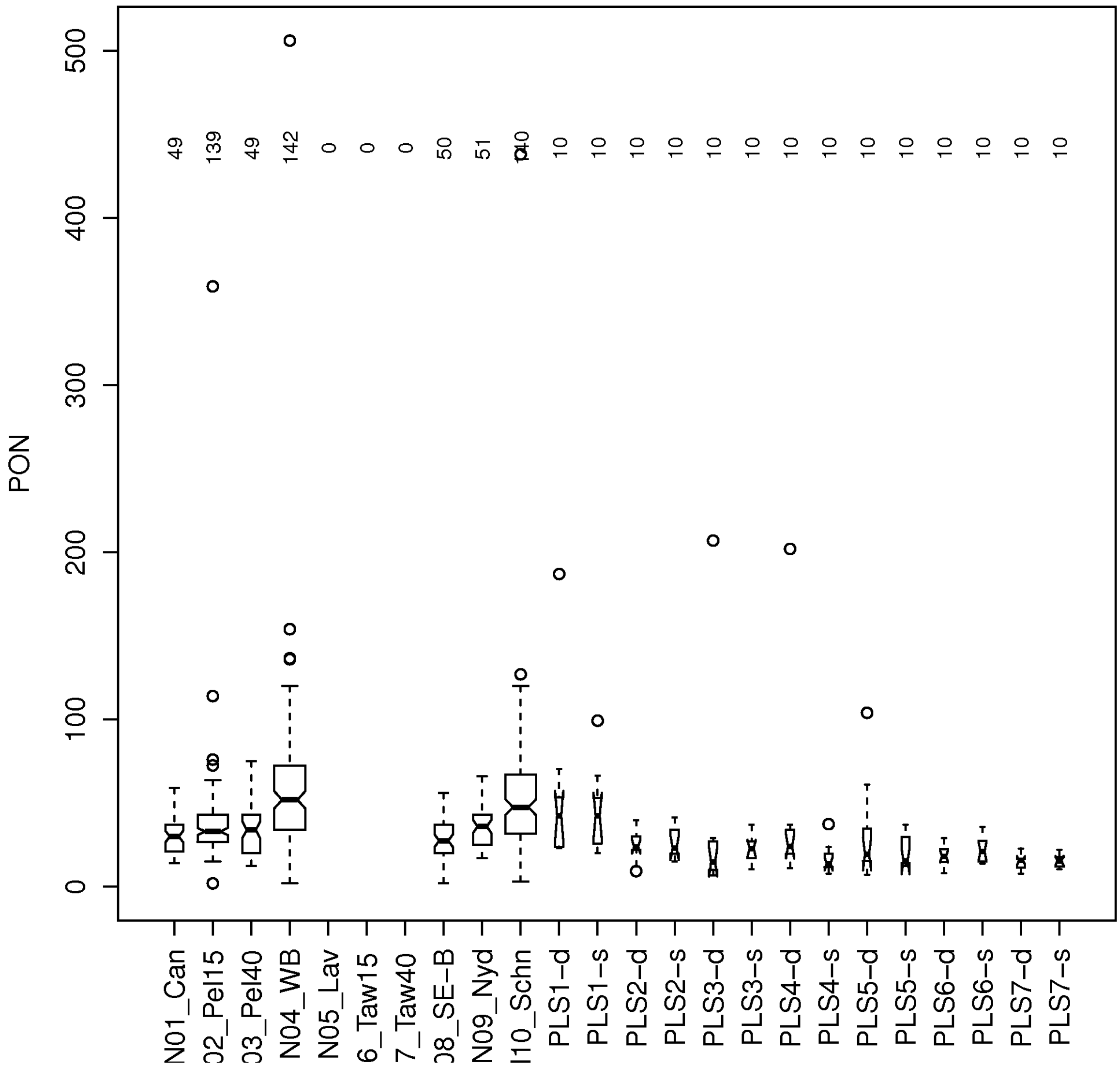


Figure 4-21: Boxplots illustrating the distributions of all particulate organic nitrogen concentrations (mg N m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

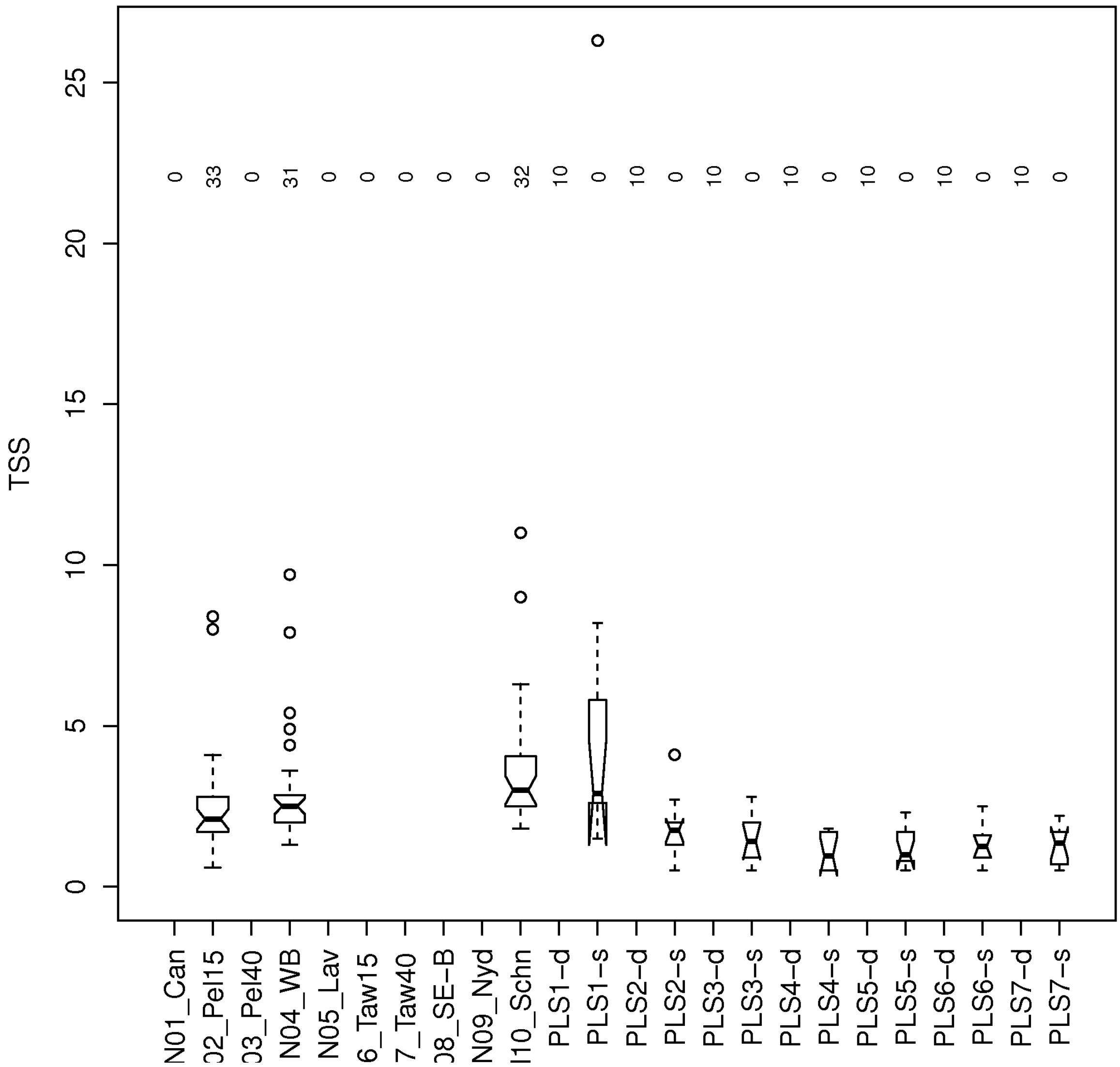


Figure 4-22: Boxplots illustrating the distributions of all total suspended solids concentrations (g DW m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

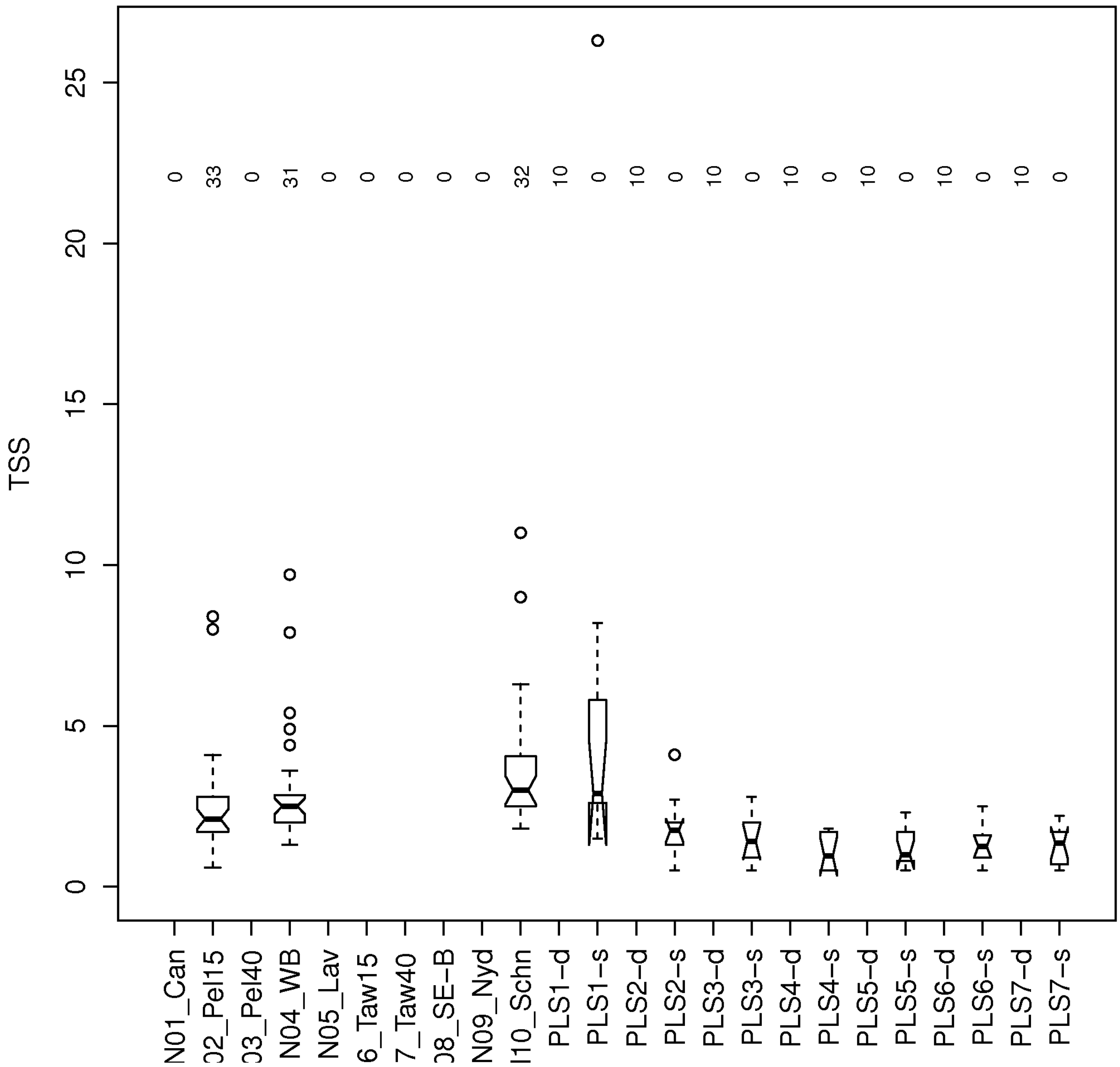


Figure 4-23: Boxplots illustrating the distributions of all total suspended solids concentrations (g DW m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

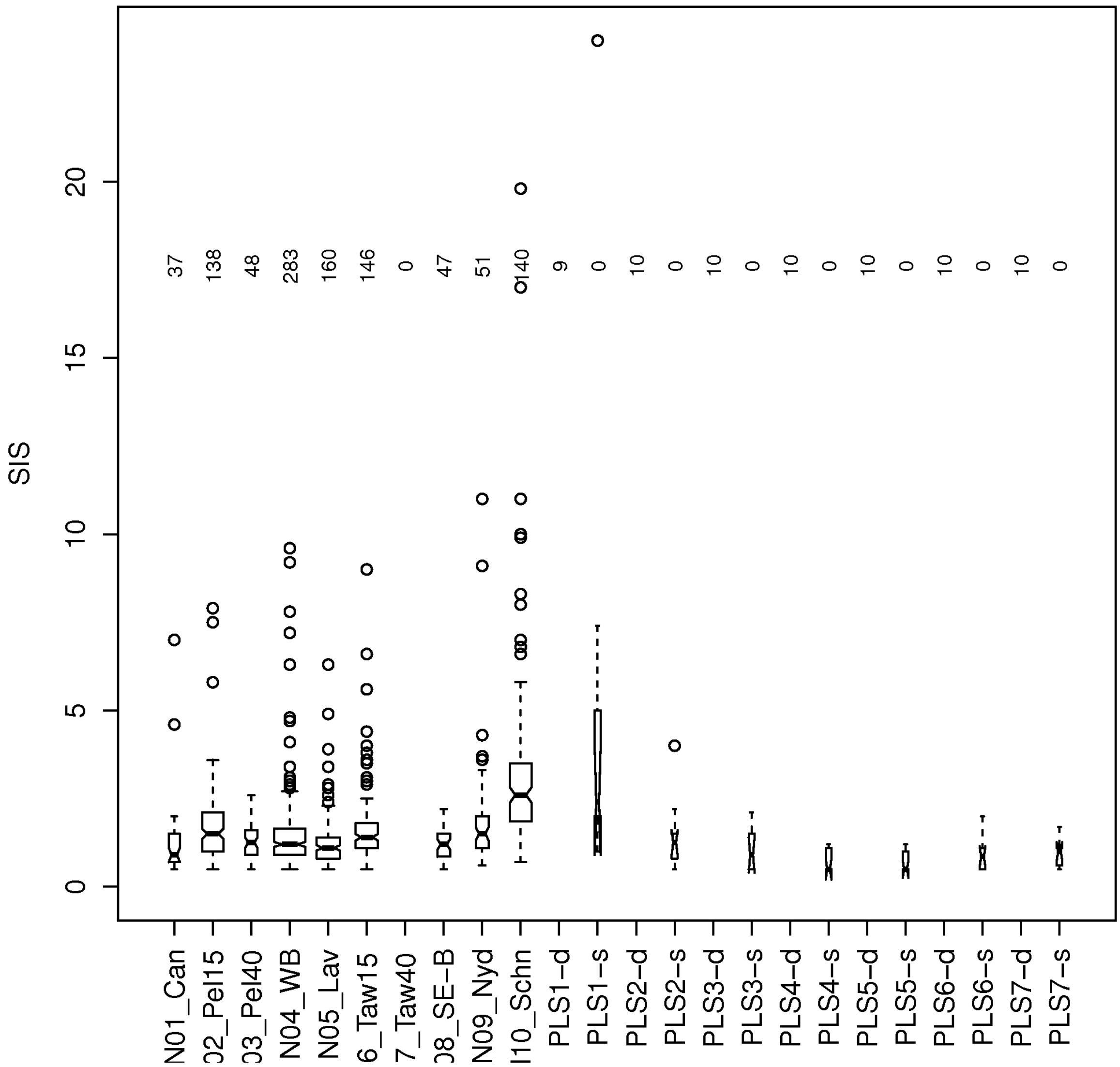


Figure 4-24: Boxplots illustrating the distributions of all suspended inorganic solids concentrations (g (DW-AFDW) m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

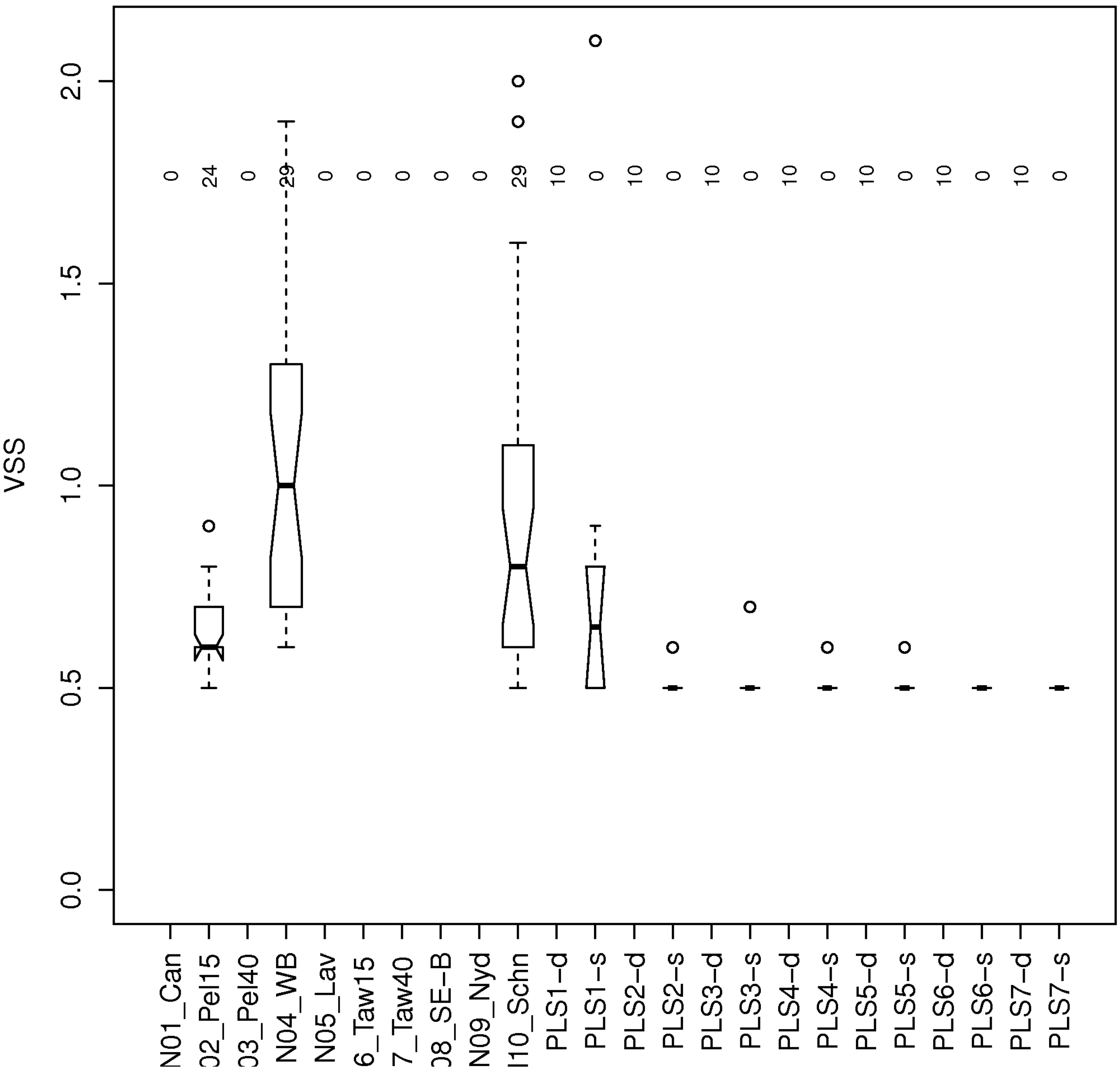


Figure 4-25: Boxplots illustrating the distributions of all volatile suspended solids concentrations (g AFDW m^{-3}; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data. VSS concentrations recorded as <0.5 g m^{-3} by the laboratory were scored as 0.5 g m^{-3} in this analysis.

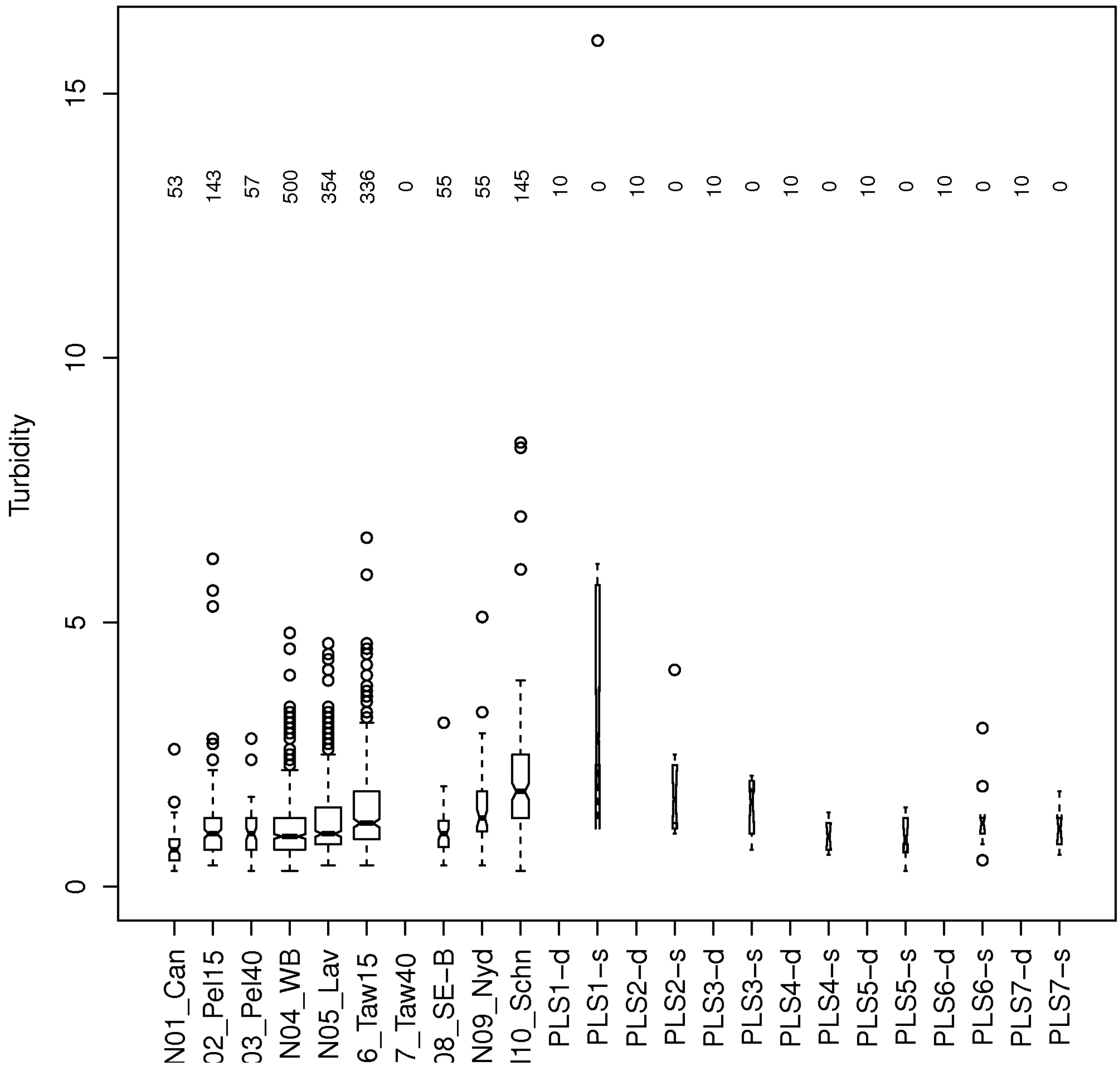


Figure 4-26: Boxplots illustrating the distributions of all turbidity values (NTU; over the entire length of each time-series) in NIWA's (N01-N10) and MDC's (PLS-1-PLS-7) Pelorus Sounds data.

4.3 Summary of MDC's Queen Charlotte Sound data

Since the MDC data extend back only to July 2011 and are based upon monthly sampling, there are (at most) two data-points per sampling station. Rather than using box-plots to summarize the data, the raw data are presented in graphical form. As with NIWA's Pelorus data, the data are grouped by month. For each variable, we produce a page with five images (one per site). Each image presents a scatter plot of property-value versus calendar month.

4.4 Inorganic nutrients

The time-series of DRSi (Figure 4-27) begin only in in the latter part of 2012. Thus, they do not yet span an entire year. In Tory Channel (site 3), near-surface and near bottom DRSi concentrations are very similar, but at the other sites (particularly those of inner Queen Charlotte), deep water DRSi concentrations are usually greater than the corresponding near-surface ones. In general, DRSi concentrations appear to have declined over the sampling period. This is probably a seasonal effect (high DRSi in winter and low in summer caused by summertime phytoplankton growth), but with so few data we cannot be confident of that.

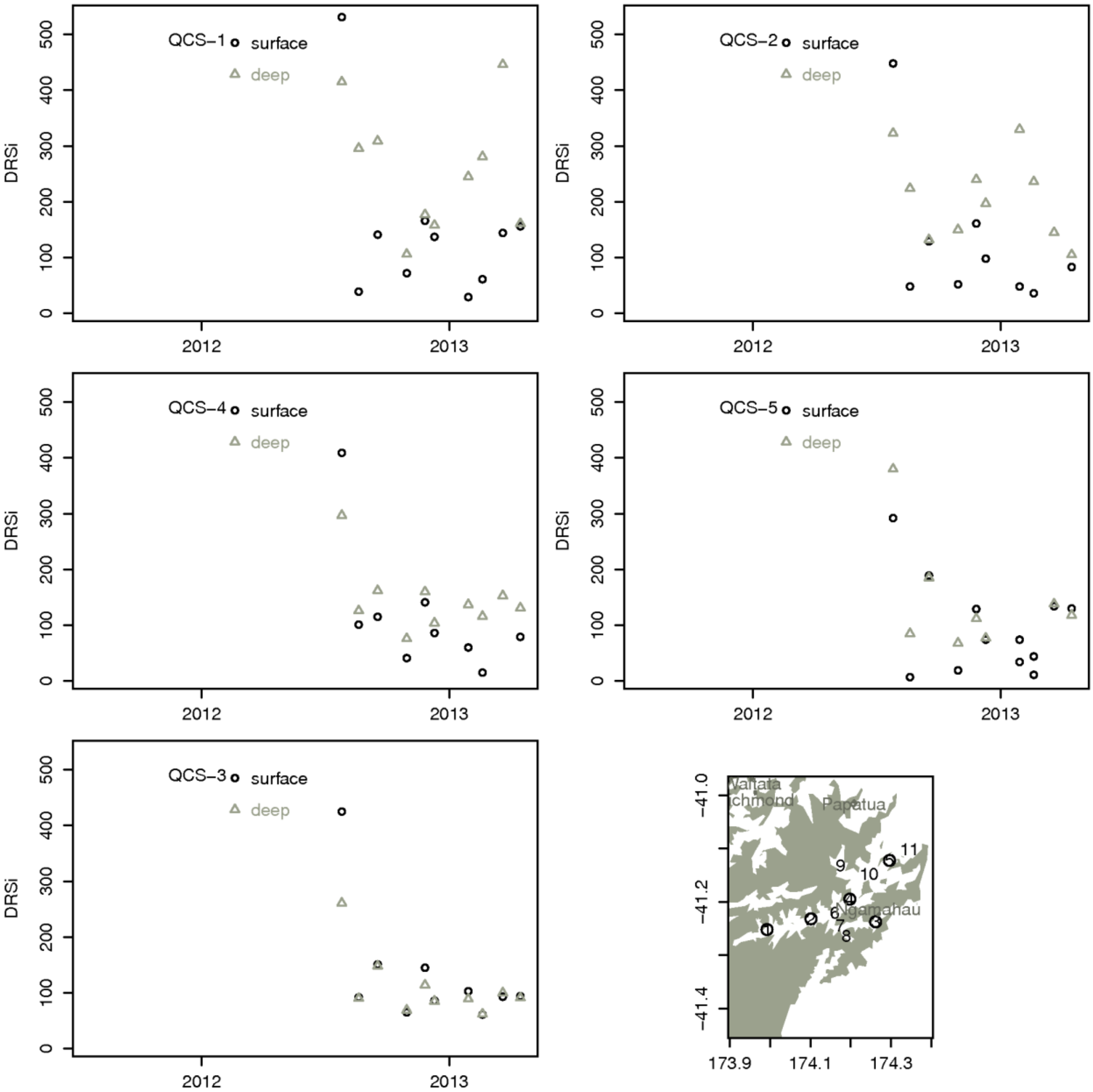


Figure 4-27: Time-series of dissolved reactive silicon (mg Si m^{-3}) measured at five sites in Queen Charlotte Sound. 'Surface' samples were collected at a depth of 4 m; 'deep' samples were collected approximately 4 m above the seabed.

The temporal dynamics of DRP (Figure 4-28), NO_3 (Figure 4-29) and NH_4 (Figure 4-30) are qualitatively similar to one another at corresponding sampling stations. As with DRSi, surface water and deep water nutrient concentrations are similar in Tory Channel. Elsewhere, the deep-water concentrations tend to be greater than near-surface ones. Again, the differential is greater at the two inner Queen Charlotte stations than at the two outer ones. Both DRP and NO_3 decline during the spring/summer months, but the decline is much greater for NO_3. This annual cycle is much clearer in the surface samples than in the near bed samples. The dynamics of ammonium are somewhat less regular, but there is some evidence that concentrations are greatest in late summer. Again, the patterns are consistent with those expected from seasonal changes in the balance of uptake and regeneration of nutrients plankton.

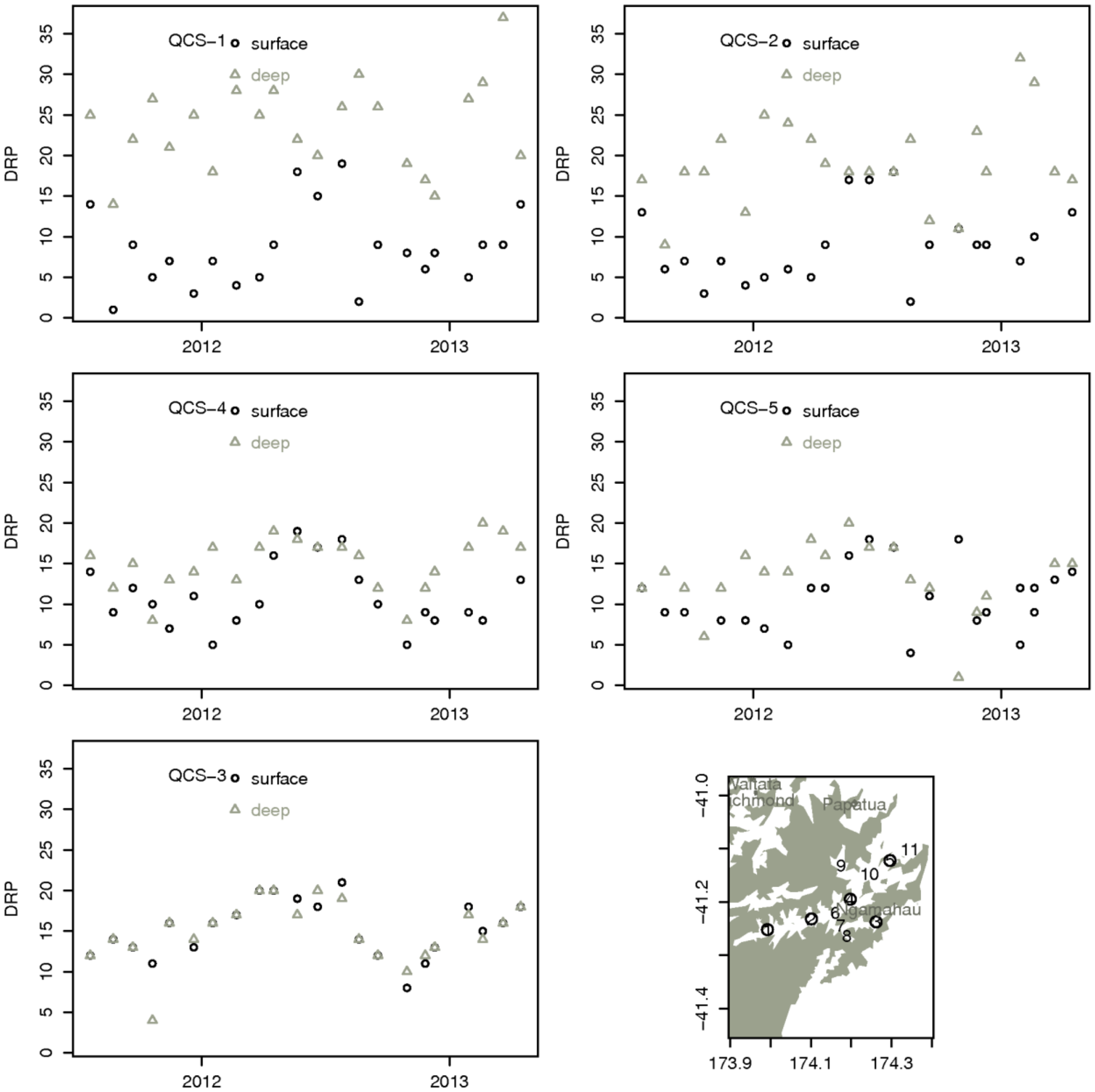


Figure 4-28: Time-series of dissolved reactive phosphors (mg P m^{-3}) measured at five sites in Queen Charlotte Sound.

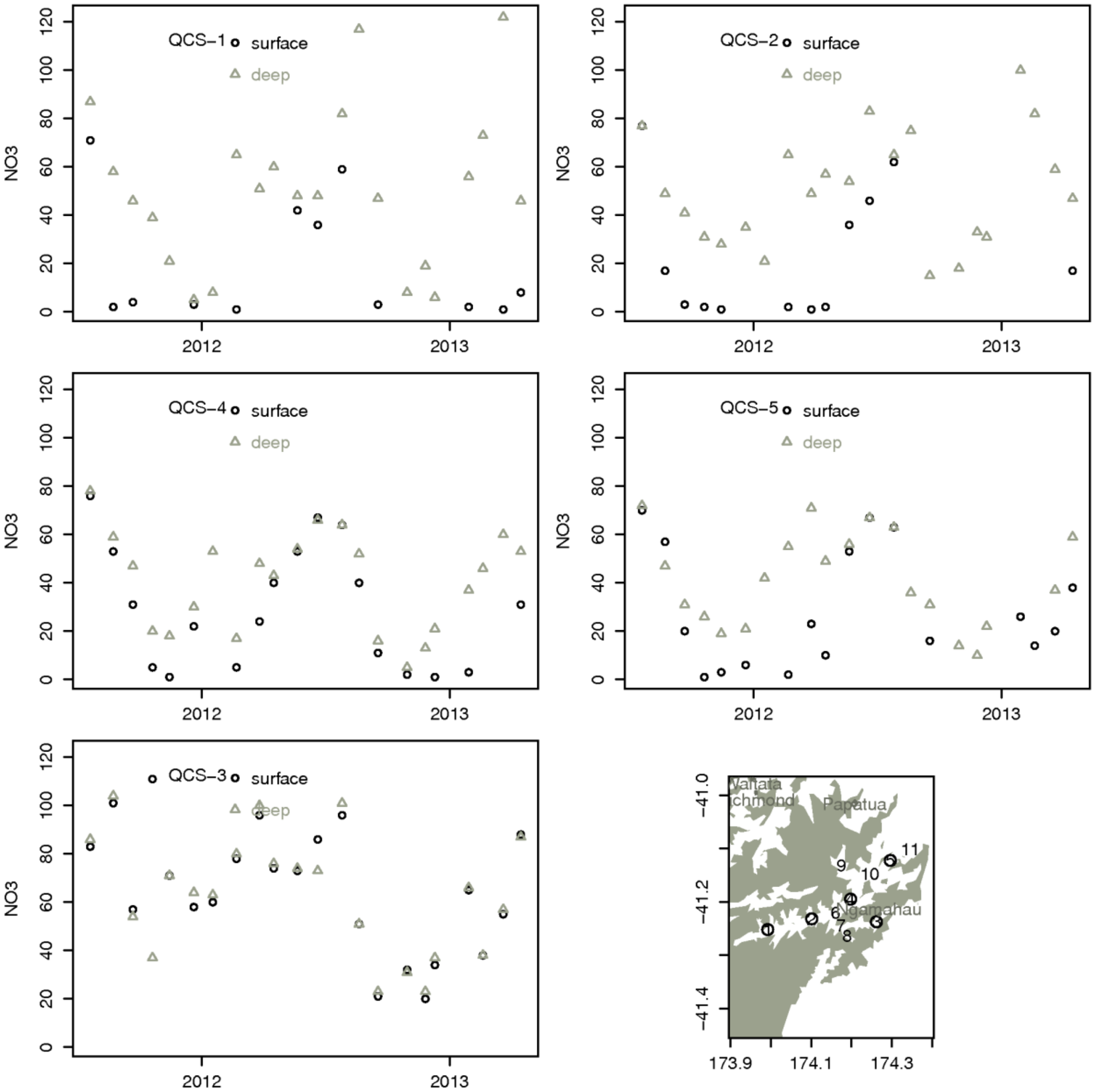


Figure 4-29: Time-series of nitrate-N (mg N m^{-3}) measured at five sites in Queen Charlotte Sound.

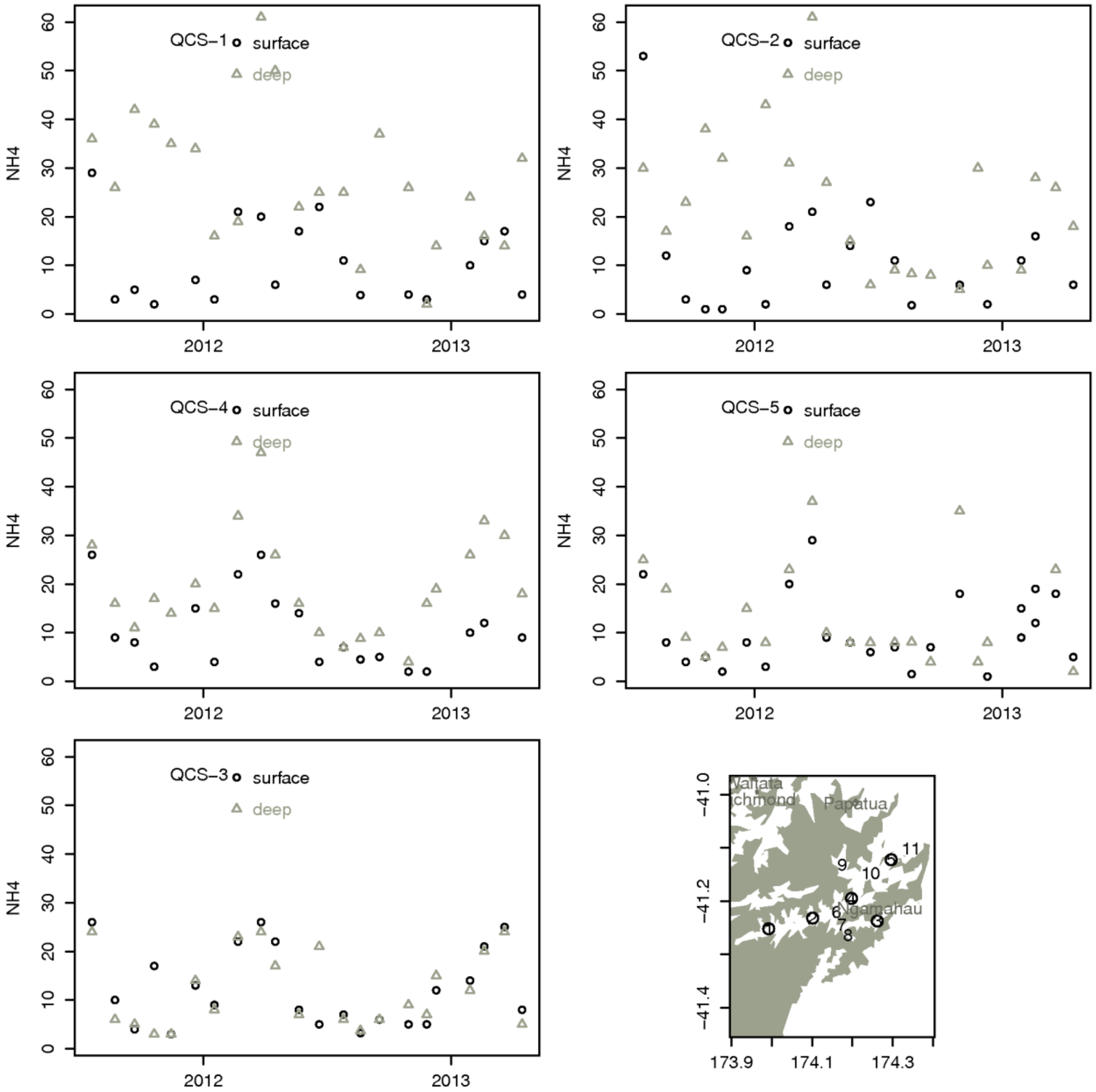


Figure 4-30: Time-series of ammoniacal nitrogen (mg N m^{-3}) measured at five sites in Queen Charlotte Sound.

4.5 Total dissolved phosphorus and nitrogen

Total dissolved phosphorus (Figure 4-31) does not show evidence of an annual cycle at any of the sites. As with the inorganic nutrients, there is no evidence of vertical structure at site 3, strong vertical zonation at sites 1 & 2 (inner Queen Charlotte) and less vertical structure at sites 4 & 5 (outer Queen Charlotte). TDP concentrations are roughly double the DRP corresponding concentrations.

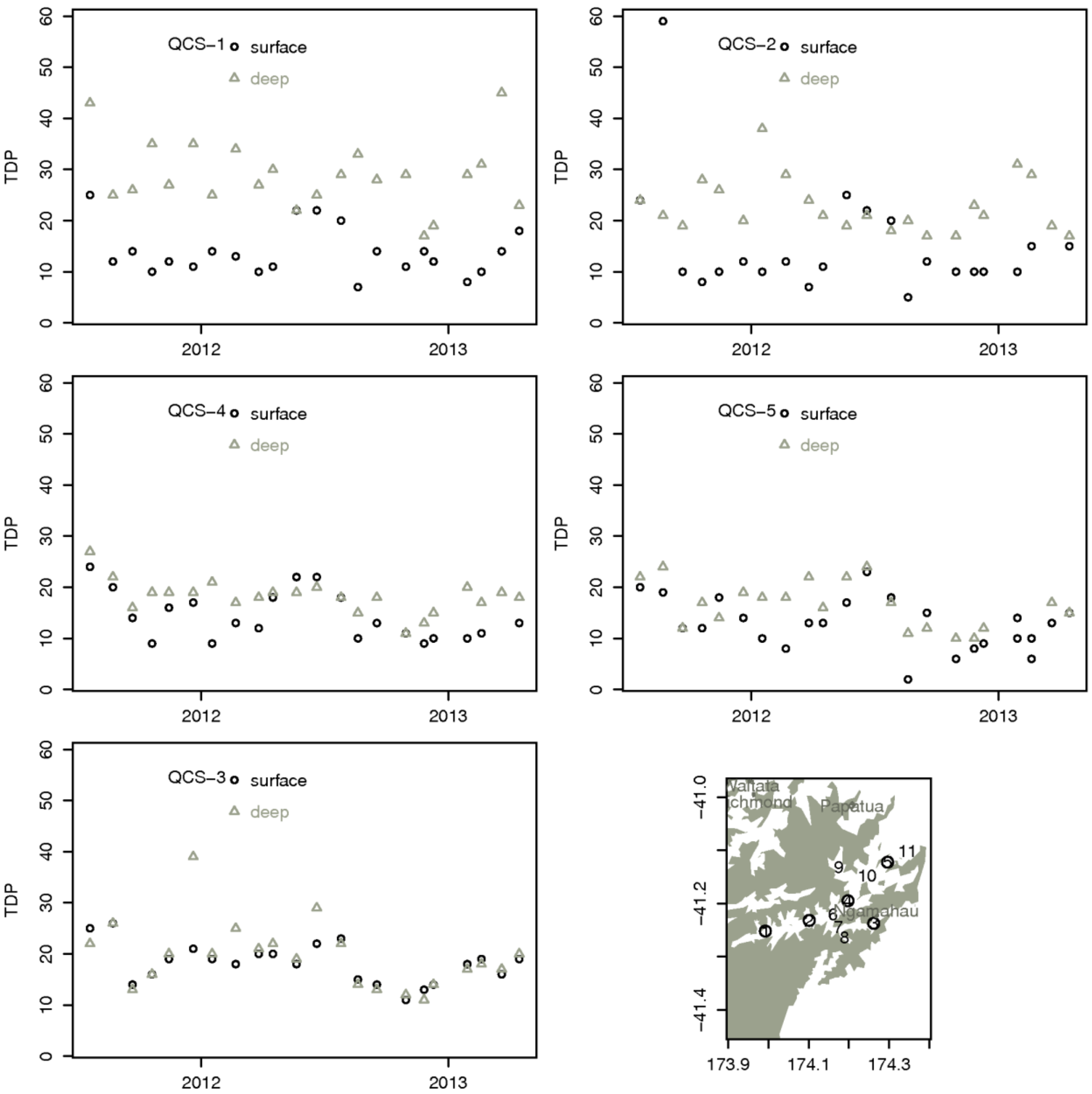


Figure 4-31: Time-series of total dissolved phosphorus (mg P m^{-3}) measured at five sites in Queen Charlotte Sound.

Unlike TDP (but like the inorganic nutrients), TDN (Figure 4-32) does appear to have an annual cycle – at least in the surface waters of sites 1-4 (albeit with less amplitude than that of NO_3. There is less evidence of cyclic behaviour in the deep-water samples and at site 3.

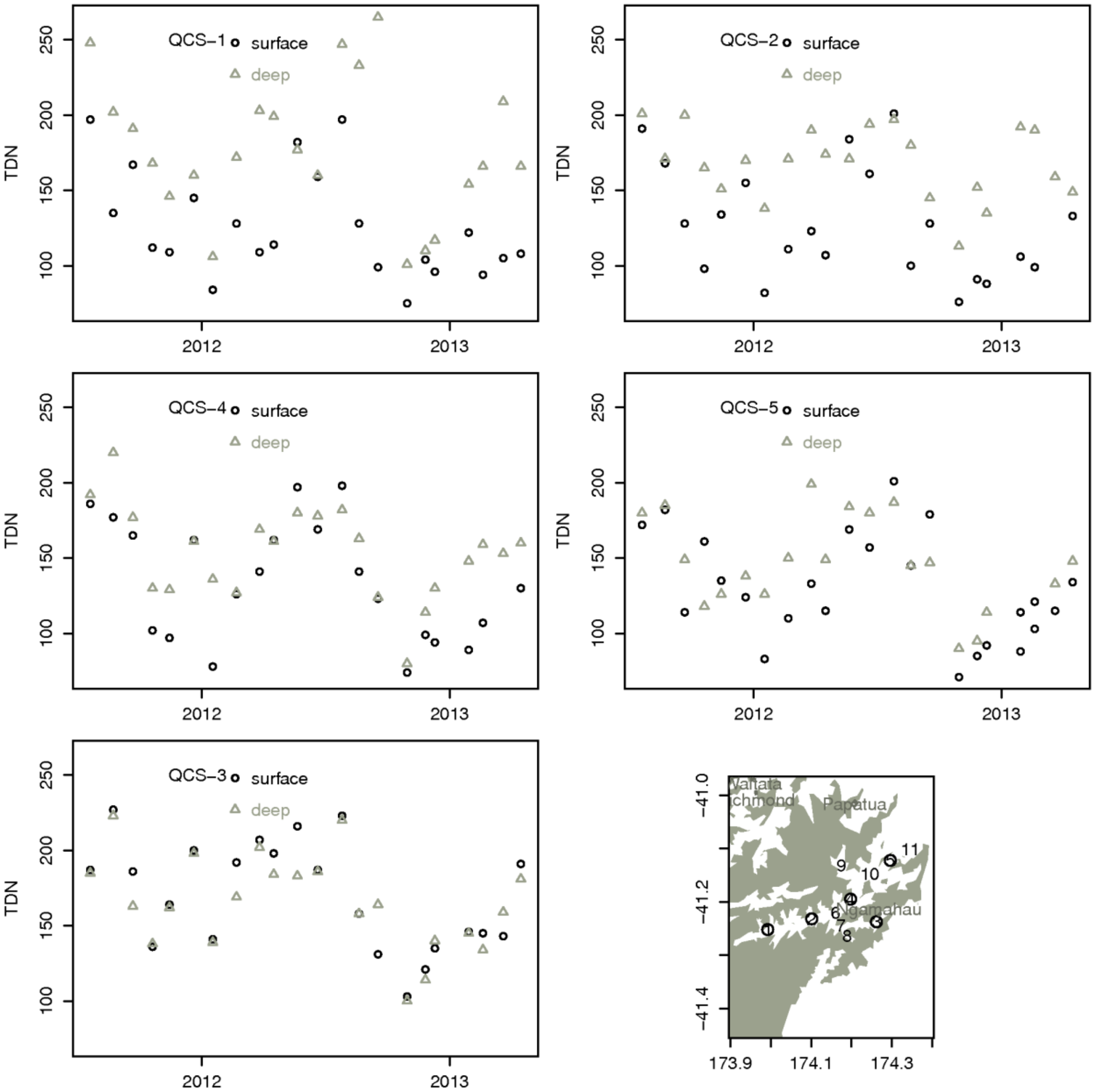


Figure 4-32: Time-series of total dissolved nitrogen (mg N m^{-3}) measured at five sites in Queen Charlotte Sound.

4.6 Chlorophyll

The times-series of chlorophyll concentration (Figure 4-33) exhibit a good deal of month-to-month variability. This variability, combined with the relative short nature of the time-series means that there is little convincing evidence for an annual cycle in any of the time-series. Once again, the differences between surface water and deep water tend to smallest in Tory Channel and greatest at the two inner Queen Charlotte stations. Surface water chlorophyll concentrations usually) exceed the deep water ones. The chlorophyll concentrations in Tory channel are generally lower than at other sites. They also show lesser month-to-month variability.

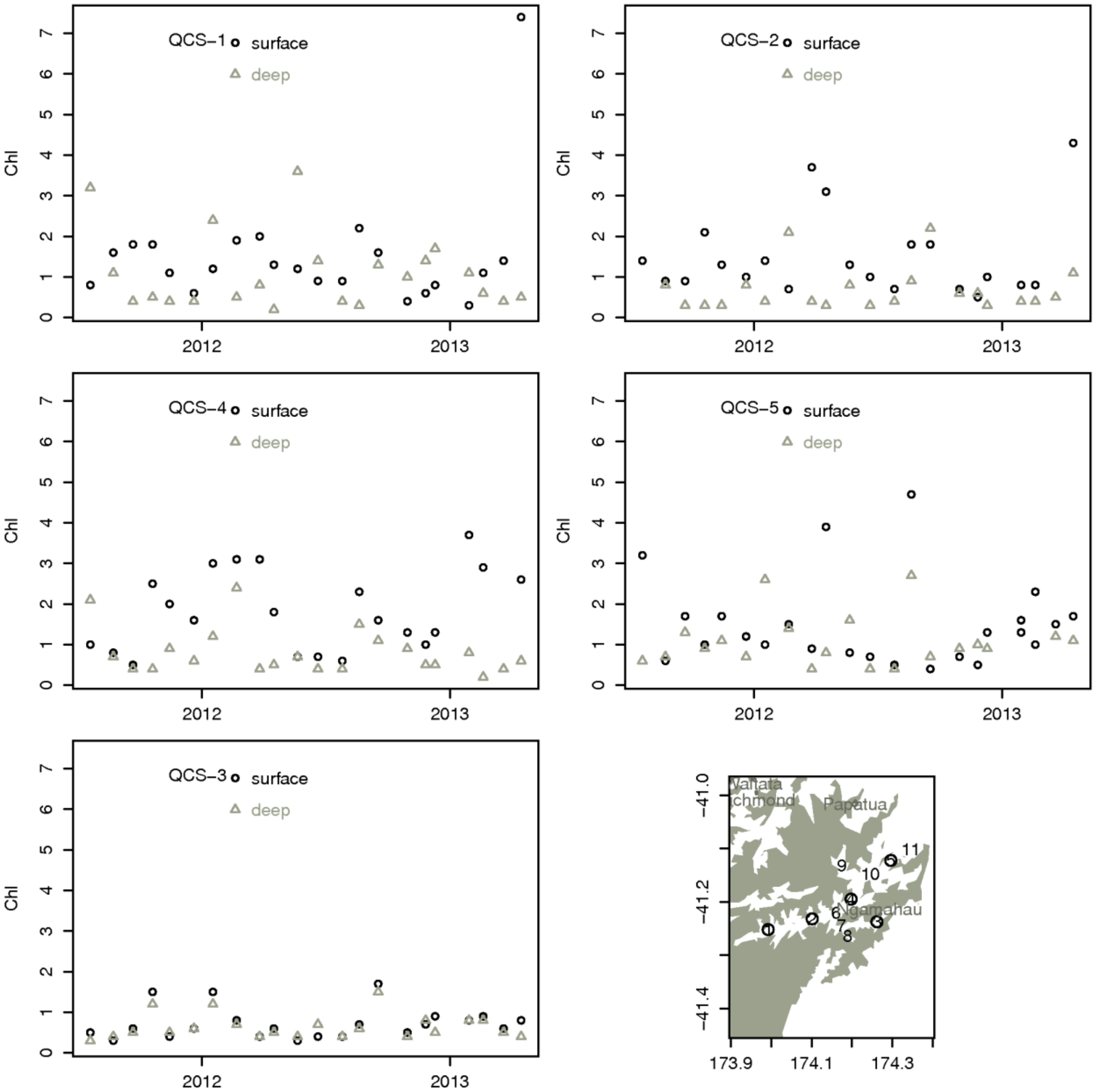


Figure 4-33: Time-series of chlorophyll (mg Chl-a m^{-3}) measured at five sites in Queen Charlotte Sound.

4.7 Particulate organic carbon & nitrogen

POC (Figure 4-34) and PON (Figure 4-35) concentrations fluctuate month to month. As with chlorophyll, there is mixed evidence for annual cycles in the data. The average standing stocks and relative size of the fluctuations seems to be smaller in Tory Channel than elsewhere. This is probably a result of the lesser phytoplankton abundance (as measured by chlorophyll) in Tory Channel.

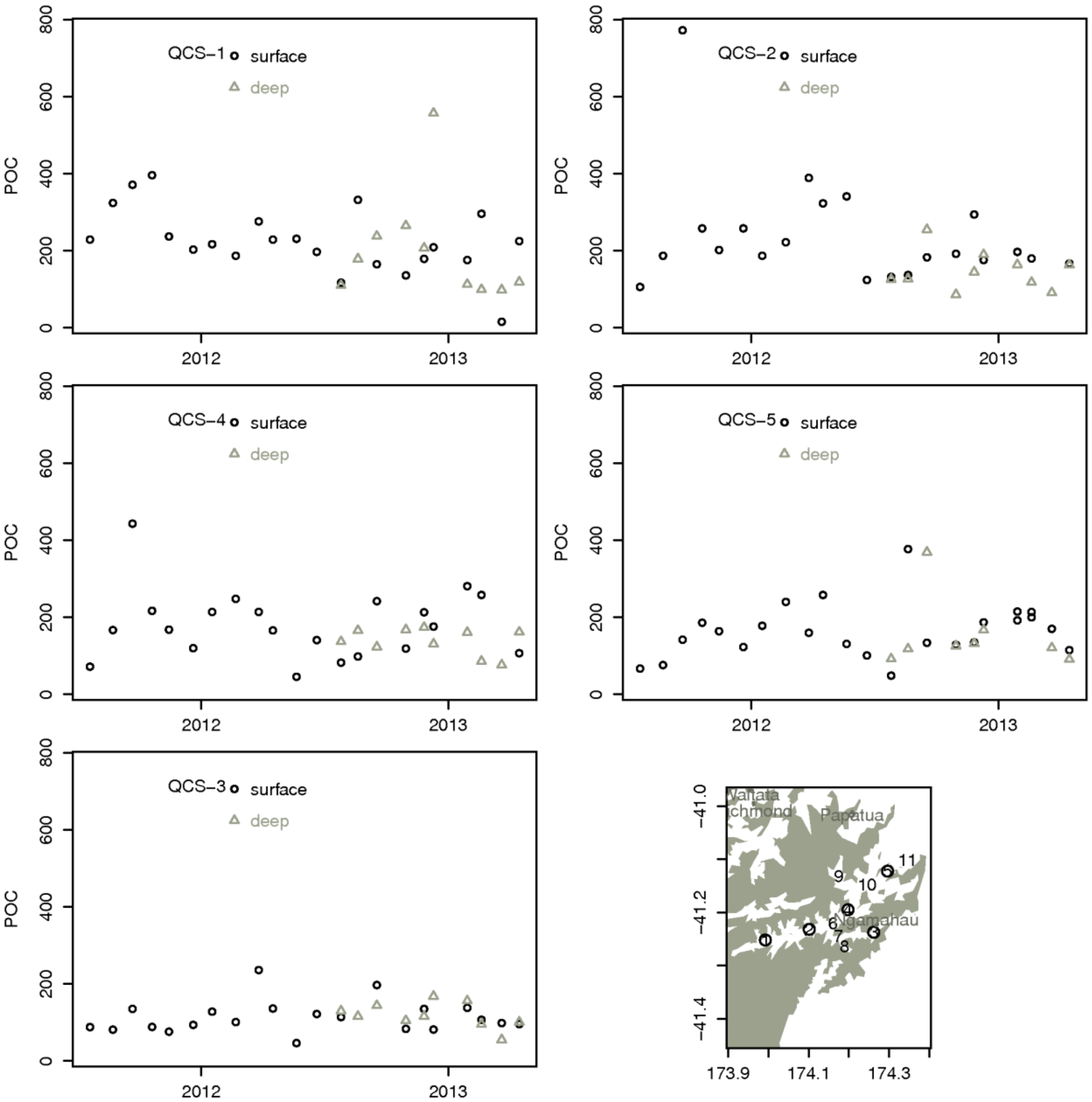


Figure 4-34: Time-series of particulate organic carbon (mg C m^{-3}) measured at five sites in Queen Charlotte Sound.

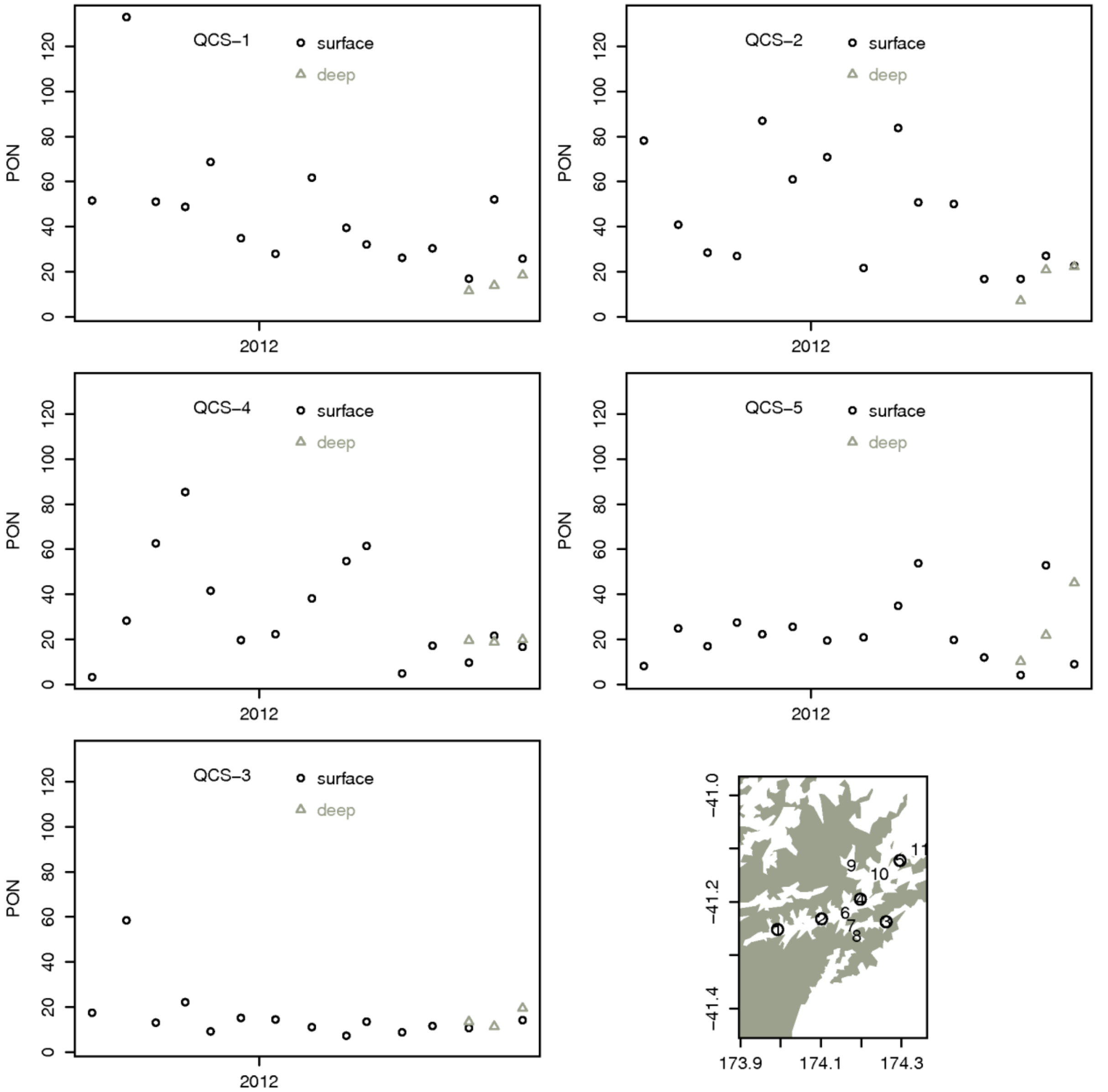


Figure 4-35: Time-series of particulate organic nitrogen (mg N m^{-3}) measured at five sites in Queen Charlotte Sound.

4.8 Suspended solids and turbidity

Neither TSS (Figure 4-36), nor VSS (Figure 4-37) show any evidence of cyclic behaviour. TSS concentrations seem to be a little higher in Tory Channel than elsewhere. In contrast, the VSS concentrations in Tory channel are lower than they are elsewhere (this is consistent with the chlorophyll abundance pattern). As was the case in Pelorus, VSS concentrations were frequently recorded as <0.5 g m^{-3} (ie less than the detection limit). One must question the value of endeavouring to measure this variable unless a more sensitive method can be found.

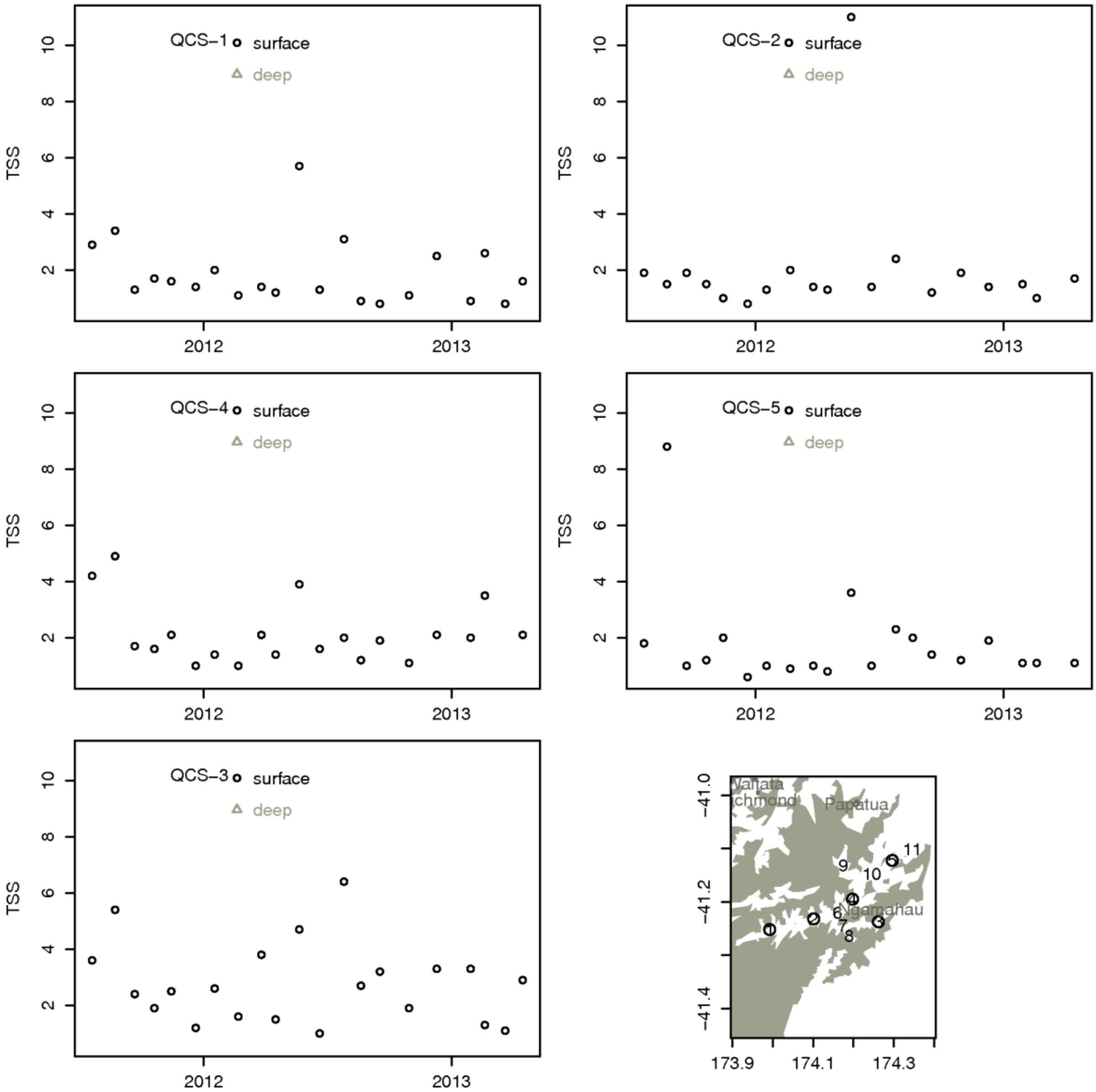


Figure 4-36: Time-series of total suspended solids (g DW m^{-3}) measured at five sites in Queen Charlotte Sound.

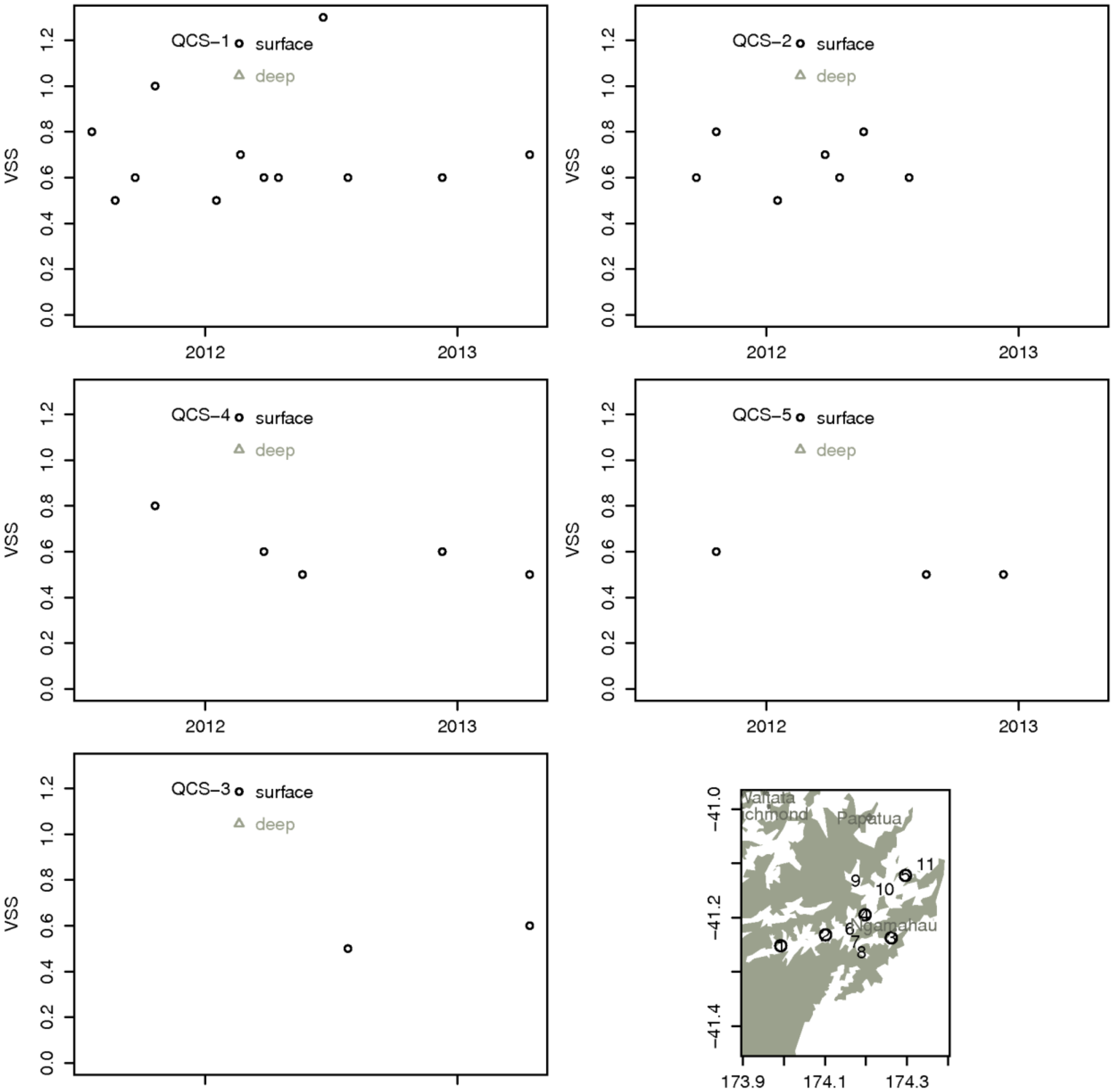


Figure 4-37: Time-series of volatile suspended solids (g AFDW m^{-3}) measured at five sites in Queen Charlotte Sound.

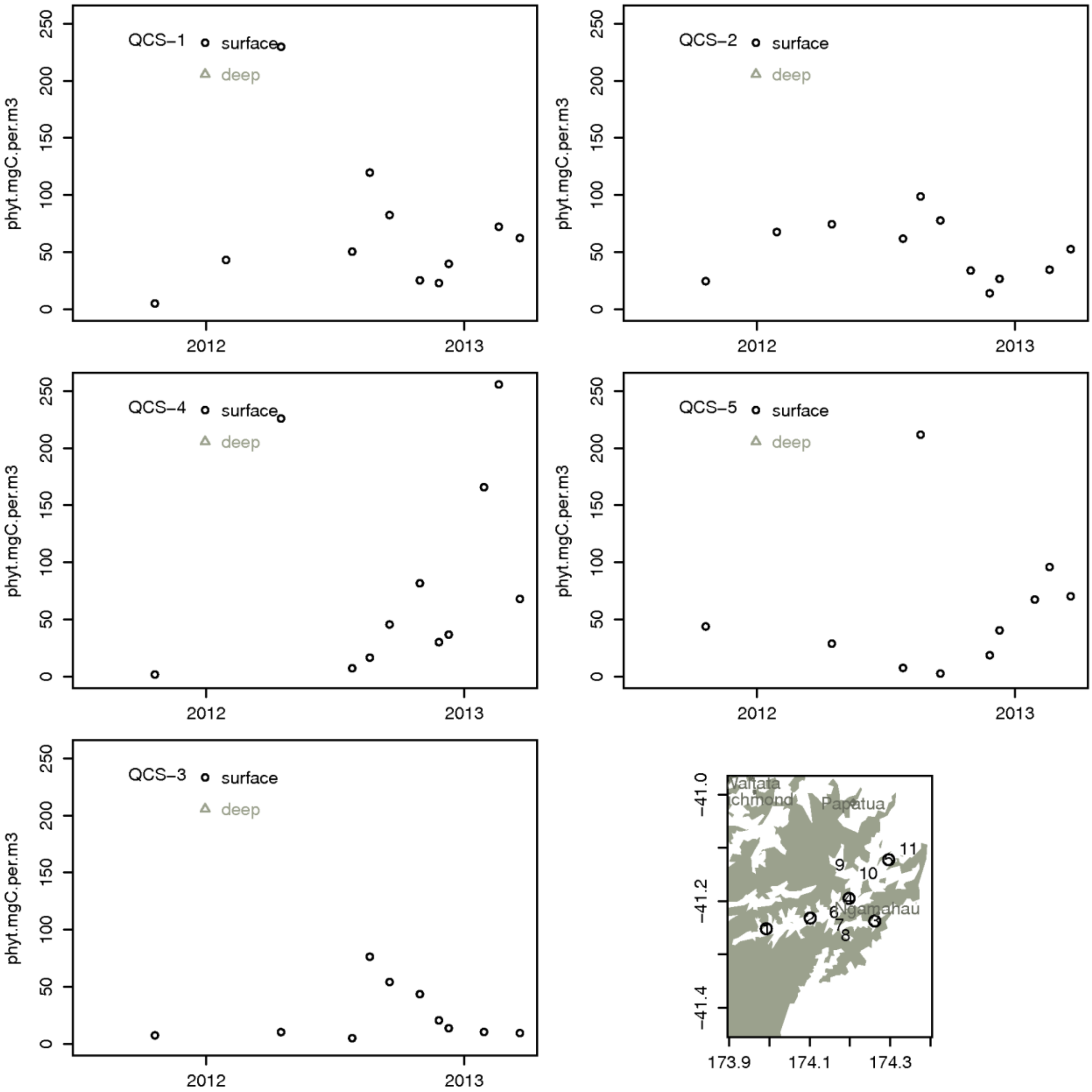


Figure 4-38: Time-series of phytoplankton carbon (mg C m^{-3}) measured at five sites in Queen Charlotte Sound. Carbon concentration was derived from cell counts and cell dimensions.

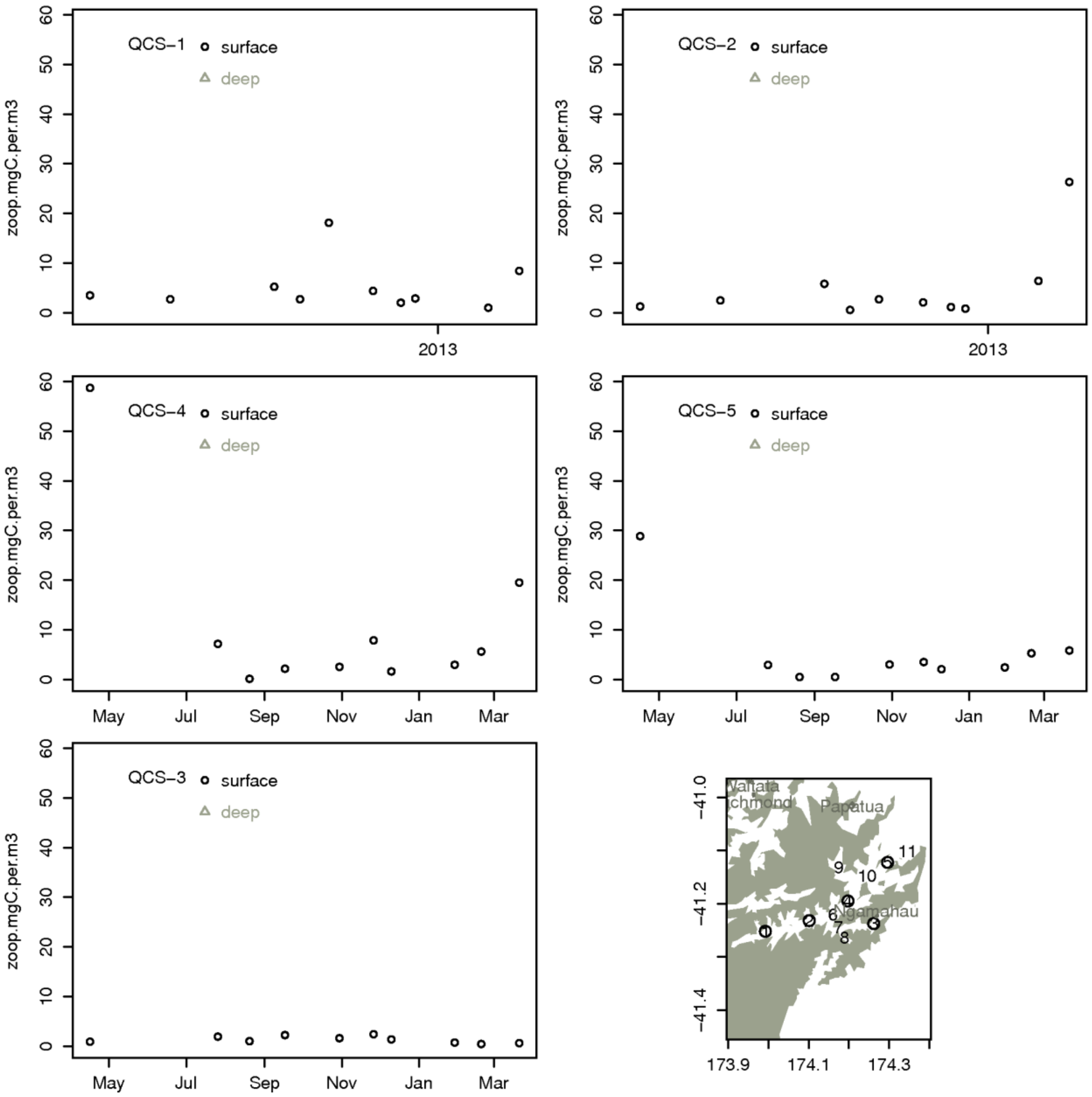


Figure 4-39: Time-series of zooplankton carbon (mg C m^{-3}) measured at five sites in Queen Charlotte Sound. Carbon concentration was derived from counts of individuals and published estimates of the weights of the relevant types of zooplankton.

4.9 Implications to be drawn from the historical monitoring data with respect to detecting fish-farm induced change

The historical data from Pelorus Sound reveal that high-frequency (fortnightly time-scale) variability and inter-annual variability are both substantial. For most materials, the combined short-term and inter-annual variability frequently exceeded both the natural seasonal-scale variability and the spatial variability through the outer and central Pelorus.

The data from Queen Charlotte Sound span a much shorter period and have only monthly (cf fortnightly) temporal resolution. Nonetheless, existing Queen Charlotte data appear to indicate that the variability evident in Pelorus is also present in Queen Charlotte. Perhaps the most striking feature is that the sole Tory Channel site consistently has markedly different water-quality properties from the four sites within the main branch of Queen Charlotte. Since there is only one sampling site in Tory Channel, it is not possible to determine whether these differences (particularly the lack of vertical structure) hold throughout Tory Channel but we suspect that they will do so since horizontal currents (hence, vertical mixing) tend to be higher in Tory Channel and because Tory Channel appears to have a larger relative water exchange with Cook Strait than does the main Queen Charlotte branch. One implication is that it is possible that the magnitude and nature of any fish-farm induced changes may differ between the Tory channel farms and the Queen Charlotte farms.

The consent conditions governing establishment of the four new NZKS farms require that NZKS implement a monitoring program. Water quality data are to be gathered at least monthly for at least one year (at least two years for the Papatua farm) prior to establishing the farms. The presence of marked inter-annual variability that seems to be driven by quasi-decadal scale El Niño/La Niña climatic oscillations (Zeldis, J.R., Hadfield et al. 2013) implies that one-two years' worth of baseline monitoring is unlikely to capture the full range of natural variability. The implication of having only one-two years'-worth of data is that, should water-quality conditions change after the farms are occupied, it will be difficult to know whether the changes are large (relative to the full scale of natural variability), let alone whether they are farm-induced or climate induced.

The existence of several relatively long-term data-sets (NIWA's historical data, albeit that none of the sampling sites are in the immediate vicinity of the farming sites) together with knowledge of their climatic drivers offers a possibility that it will be possible to disentangle climate-induced change from farm-induced change in Pelorus Sound. Unfortunately, there is less hope in Queen Charlotte Sound. The MDC time-series (reported here) are too short to reveal climate influences at present – and will still be too short when the farms are initiated in one-two years' time. Even the other unpublished time-series data from Queen Charlotte (Cawthron data and data of Drs Bedford & Leader) are also too short (circa three-four years) to properly reveal climatic influences (even assuming that appropriate variables have been measured).

We believe that the MSQP data (fortnightly counts of phytoplankton cells by species) stretch back to the mid-1990s. The MSQP data includes sampling sites within Queen Charlotte and Port Gore. Whilst we have not seen the data (we do not know whether the cell counts are for toxic species only, or for all species), these appear to be the only extant data that may be capable of revealing climatic influences in Queen Charlotte and Port Gore. If these data prove unsuitable (or are not analysed) and if water-quality in Queen Charlotte (or Port Gore) changes after the new fish farms are established, the only ways of (even approximately) determining whether the changes are farm-induced will be: (a) remove the farms and see whether things revert, or (b) wait for the El-Nino/La Nina cycle to complete and determine whether conditions revert to pre-farm when the cycle passes through a phase consistent with that which holds during the baseline monitoring period.

It might be argued that substantial natural variability implies that the system is 'pre-adapted' to cope with intermittent variability and that a chronic (ie step-wise, ongoing) incremental change due to the introduction of farms will therefore have little, or no effect. This is a tempting but, possibly, fallacious argument. Zeldis, J.R., Hadfield et al. (2013) demonstrated a strong correlation between mussel yield in the Pelorus Sound and inter-annual variations in climatic conditions. The conclusion must be that there are at least some components of the system that cannot fully compensate against natural variability at the base of the food-chain.

There is convincing evidence that climate-related changes in wind-driven upwelling and river inputs modifies the quantities of nitrogen that are introduced into the Sounds (Zeldis, J.R., Howard-Williams et al. 2008; Zeldis, J.R., Hadfield et al. 2013). In turn, this influences primary production and, hence, the quantity of seston (plankton and planktonic detritus) in the water column. Seston is the material upon which mussels feed. Whilst fortnightly-scale variation in nutrient input may not influence long-term average mussel growth, there is no doubt that variations that persist over a substantial fraction of a mussel's life-span will influence its growth. By a similar argument, this raises the possibility that a prolonged chronic increase in nutrient supply to the Sounds could influence the performance of mussels (and any other species depend upon Sounds-derived primary production). Whether such changes prove to be detectable will depend upon two factors: (a) the statistical power of the sampling scheme and (b) the magnitude of farm-induced change. The statistical power of the sampling scheme will increase as more samples accrue, but during the NZKS hearings it was argued that the farm-induced effects upon water-column water characteristics were unlikely to be large. This means that many samples will be required if the aim of the sampling is to detect a 'statistically significant' effect (no matter how small) – but does not necessarily imply that a correspondingly large number of samples be gathered if the aim is 'only' to detect that 'large changes (relative to historical values)' are not arising[4].

It is well known that the quantum of change that is required to be judged 'statistically significantly different' declines as the number of samples increases. Given a sufficiently large time-series of samples, even meaninglessly (in an ecological context) small differences may be deemed statistically significant. In the field of medical interventions, so-called equivalence tests (McBride 1997) are frequently used in preference to standard significance tests in order to overcome this problem. Equivalence tests require the user to specify an *a-priori* magnitude of change that is deemed meaningful (in our context, ecologically meaningful). The test then uses the data to determine whether or not the treatment has induced a change in excess of said magnitude (rather than a change which is 'statistically significant' (ie unlikely to have arisen by chance, but perhaps still ecologically irrelevant)). A particularly appealing feature of equivalence tests is that merely increasing the sample size does not increase the probability that the null hypothesis will be rejected. Rather it increases the probability that the correct conclusion (whether it be rejection or acceptance of the null hypothesis) will be arrived at.

Whilst the possibility that meaninglessly small differences will be detectable is unlikely to arise until many years' worth of data have accrued we recommend that careful thought be paid to defining 'ecologically significant quanta of change' with a view to adopting Equivalence Tests. The definition of 'ecologically significant quanta of change' is conceptually akin to defining a 'Limit of Acceptable Change' (Zeldis, J., Felsing et al. 2005). We know of no definitive, objective means by which the threshold-quanta can be defined, but (perhaps differing) thresholds can be inferred by reference to a variety of considerations. These might include setting them by reference to:

- the quantiles of historical natural variability

[4] If large changes are detected, it may remain difficult to unequivocally ascribe them to the fish-farms, but at least a warning will have been raised that may, for example, trigger more intensive monitoring to better determine the reasons for the change.

- For nutrients: published half-saturation nutrient concentrations for phytoplankton (eg Caperon and Meyer 1972; Hein, Pedersen et al. 1995; Chang and McClean 1997).
- For mussels etc.: published half-saturation seston concentrations and analyses such as Zeldis, J.R., Howard-Williams et al. (2008) and Zeldis, J.R., Hadfield et al. (2013).
- For dissolved oxygen: thresholds for chronic and acute hypoxia in key species (Vaquer-Sunyer and Duarte 2008).
- For sulphide (and ammonia etc.,) toxicity: thresholds for chronic and acute sulphide (ammonia etc.,) toxicity (taking due account of pH effects upon ionic form of the toxins) (Hargrave 2010).

Regardless of the ultimate length of the monitoring time-series generated by NZKS (or MDC), the high-frequency variability is such that it will be impossible to reliably detect any sporadic, short-lived farm-induced effects in a practicable (ie affordable) monitoring scheme based upon collection and analysis of water-samples at circa monthly intervals. Indeed, whilst formal power-analyses have not been undertaken, it seems likely that even persistent (cf short-lived) farm-induced change (should it exist) will only become detectable once several years' worth of data (with e.g., monthly resolution) have been collected. Even then, and regardless of what form of statistical analyses are adopted, the data will be capable of revealing only relatively large changes (at least, several tens of percent).

5 References

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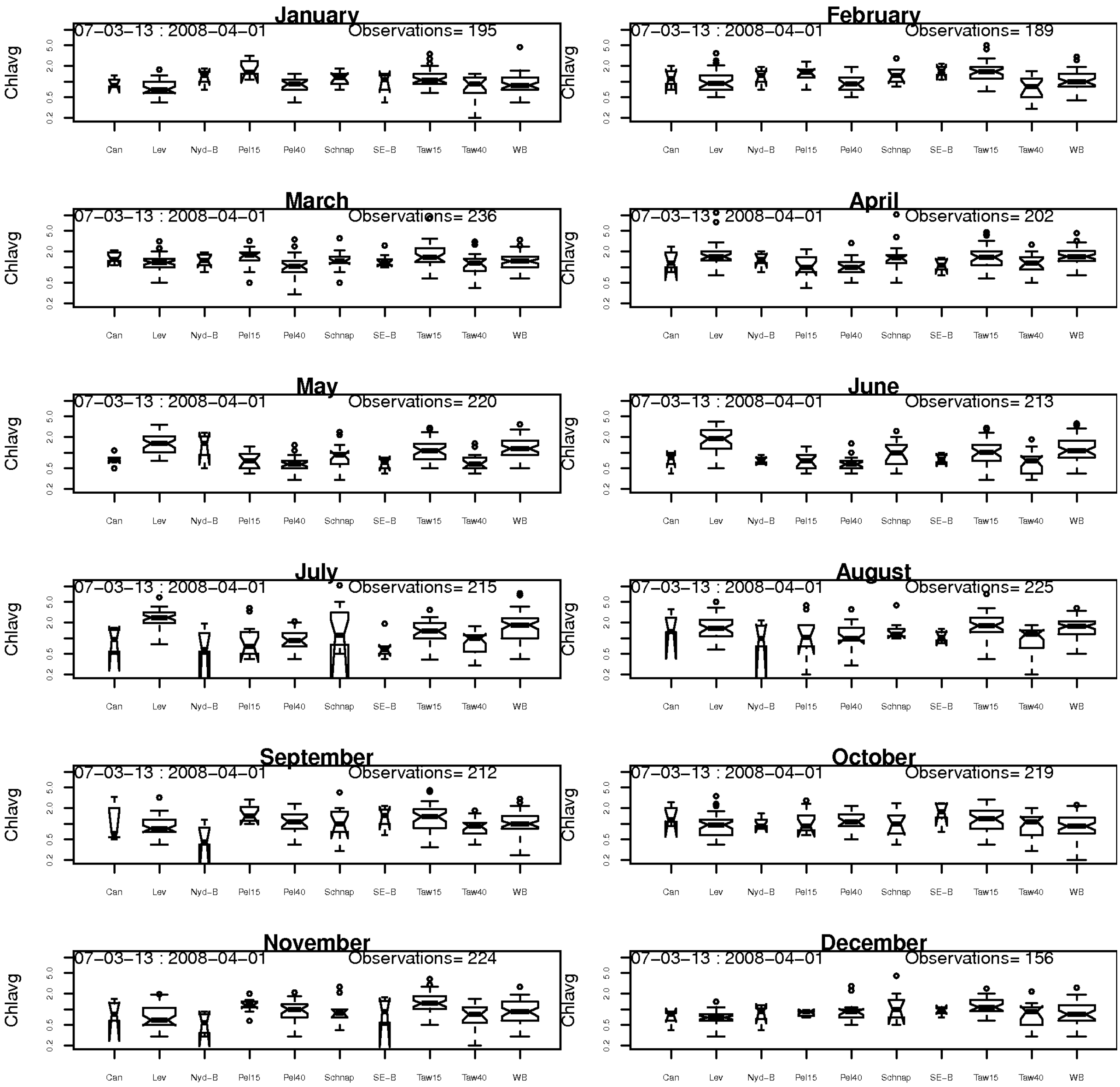
Zeldis, J.R., Howard-Williams, C., Carter, C.M., Schiel, D.R. (2008) ENSO and riverine control of nutrient loading, phytoplankton biomass and mussel aquaculture yield in Pelorus Sound, New Zealand. *Marine Ecology - Progress Series*, 371(131–142). http://www.int-res.com/articles/meps2008 /371/m371p131.pdf

6 Appendix 1. Alternative arrangement of the boxplots of NIWA's Pelorus Sound data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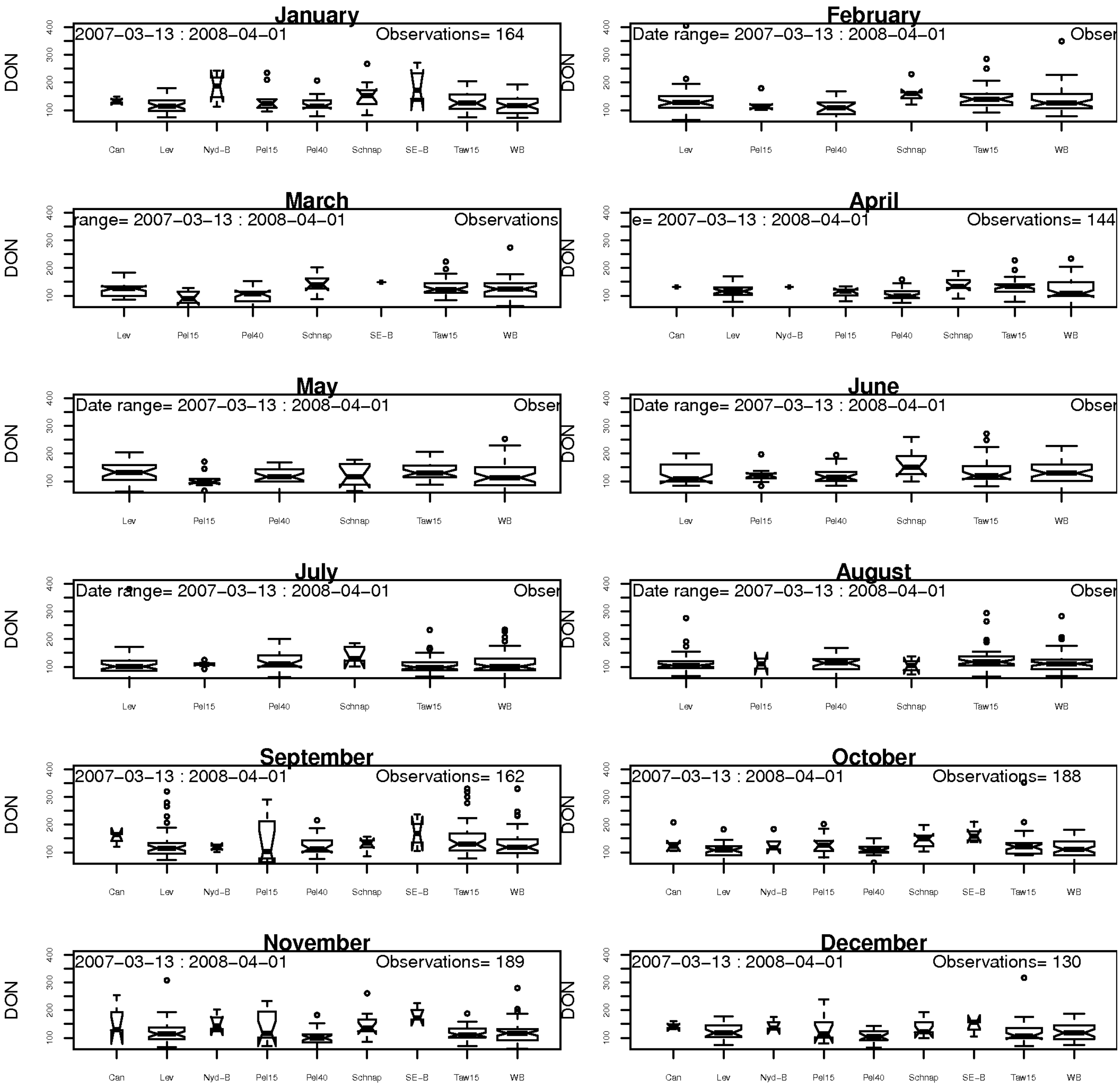
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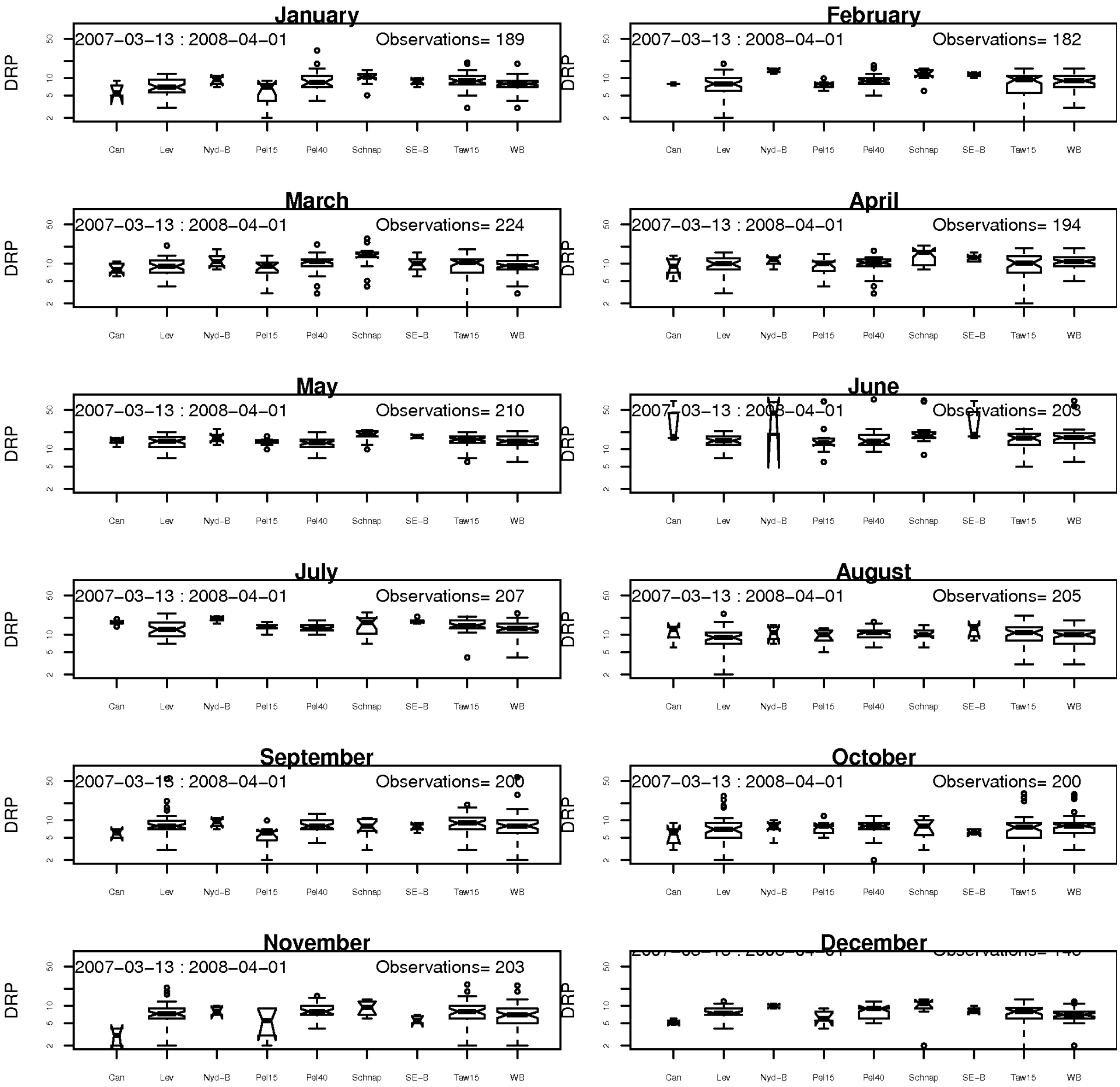
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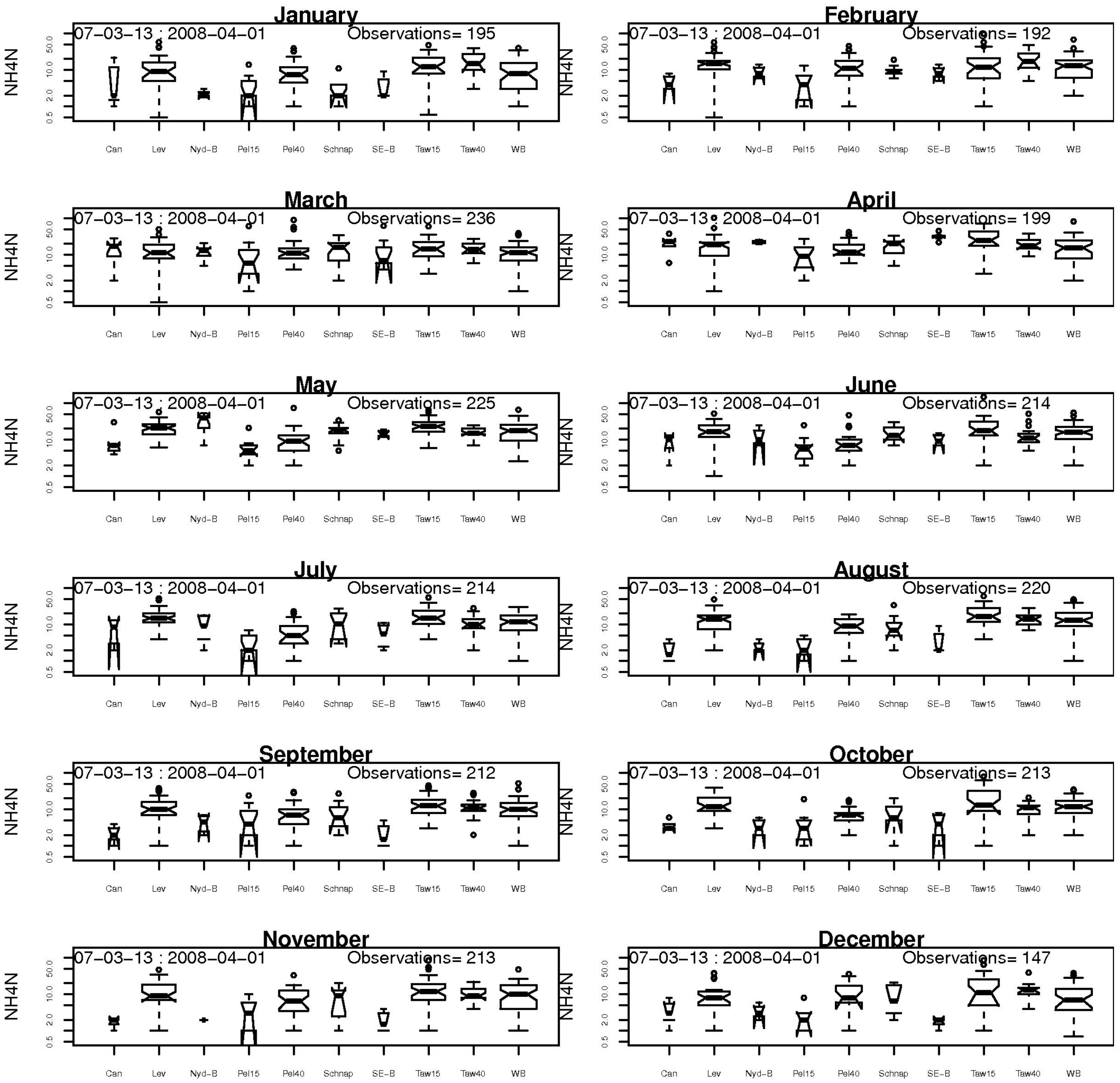

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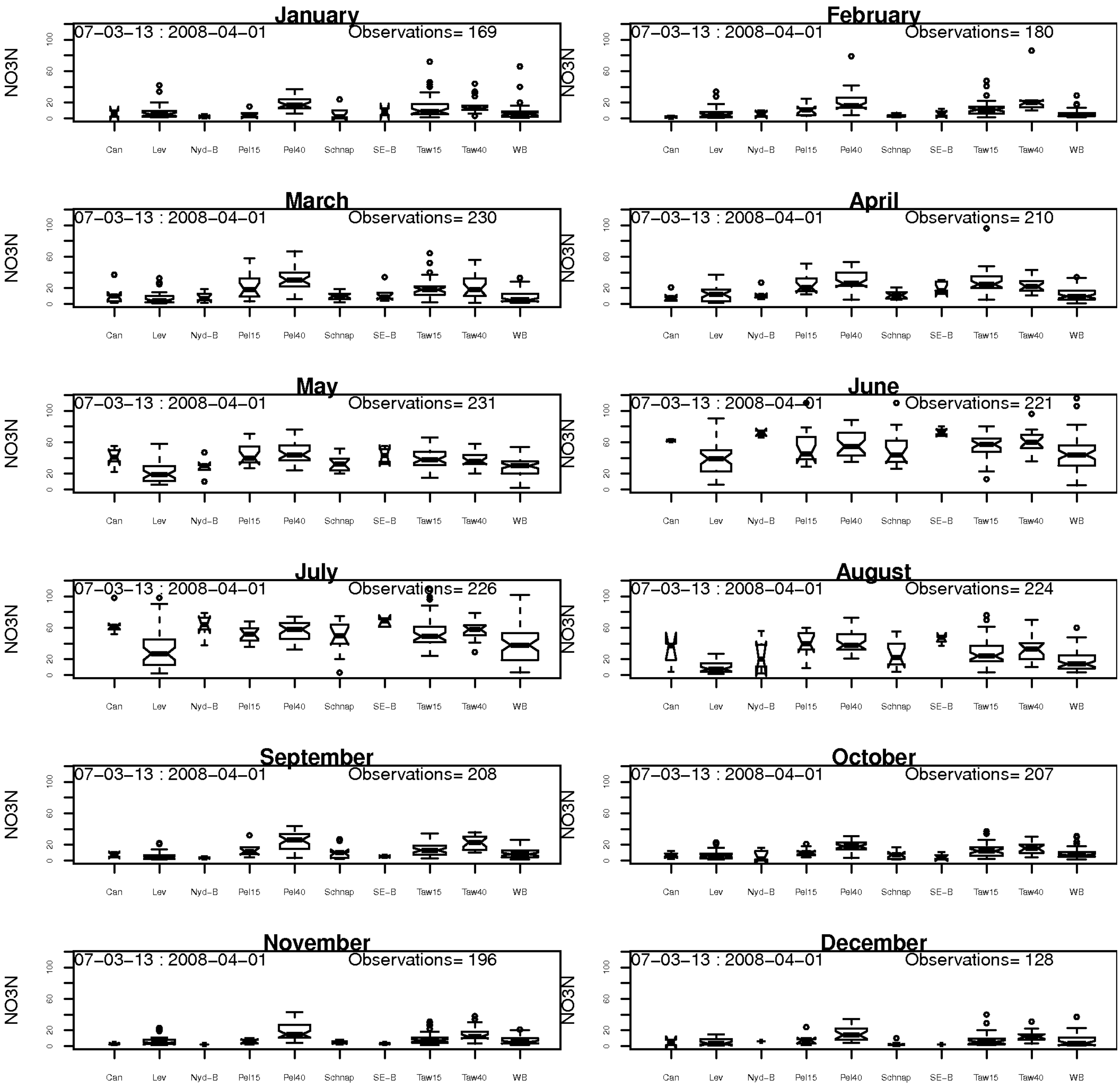
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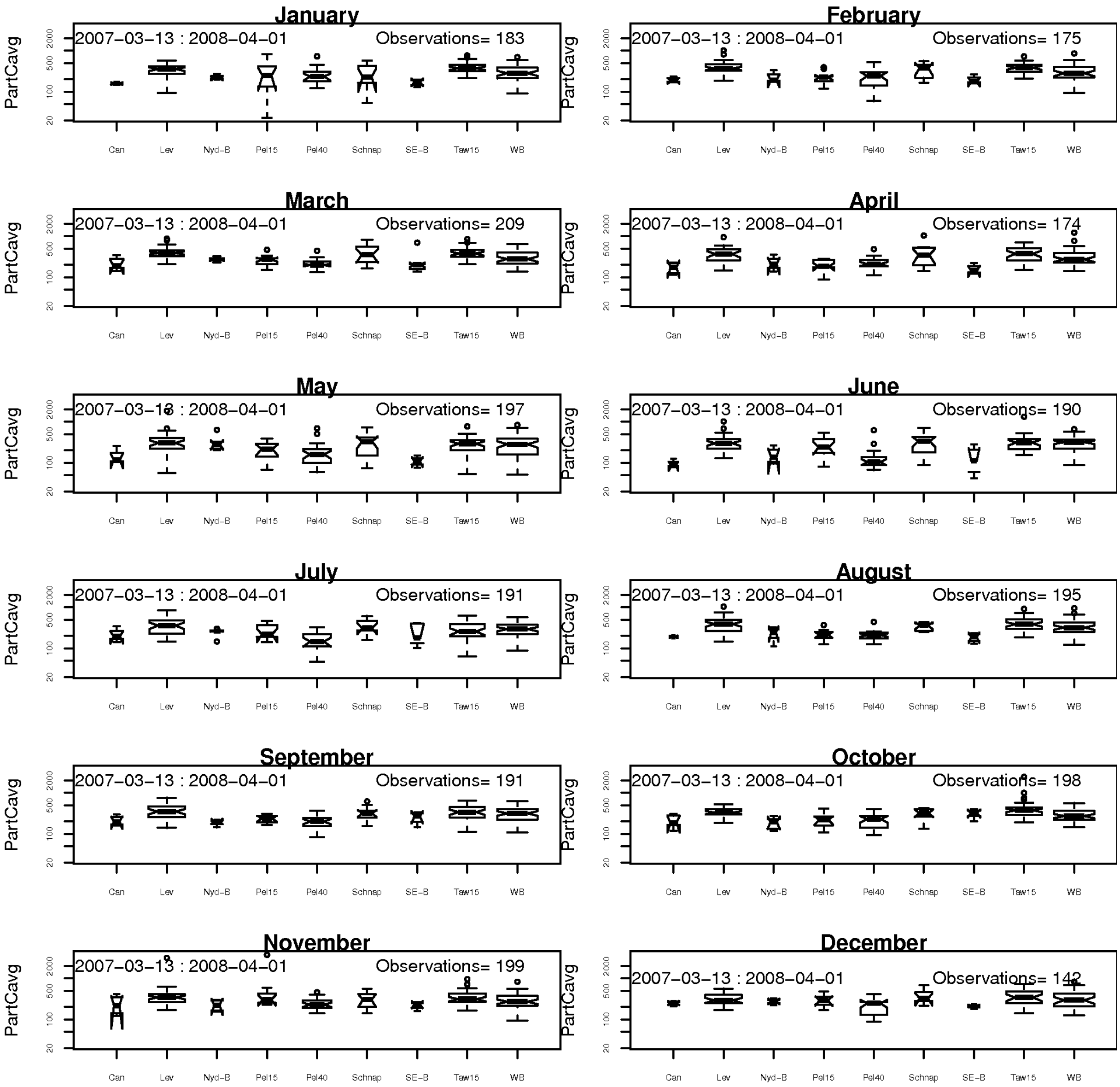
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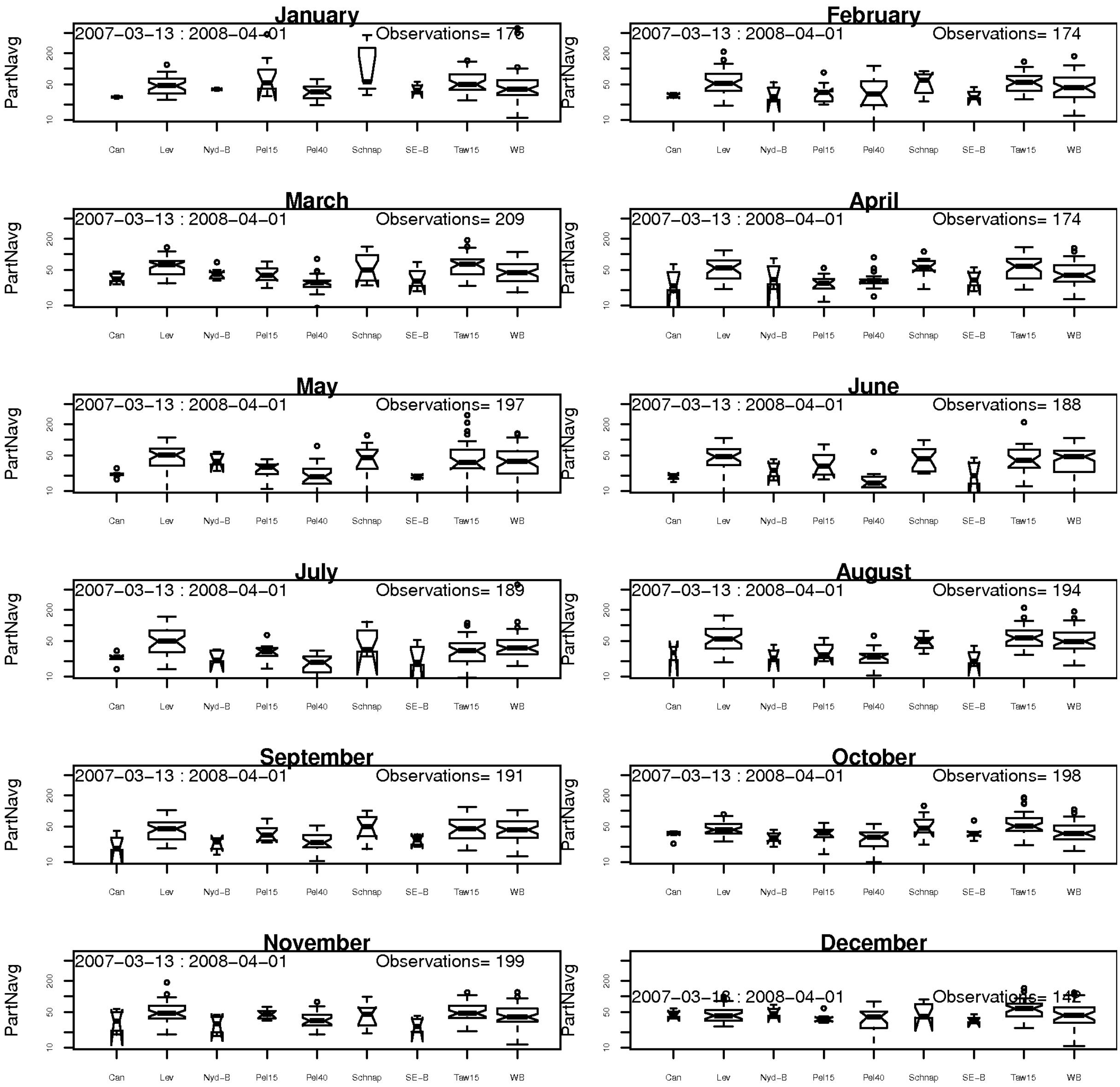
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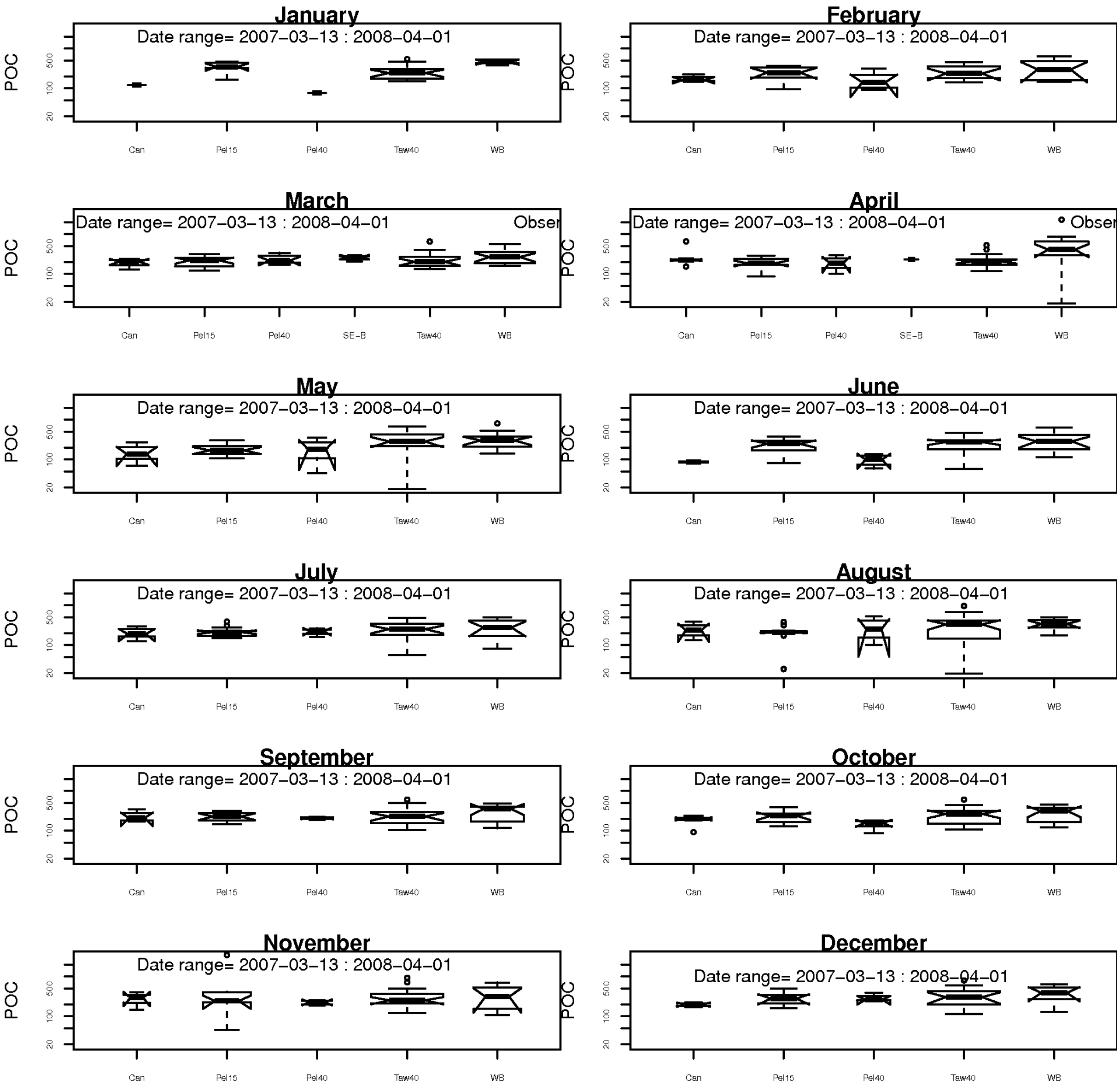
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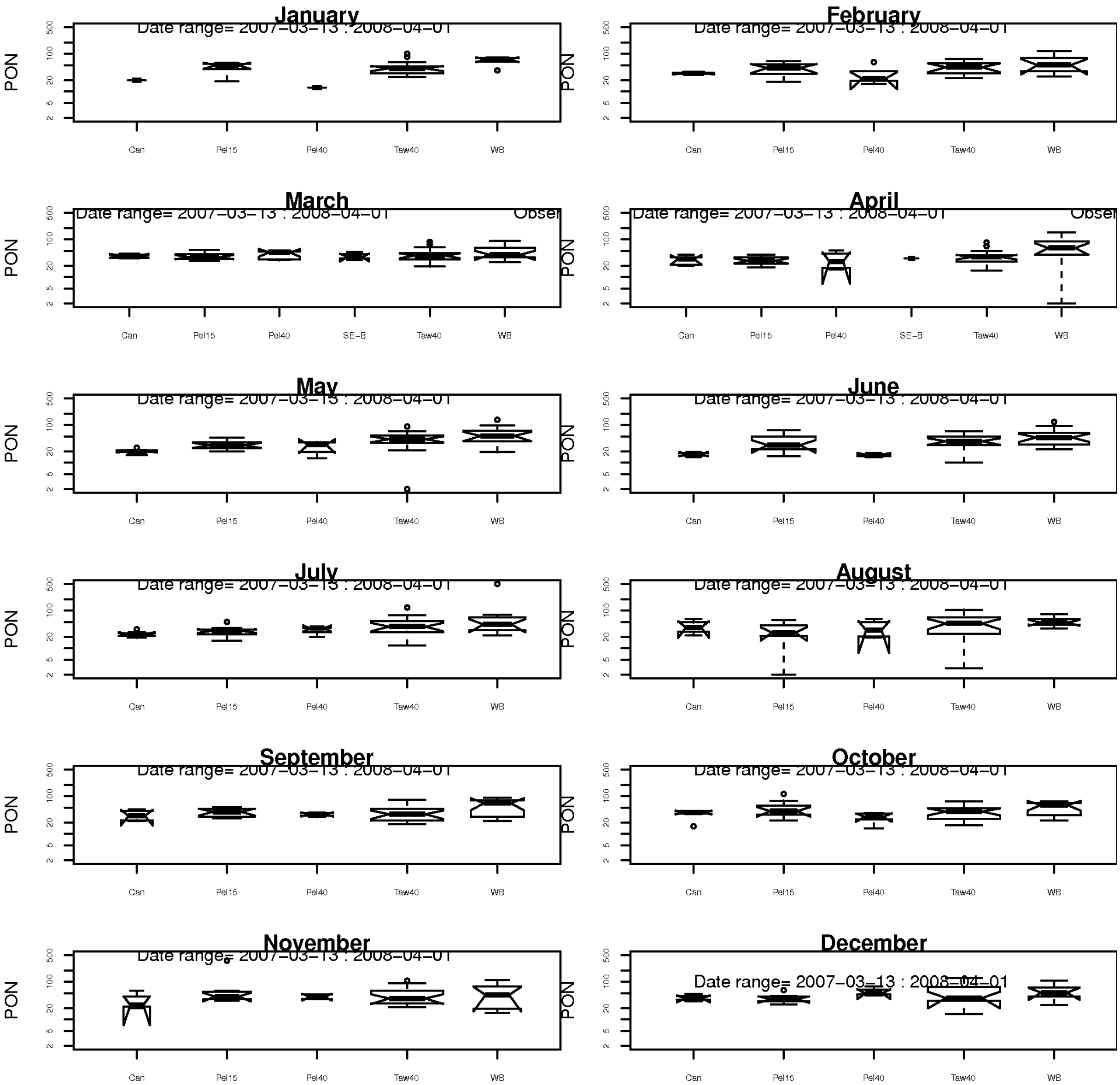
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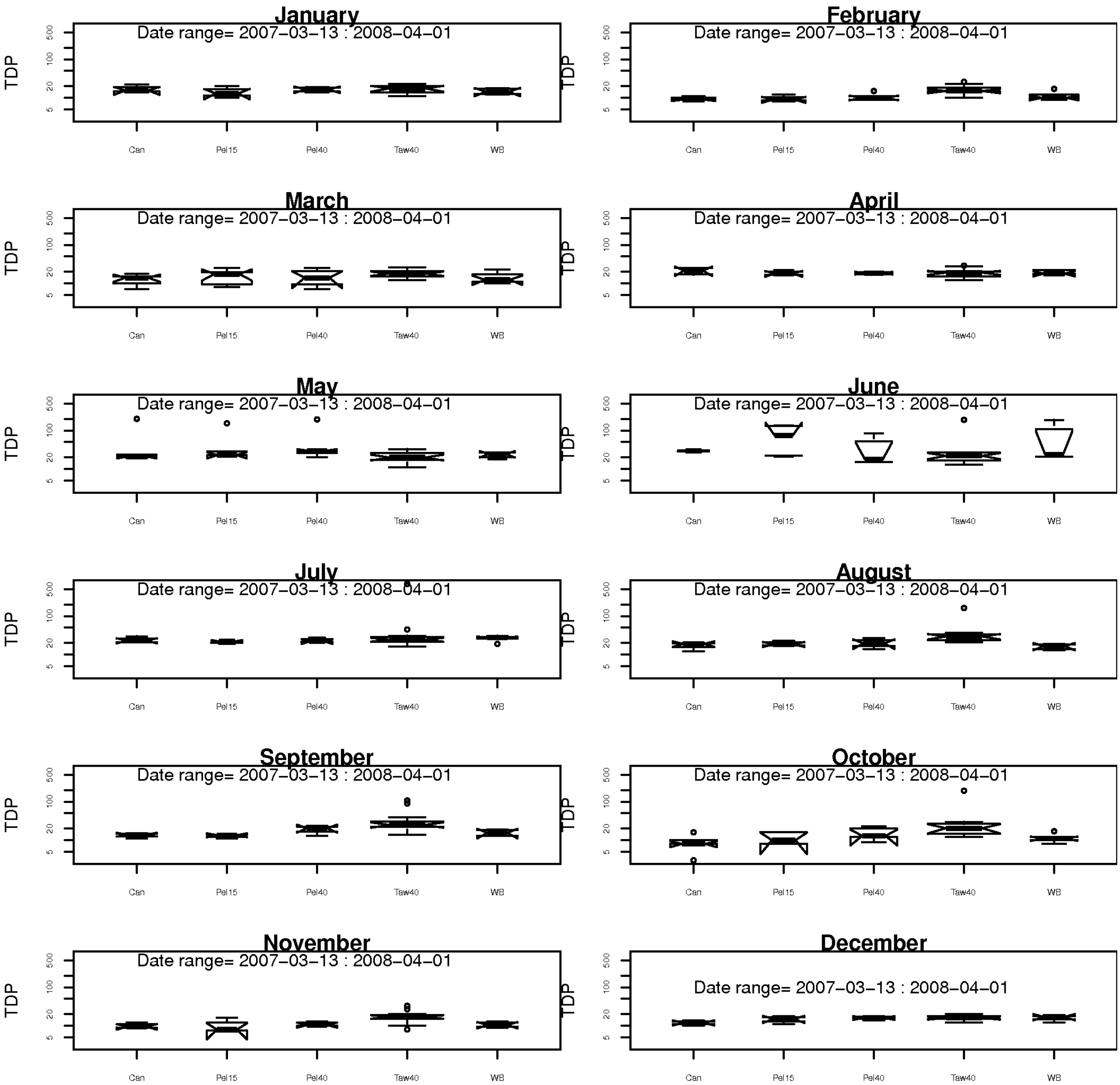
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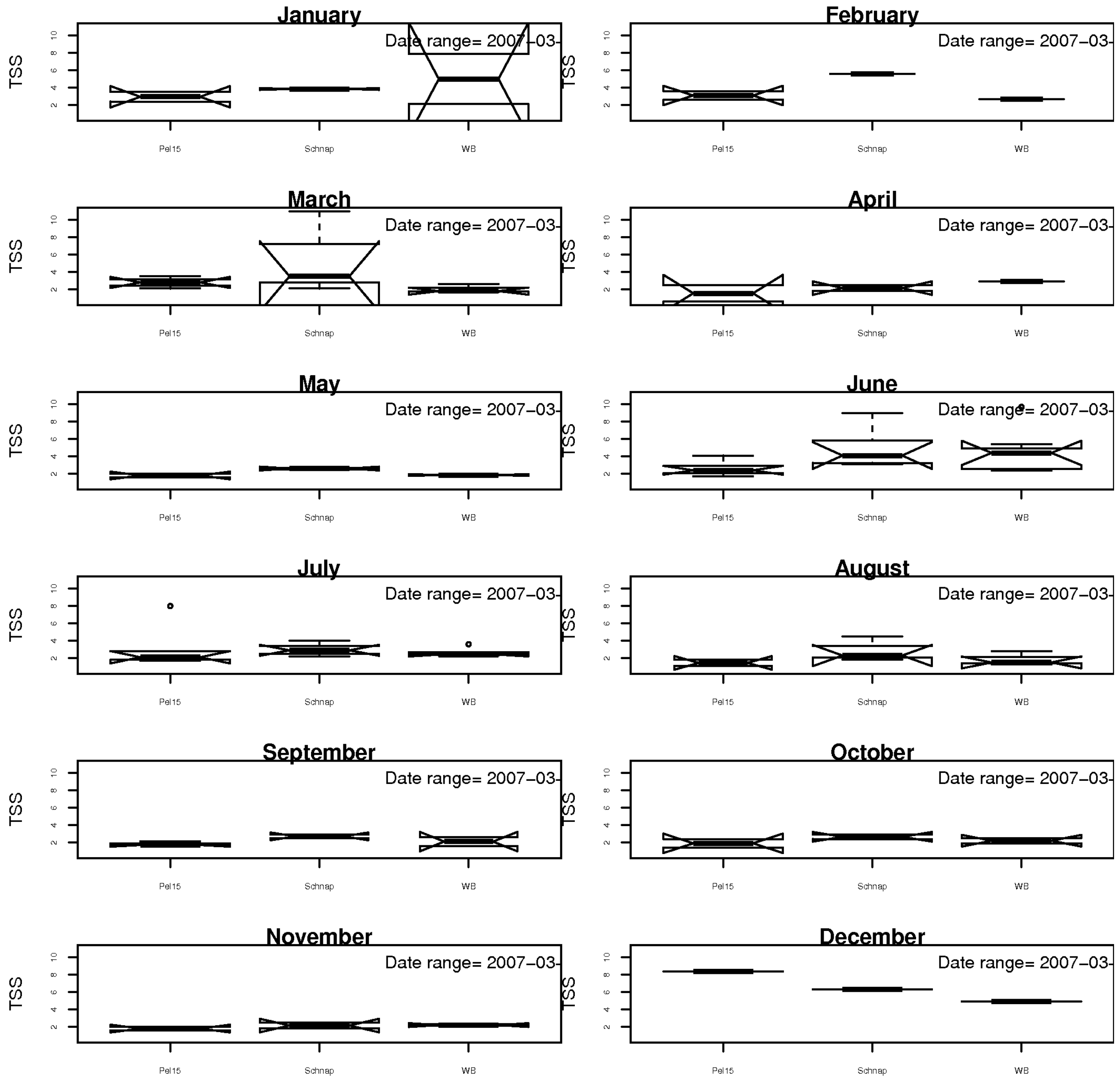
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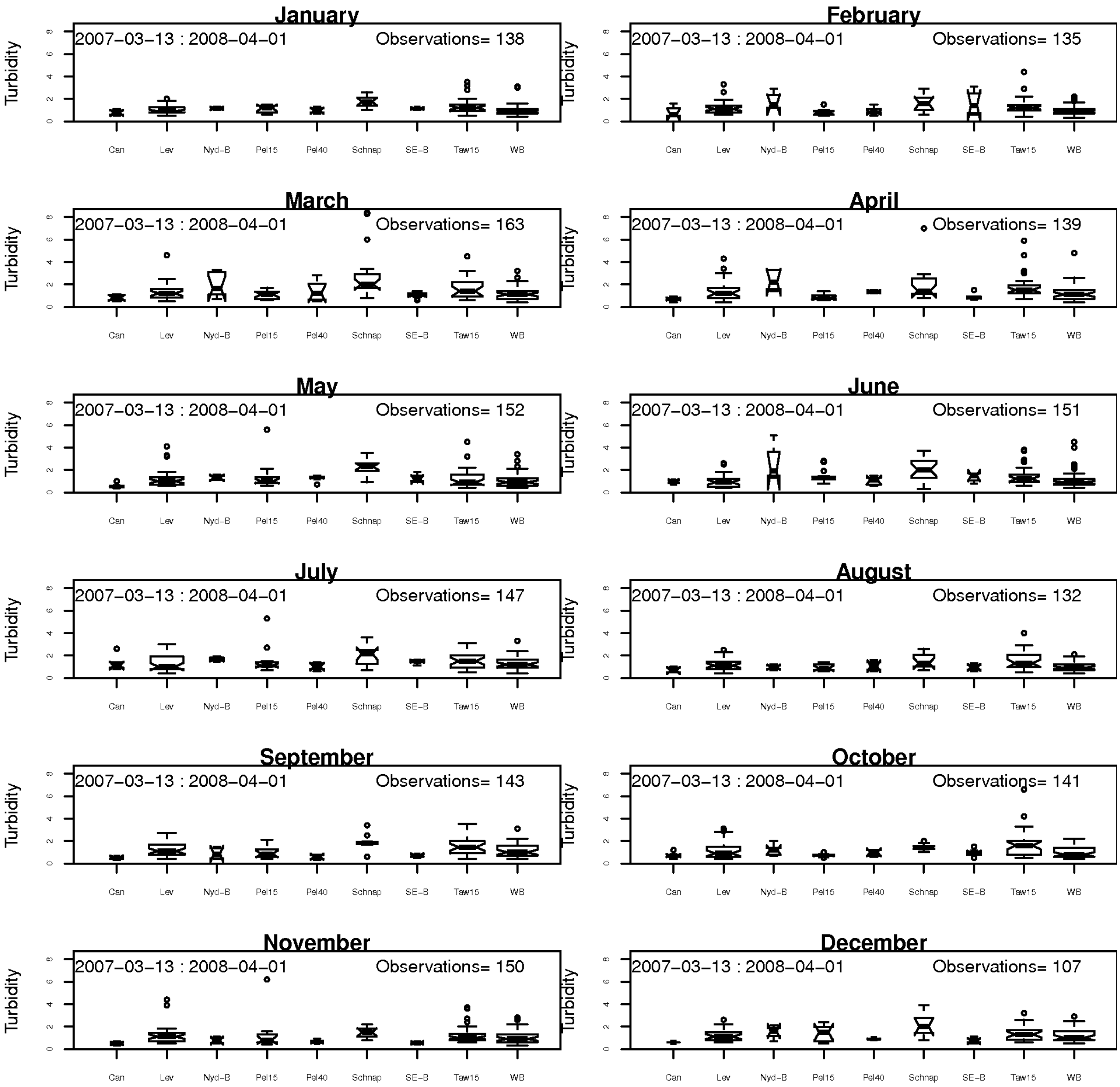
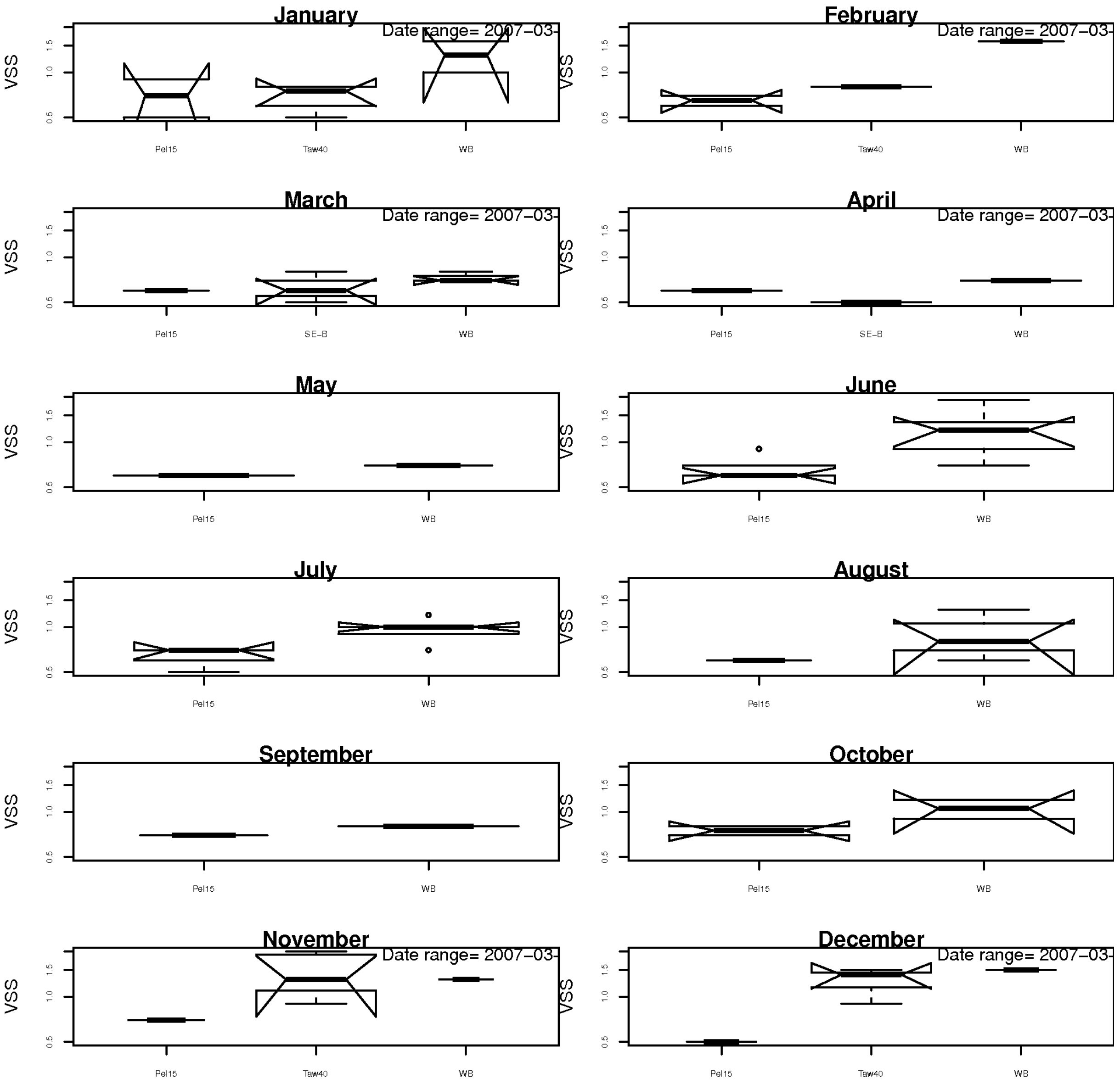
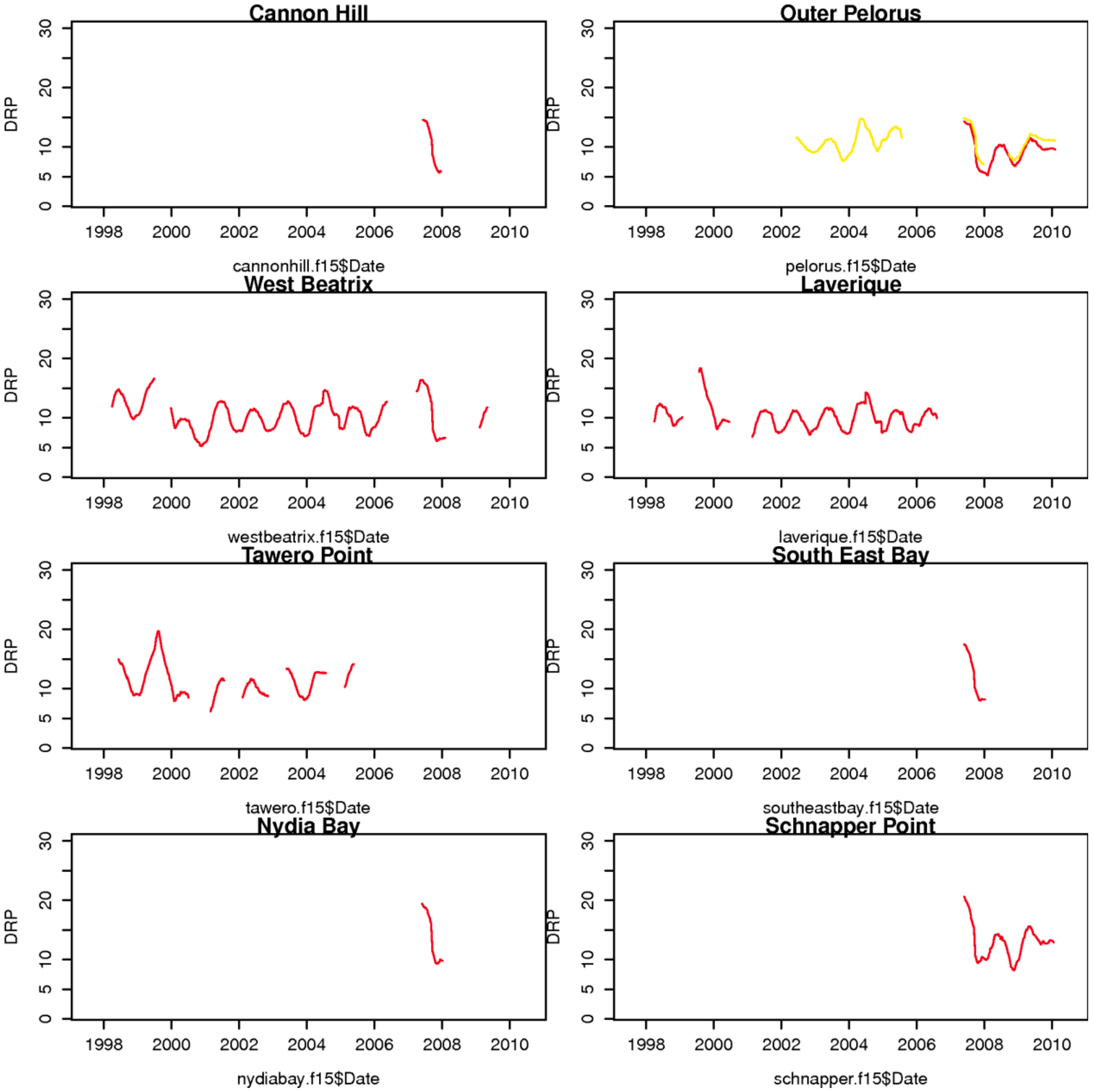
October
November
December
TSS
Date range= 2007–03-
Pel15
Schnap
WB

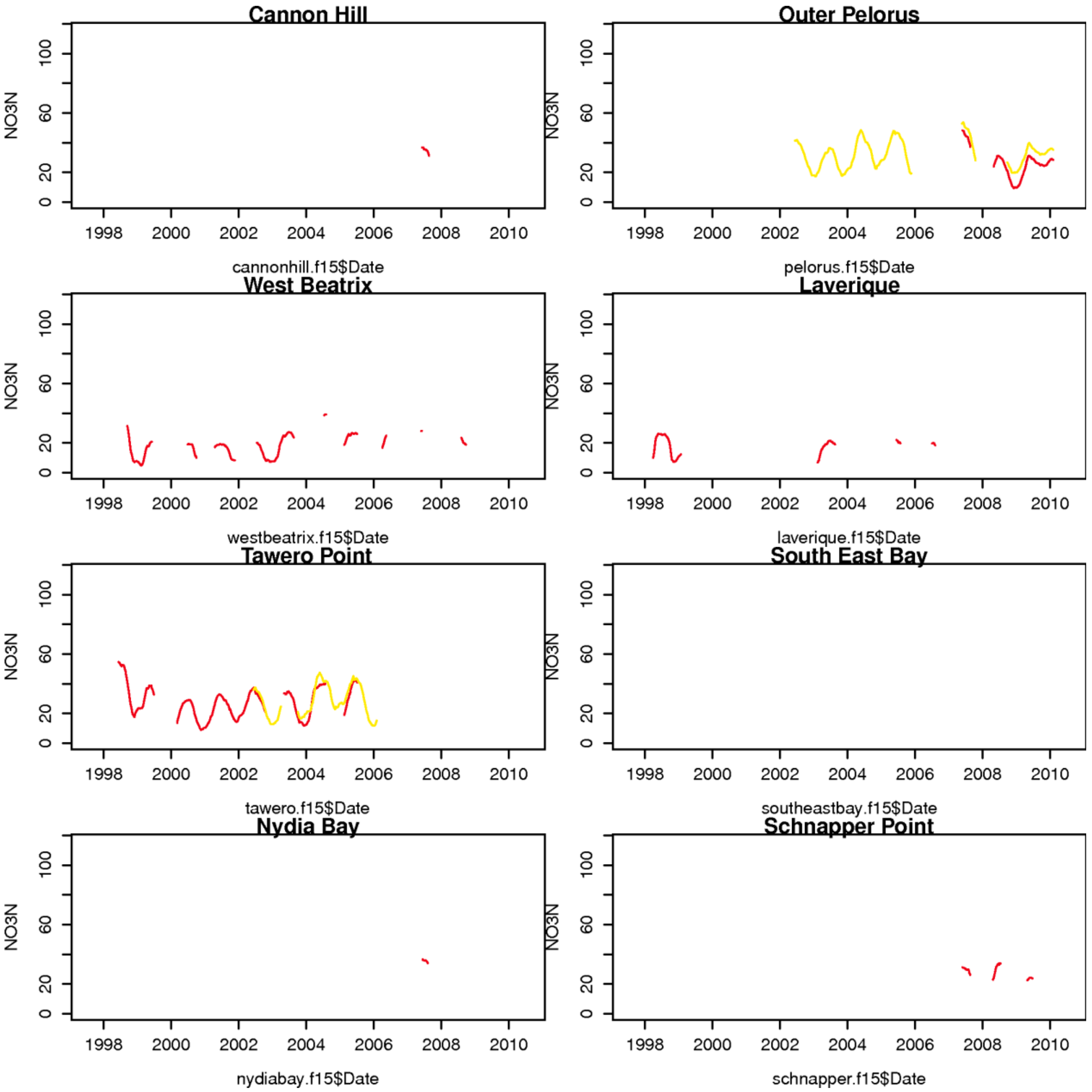

January
2007–03–13 : 2008–04–01
Observations= 138
February
2007–03–13 : 2008–04–01
Observations= 135
March
2007–03–13 : 2008–04–01
Observations= 163
April
2007–03–13 : 2008–04–01
Observations= 139
May
2007–03–13 : 2008–04–01
Observations= 152
June
2007–03–13 : 2008–04–01
Observations= 151
July
2007–03–13 : 2008–04–01
Observations= 147
August
2007–03–13 : 2008–04–01
Observations= 132
September
2007–03–13 : 2008–04–01
Observations= 143
October
2007–03–13 : 2008–04–01
Observations= 141
November
2007–03–13 : 2008–04–01
Observations= 150
December
2007–03–13 : 2008–04–01
Observations= 107
Turbidity
Can
Lev
Nyd–B
Pel15
Pel40
Schnap
SE–B
Taw15
WB

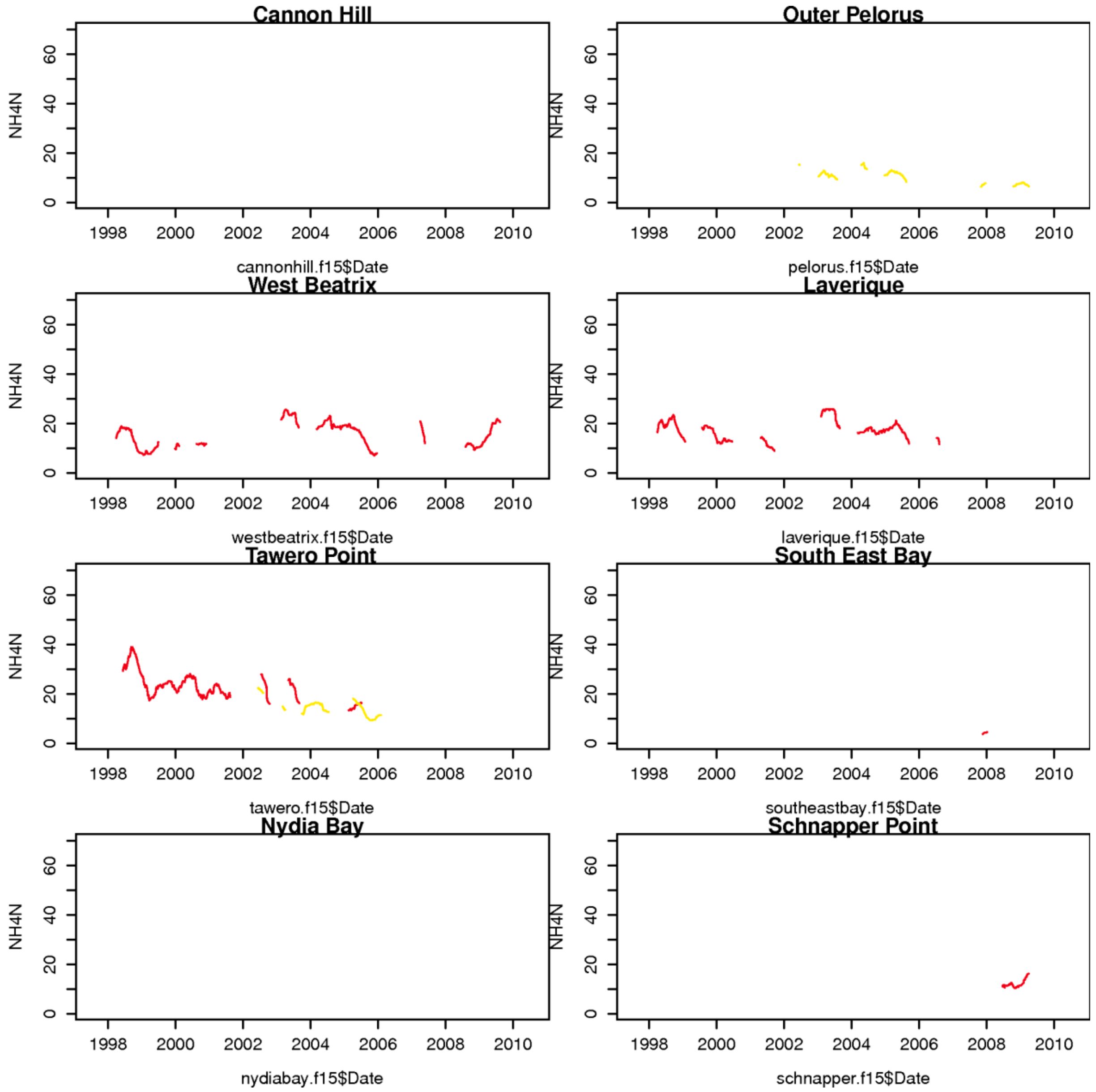

January
Date range= 2007-03-
VSS
Pel15
Taw40
WB
February
Date range= 2007-03-
VSS
Pel15
Taw40
WB
March
Date range= 2007-03-
VSS
Pel15
SE-B
WB
April
Date range= 2007-03-
VSS
Pel15
SE-B
WB
May
VSS
Pel15
WB
June
VSS
Pel15
WB
July
VSS
Pel15
WB
August
VSS
Pel15
WB
September
VSS
Pel15
WB
October
VSS
Pel15
WB
November
Date range= 2007-03-
VSS
Pel15
Taw40
WB
December
Date range= 2007-03-
VSS
Pel15
Taw40
WB

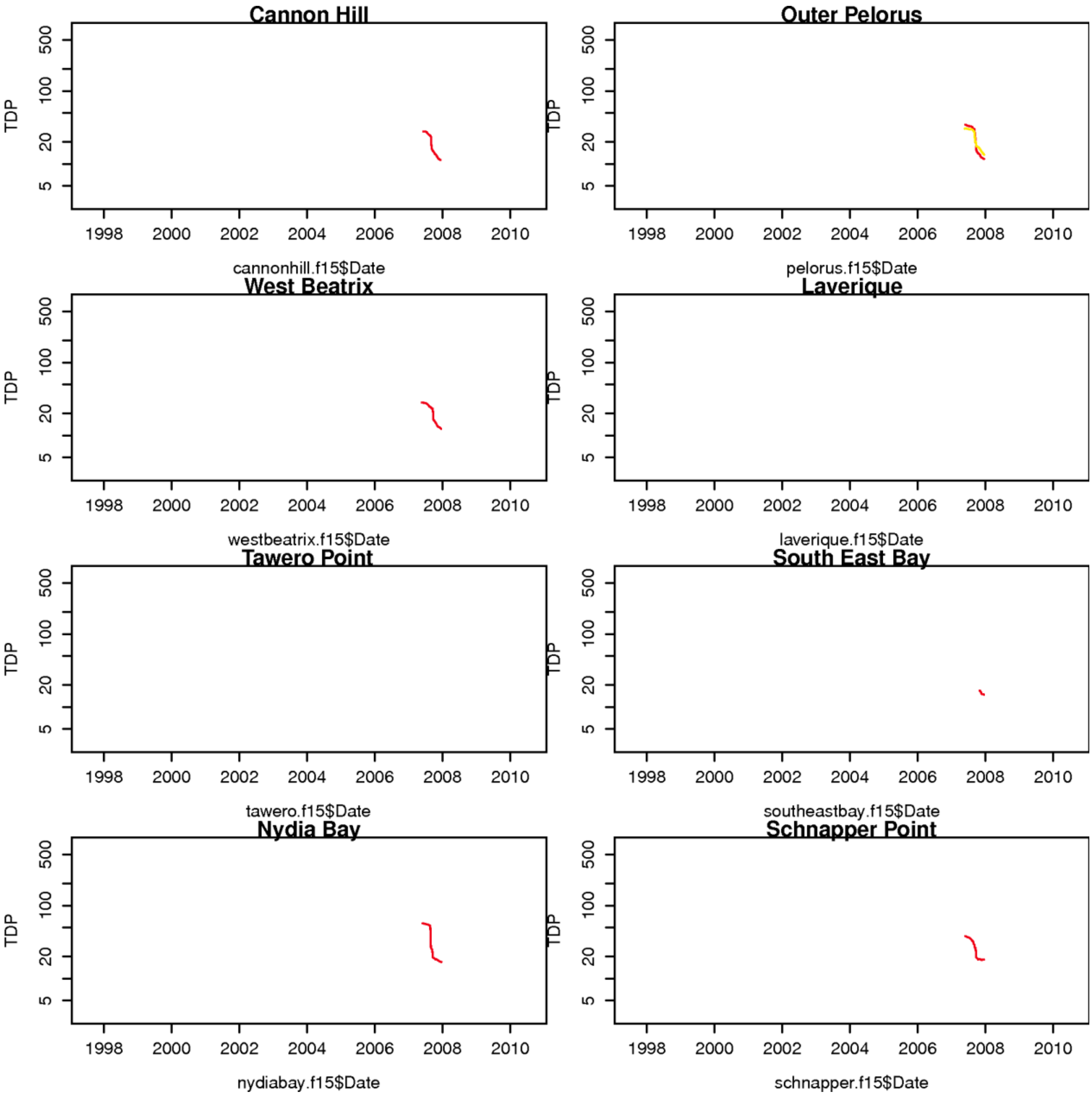
7 Appendix 2. Time-centred 12 month moving average time-series of water-quality properties at the historical NIWA Pelorus Sounds sites

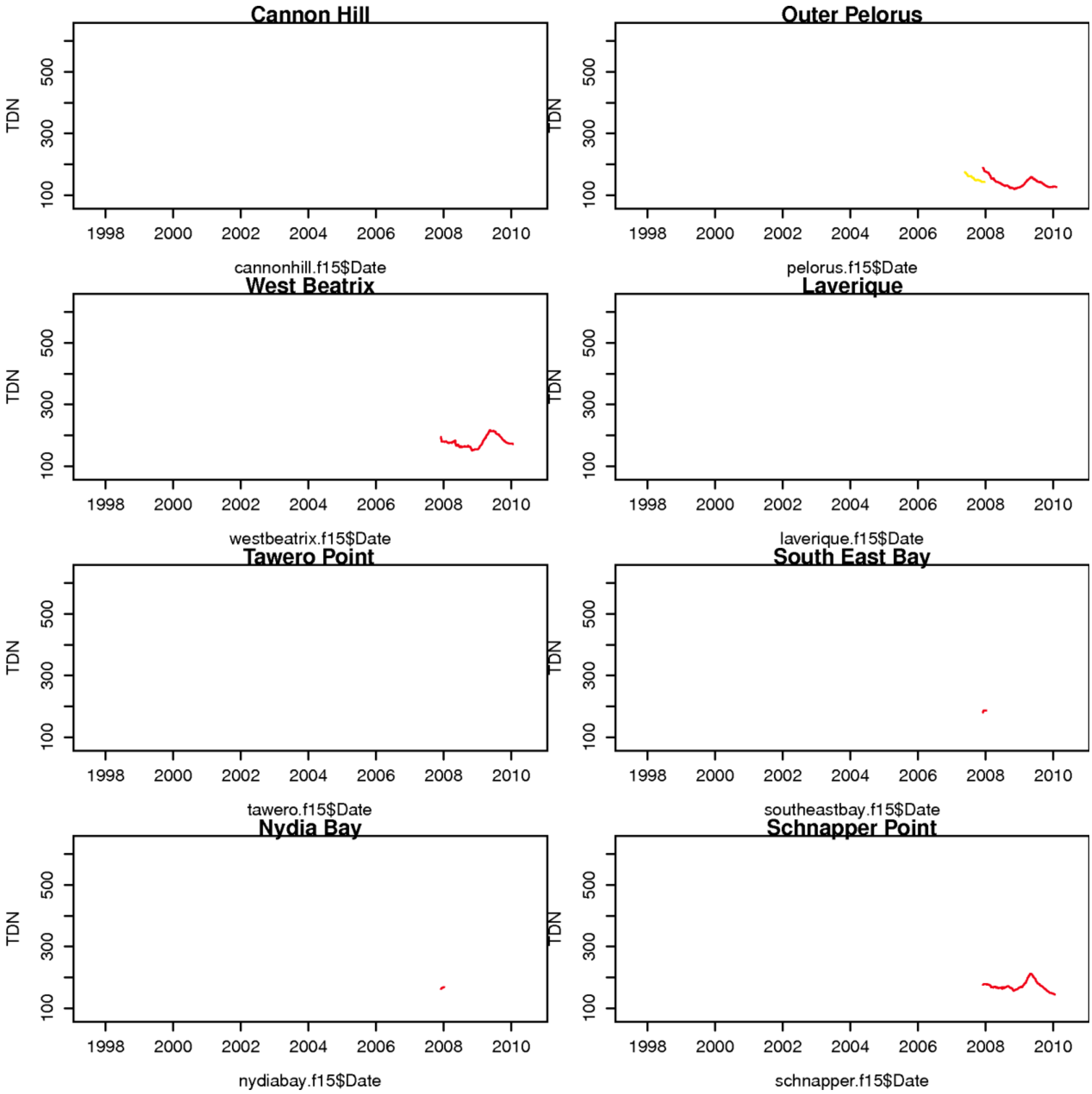
These plots illustrate the time-centred 12 month moving average time-series of water-quality properties at the historical NIWA Pelorus Sounds sites. Unfortunately, most of the time-series contain missing values. Each missing value forces a break (spanning six months either side of the missing value) in the moving average. Red lines are surface-layer data, yellow lines are data from the 40 m sampling depth.

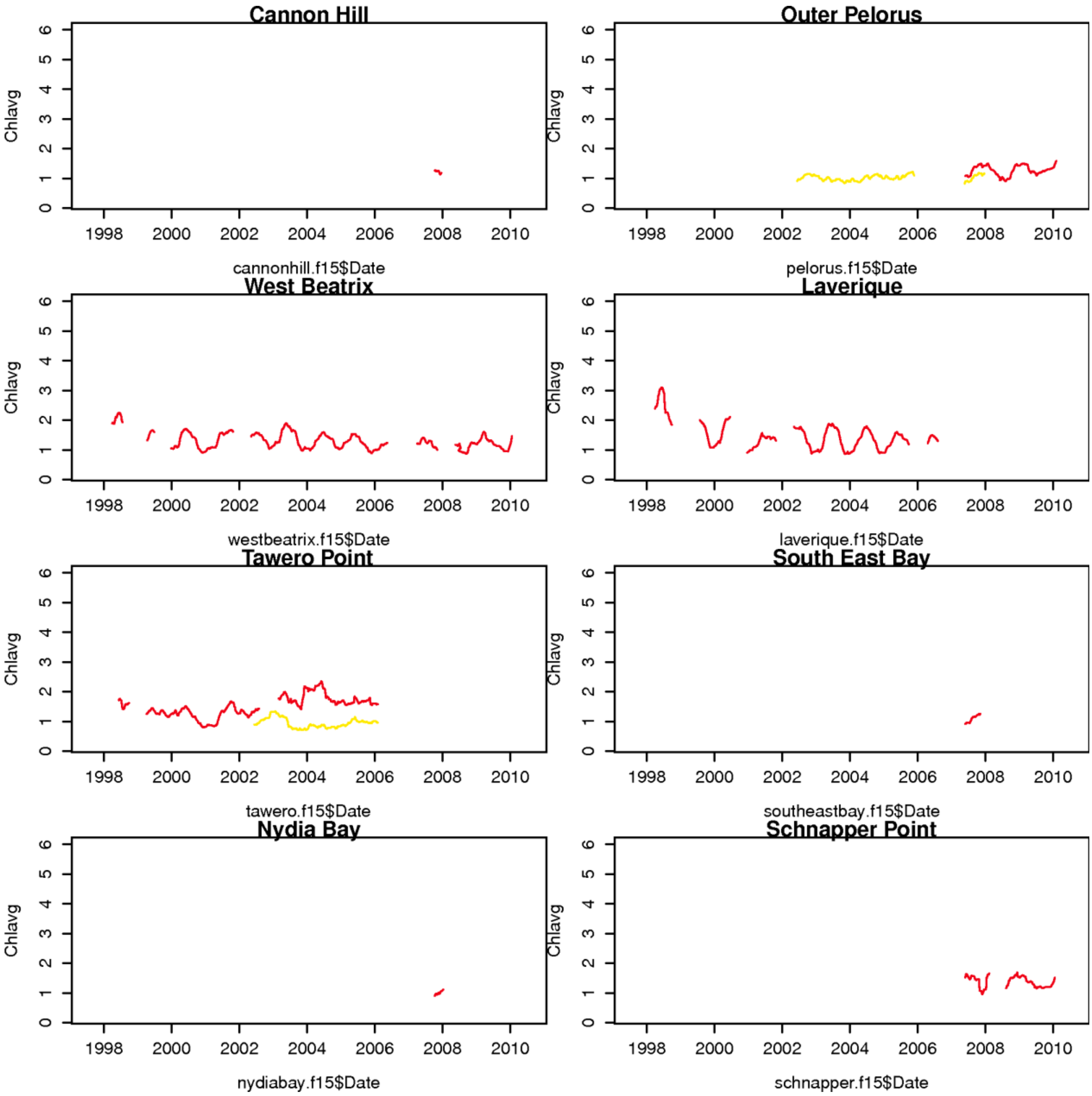


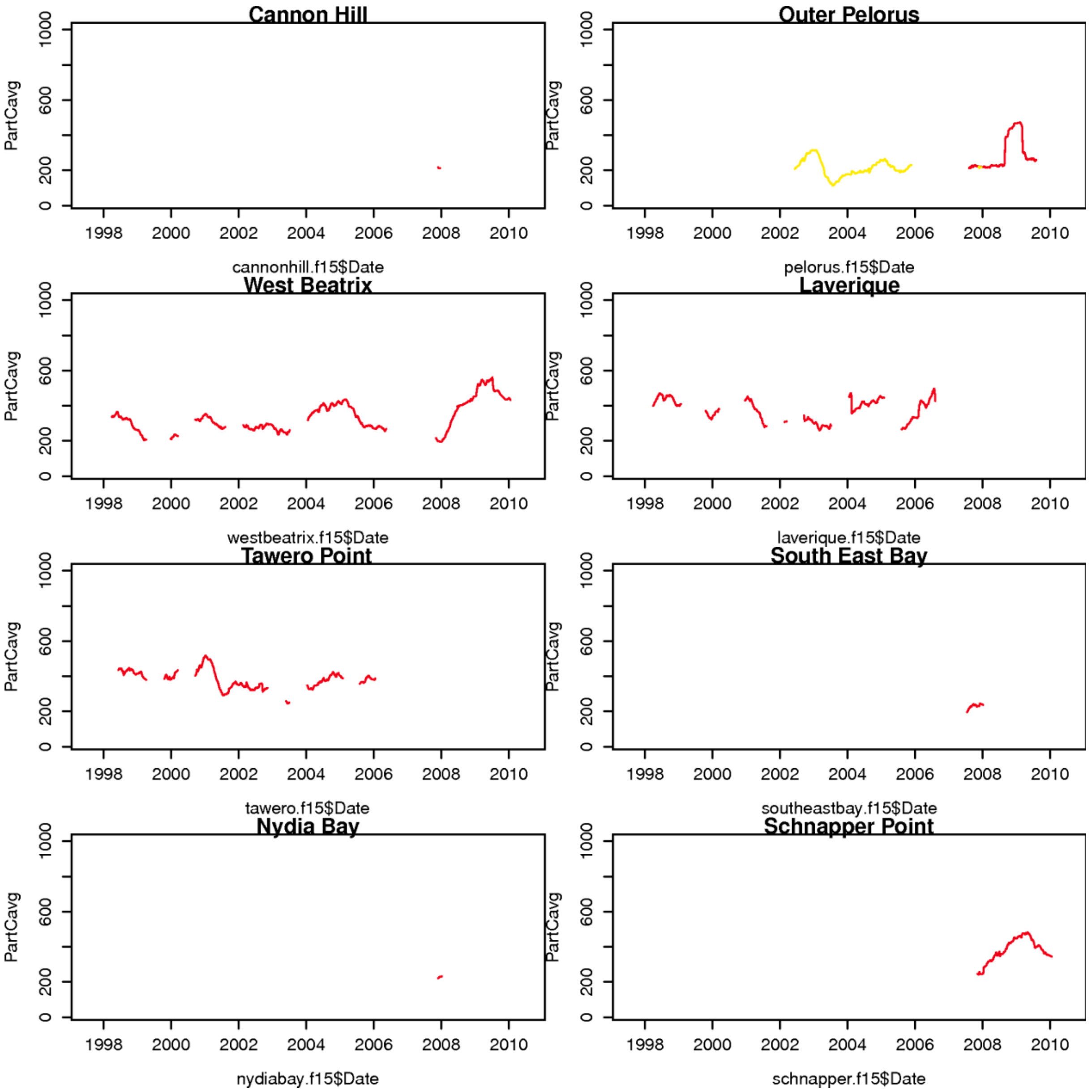

Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
NO3N
0
20
60
100
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date

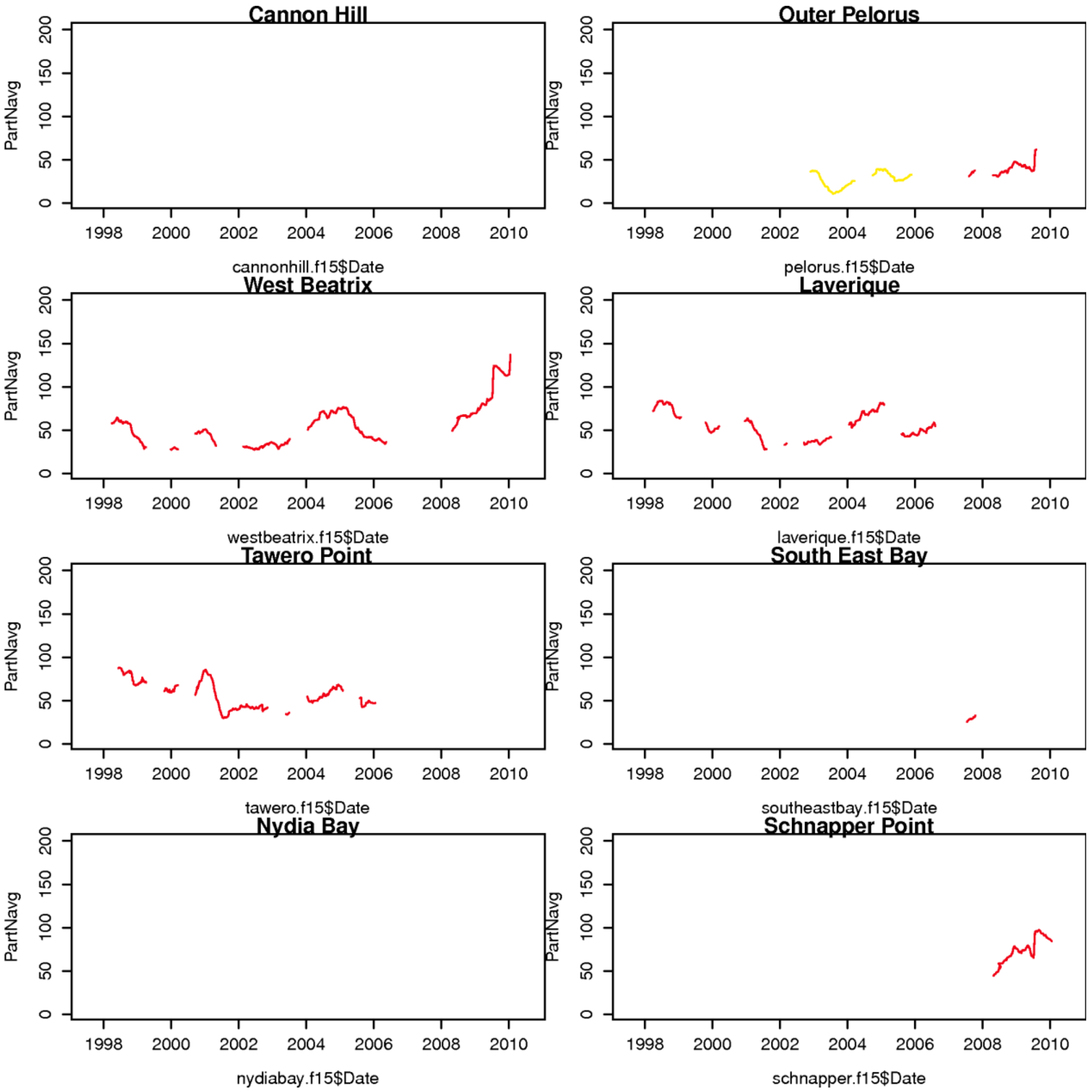

Cannon Hill
NH4N
0
20
40
60
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
Outer Pelorus
NH4N
pelorus.f15$Date
West Beatrix
westbeatrix.f15$Date
Laverique
laverique.f15$Date
Tawero Point
tawero.f15$Date
South East Bay
southeastbay.f15$Date
Nydia Bay
nydiabay.f15$Date
Schnapper Point
schnapper.f15$Date

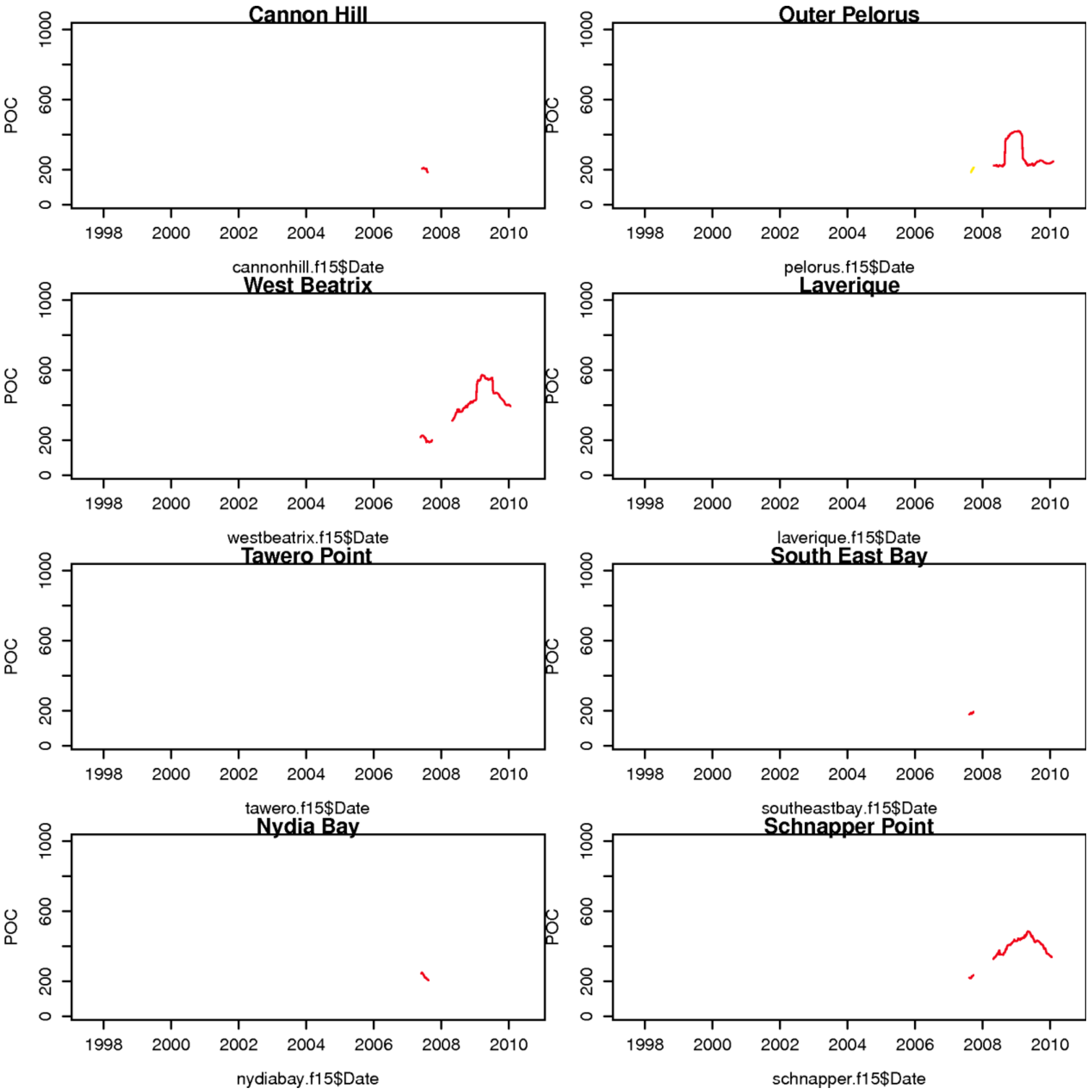

Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
TDP
5
20
100
500
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date

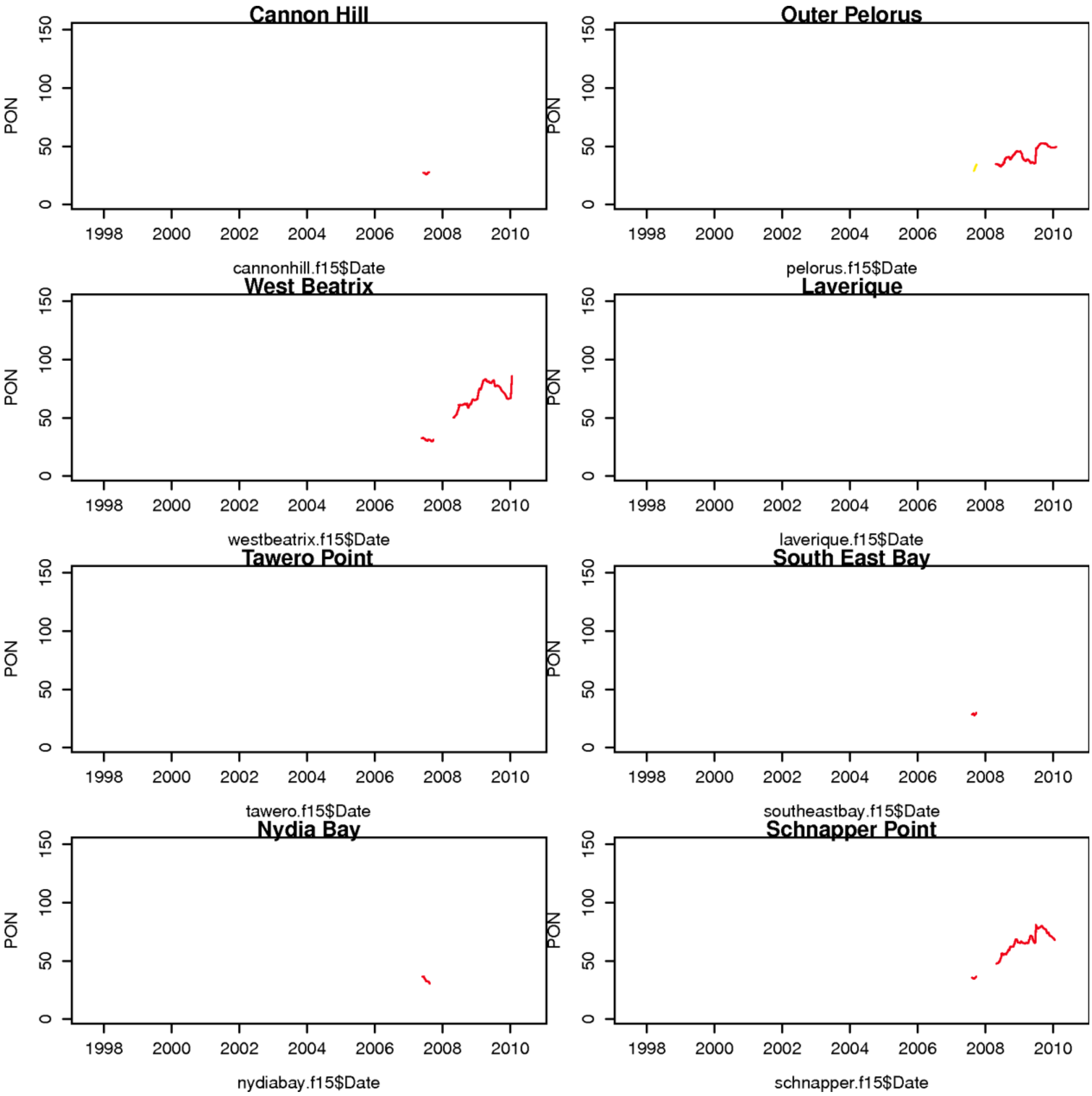

Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
TDN
100
300
500
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date


Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
Chlavg
0
1
2
3
4
5
6
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date

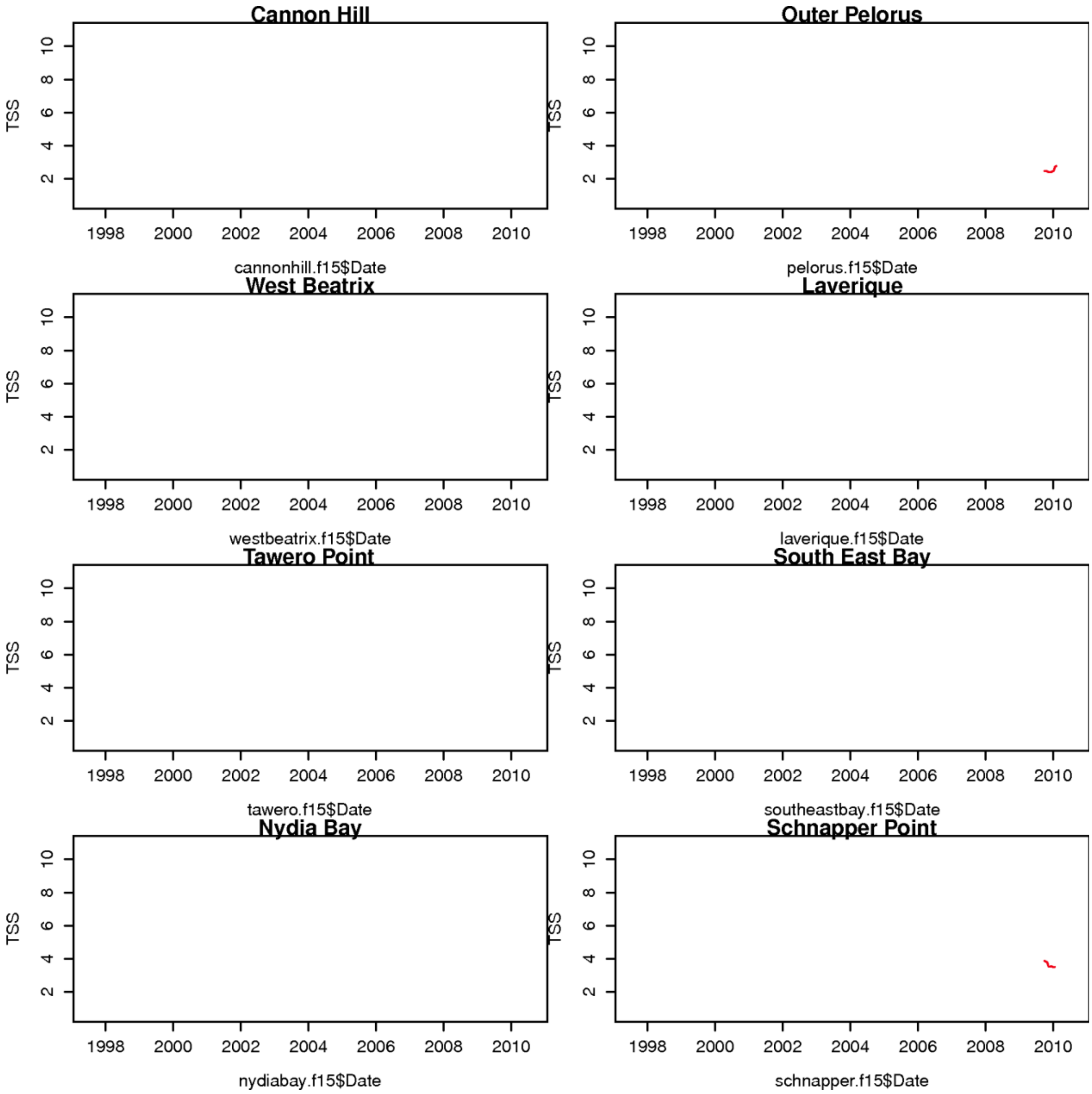

Cannon Hill
PartCavg
cannonhill.f15$Date
Outer Pelorus
PartCavg
pelorus.f15$Date
West Beatrix
PartCavg
westbeatrix.f15$Date
Laverique
PartCavg
laverique.f15$Date
Tawero Point
PartCavg
tawero.f15$Date
South East Bay
PartCavg
southeastbay.f15$Date
Nydia Bay
PartCavg
nydiabay.f15$Date
Schnapper Point
PartCavg
schnapper.f15$Date
0
200
600
1000
1998
2000
2002
2004
2006
2008
2010


Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
PartNavg
0
50
100
150
200
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date


Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
POC
0
200
600
1000
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date



Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
PON
0
50
100
150
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
schnapper.f15$Date


Cannon Hill
Outer Pelorus
West Beatrix
Laverique
Tawero Point
South East Bay
Nydia Bay
Schnapper Point
TSS
2
4
6
8
10
1998
2000
2002
2004
2006
2008
2010
cannonhill.f15$Date
pelorus.f15$Date
westbeatrix.f15$Date
laverique.f15$Date
tawero.f15$Date
southeastbay.f15$Date
nydiabay.f15$Date
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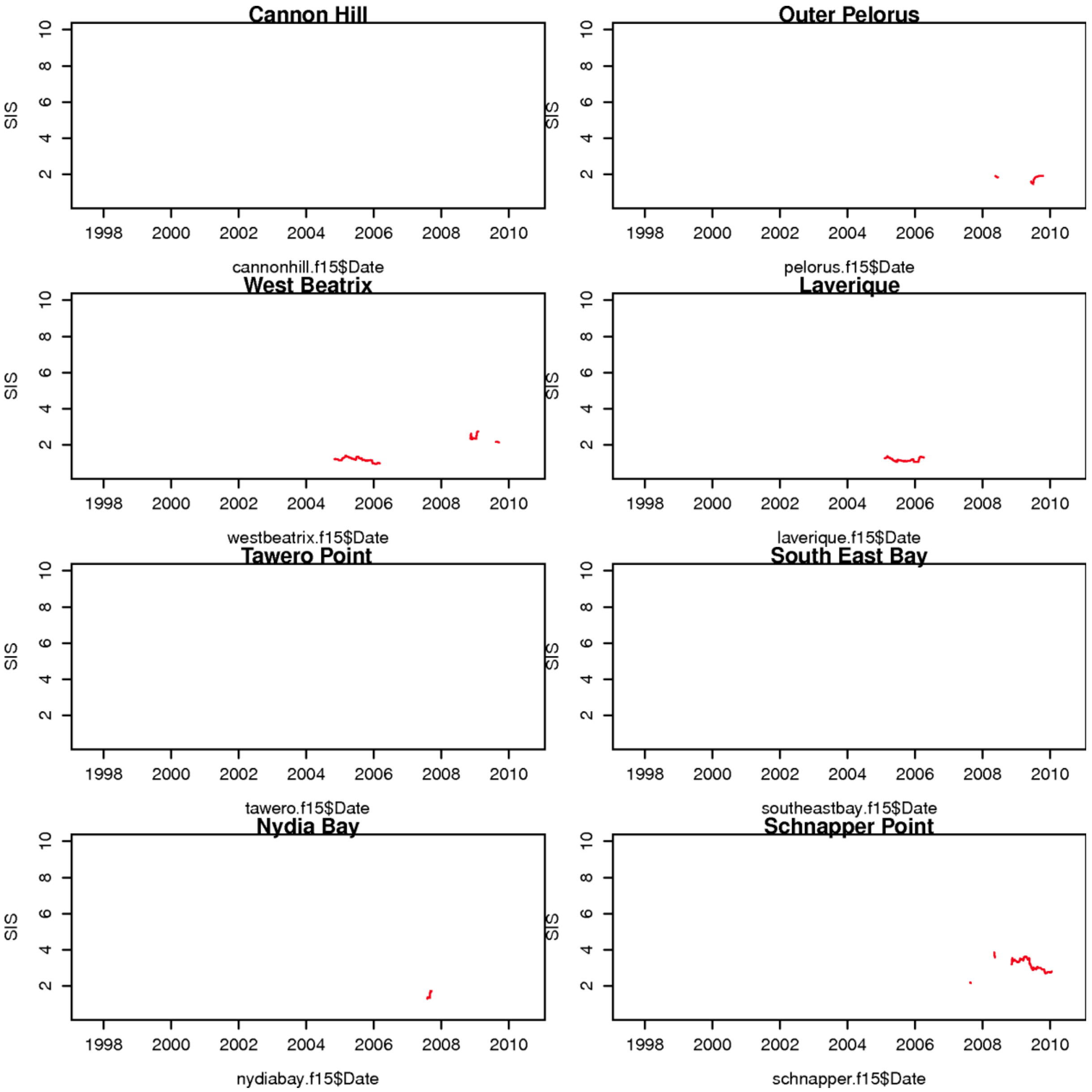
Cannon Hill
SIS
cannonhill.f15$Date
Outer Pelorus
pelorus.f15$Date
West Beatrix
westbeatrix.f15$Date
Laverique
laverique.f15$Date
Tawero Point
tawero.f15$Date
South East Bay
southeastbay.f15$Date
Nydia Bay
nydiabay.f15$Date
Schnapper Point
schnapper.f15$Date
1998
2000
2002
2004
2006
2008
2010
2
4
6
8
10