Lyttelton Harbour / Whakaraupō nutrient status

April 1988 – June 2003

Environment Canterbury
Your regional council

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Executive Summary

Water quality monitoring was carried out at 7 sites in greater Lyttelton Harbour and at 10 sites in the port area. Sampling at the greater Lyttelton Harbour sites was carried out approximately monthly over four year-long periods between April 1988 and June 2003 and at the port sites was carried out approximately monthly between September 1999 and June 2000.

In greater Lyttelton Harbour, significant differences occurred in the concentration of the nutrients between at least two of the seven sites in each year-long sampling period. For ammonia nitrogen, total organic nitrogen and total nitrogen there was no obvious pattern to the difference in concentration between sites while for nitrate-nitrite nitrogen, dissolved reactive phosphorus and total phosphorus there was a pattern to the difference in concentration between sites over all sampling periods. These patterns consisted of:

- Generally higher concentrations of nitrate-nitrite nitrogen at the port entrance than at other sites
- Generally higher concentrations of dissolved reactive phosphorus and total phosphorus at inner harbour sites (Charteris Bay, Governors Bay and Corsair Bay) and the port entrance than at outer harbour sites (Harbour entrance, Purau and Ripapa).

Within the port area there were generally higher concentrations of nitrate-nitrite nitrogen, total nitrogen, dissolved reactive phosphorus and total phosphorus at the Fox II mooring, between wharves 5 and 6 and between the fishing boats and the yachts than at the other sites.

The results indicate:

- Site-specific sources of nutrients within the Port of Lyttelton
- Irregular nutrient inputs at various locations, within the Port of Lyttelton
- Nutrient input into or near to the port entrance
- DRP and TP input/s into the inner harbour

Over time the concentrations of dissolved reactive phosphorus and total phosphorus were significantly lower in 2002 and early 2003 than in one or more of the other sampling periods at all greater Lyttelton Harbour sites except the port entrance. Over time the concentrations of nitrate-nitrite nitrogen, total organic nitrogen and total nitrogen were only significantly different at the port entrance.

For all nutrients there was no apparent overall trend (of a decrease or increase) in concentration between 1988 and 2003.

The concentrations of dissolved inorganic nitrogen (=ammonia nitrogen + nitrate-nitrite nitrogen), total nitrogen, dissolved reactive phosphorus and total phosphorus at sites in greater Lyttelton Harbour and the Port of Lyttelton frequently exceeded the ANZECC (2000) trigger levels for ‘slightly disturbed marine water’. At concentrations above the trigger level there is potential for excessive growth of aquatic plants. However the relative availability of inorganic nitrogen (DIN) to inorganic phosphorus (DRP) i.e. the N:P ratio, also influences aquatic plant growth and in particular phytoplankton growth.

At all sites in greater Lyttelton Harbour in 1988, 1992-1993, 1993-1994 and 2002-2003, and at sites in the port on most sampling occasions in 1999-2000 aquatic plant growth was, as indicated by an N:P ratio of<16:1, nitrogen limited. Phosphorus-limited aquatic plant growth i.e. an N:P ratio of>16:1, occurred at some sites on some occasions in the port in 1999-2000. Optimal nutrient conditions i.e. an N:P ratio of 16:1 for phytoplankton growth did not occur in any of the samples collected at the sites in greater Lyttelton Harbour or the port.

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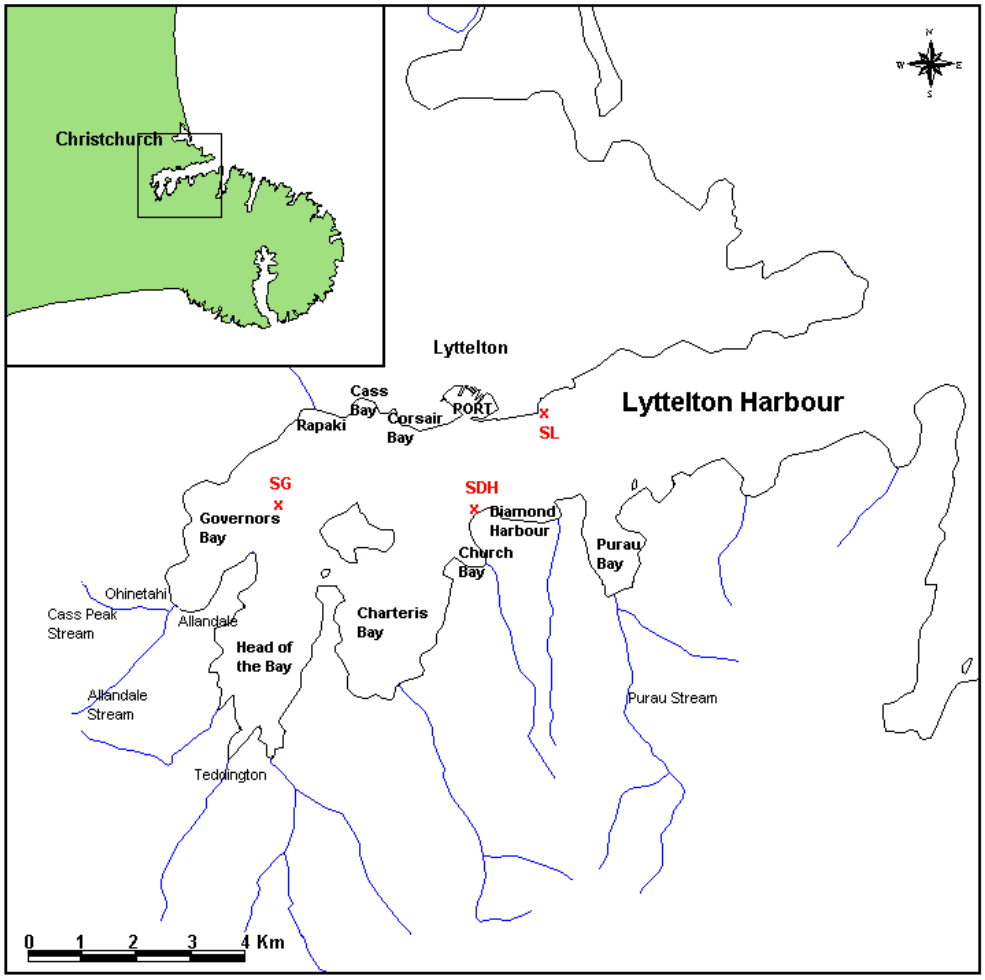
1 Introduction

1.1 Lyttelton Harbour/ Whakaraupō

Lyttelton Harbour, formed by the drowning of the erosion crater of an extinct volcanic complex, is characterised as a muddy bottomed, relatively shallow, rock-walled inlet. The harbour width varies from 1.35 - 5.5 km and at high tide it is approximately 15 km long, covering an area of about 44 km^2 (Spigel, 1993). At low tide a quarter of the harbour area, i.e. 11 km^2, is exposed mud flat with these mud flats occurring at the head of the harbour in Governors Bay, Charteris Bay and Head of the Bay (Figure 1.1). The water within the harbour is essentially marine with the freshwater inflows via small streams insufficient for the establishment of estuarine conditions within the inner harbour. Even after major storm events salinity concentration gradients are small (Spigel, 1993).

The Port of Lyttelton, located about midway down the northern side of the harbour (Figure 1.1), is a busy commercial port that has serviced the Canterbury Province for some 150 years. The present day port facilities include container, oil tanker and roll-on roll-off facilities, coal storage and loading facilities, a dry dock, a cattle wharf, general shipping, fishing boat and cement shipping berths and yacht moorings. Stormwater runoff from port facilities and day-to-day activities in the port area are potential sources of heavy metals, organic compounds and nutrients that could end up in the water within the port area.



Approximate position of sewage discharges: x SG - Governors Bay
x SL - Lyttelton
x SDH - Diamond Harbour

Figure 1.1 Lyttelton Harbour/ Whakaraupō: location, bays, streams and sewage discharges

Land use of the surrounds of Lyttelton Harbour has over time, changed from a predominantly rural landscape to a semi-rural one with numerous lifestyle blocks and ever-increasing housing subdivisions within the bays i.e. Purau, Diamond Harbour, Charteris Bay, Church Bay, Governors Bay, Rapaki and Cass Bay (Figure 1.1). The township of Lyttelton has also increased in size over time. Hand in hand with the increase in the human population of the area has been the increasing burden of sewage disposal. Reticulated sewage systems are in place in Governors Bay, Diamond Harbour/Church Bay and Lyttelton, with the Lyttelton system servicing the communties of Lyttelton, Corsair Bay, Cass Bay and Rapaki. From the reticulated systems the sewage is discharged into the harbour through outfalls off Diamond Harbour (Pauaohinekotau Head), Governors Bay and Lyttelton (Sticking Point) (Figure 1.1). Meanwhile, households in Ohinetahi, Allandale, Teddington, Head of the Bay, Charteris Bay and Purau rely on septic tanks or more modern on-site systems for disposal of their sewage (J. Porter, BPDC, *pers.comm.*). Sewage is a source of nitrogen and phosphorus compounds (i.e. nutrients) (Harris *et al.*, 1996).

Concomitant with the increasing urbanisation of the harbour surrounds has been an increase in impervious surface area and hence stormwater runoff. Most of the stormwater in the region is discharged into the small streams which then flow into the harbour; nonetheless stormwater flow can result in inputs of rubbish, sediments, pathogens, organic matter, chemical contaminants such as heavy metals and organic compounds, and possibly nitrogen and phosphorus compounds into harbour water (Morrisey, 1997; Vincent and Thomas, 1997; Bolton-Ritchie, 2003).

With the increasing human presence and on-going port activities there is potential for the water quality of Lyttelton Harbour to differ in different parts of the harbour and to change over time. With increasing nutrient-rich discharges/runoff into the harbour water the likelihood of eutrophication[1] also needs to be assessed. Eutrophication can result in changes in the structure and functioning of marine ecosystems, reduced biodiversity, increase harmful algal blooms and impact on fisheries, aquaculture, recreation and tourism (Rosenberg, 1985; EEA, 2001). Nutrient over–enrichment resulting in eutrophication is now evident in many coastal regions of Europe (Bonsdorff *et al*, 1977) and represents the greatest threat to coastal marine environments around the world (NRC, 2001). In the marine environment nitrogen is the critical limiting nutrient for phytoplankton (plant plankton) growth (NRC, 2001; Rosenberg, 1985; Valiela, 1995). Under optimal conditions phytoplankton will take up nutrients in the ratio C:N:P of 106:16:1 (Redfield *et al,* 1963), i.e. when the nutrients are available in this ratio phytoplankton growth will not be limited. If the ratio of N:P is less than 16:1 then growth is nitrogen-limited and if it is greater than 16:1 growth is phosphorus limited (NRC, 2001).

[1] Eutrophication - the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of aquatic plants (phytoplankton, cyanobacteria, algae and seagrasses) to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned (from Bock *et al,* 1997)

1.2 Lyttelton Harbour/ Whakaraupō water quality

In 1988 the North Canterbury Catchment Board and Regional Water Board, the local body then responsible for the quality of the water in Lyttelton Harbour, set up a programme to routinely sample the harbour water at a number of sites, and where relevant, a number of water depths at a site. The sites and depths sampled were the same as those sampled by Millhouse in 1976 (Millhouse, 1977). This monitoring programme, which continued after the Catchment Board amalgamated with other bodies to form the Canterbury Regional Council, was repeated over three other year long time periods between 1990 and June 2003. In addition, routine sampling was carried out over a one year period at sites in the Port of Lyttelton. The considerable amount of Lyttelton Harbour water quality data that now exists is the focus of this report.

1.3 Objectives of the analyses of these water quality data

To investigate if:

1. There was a significant difference in water quality between sites in greater Lyttelton harbour in each sampling period and between sites in the Port of Lyttelton

2. There was a significant difference in water quality with water depth at each site in each sampling period

3. There was a significant difference in water quality at each site over time

4. The water quality in Lyttelton Harbour is a cause for ecological concern, i.e.
   - How do the nutrient concentrations in Lyttelton Harbour water compare to trigger concentrations in the ANZECC (2000) guidelines?
   - The N:P ratios in Lyttelton Harbour water compared to the 16:1 ratio considered optimal for aquatic plant growth.

2 Methods

2.1 Sites and depths

Samples were collected from 17 sites in Lyttelton Harbour (Figures 2.1 and 2.2). At each site the surface water was sampled and at six of the sites (d, e, f, g, m and p), samples were also collected at one or more depths below the surface. Details of the sites and depths sampled at each site are given in Appendix I.

2.2 Sampling regime

Seven of these sites (a-g) were sampled in the following time periods:

- 1988 (on 8 occasions between 19th April and 23rd of November 1988)
- 1992-1993 (on 11 occasions between 16th July 1992 and 17th of June 1993)
- 1993-1994 (on 12 occasions between 12th of July 1993 and 30th May 1994)
- 2002-2003 (on 11 occasions between 29th July 2002 and 16th June 2003)

The other 10 sites (h-q) were sampled in 1999-2000 (on 10 occasions between 2nd September 1999 and 30th June 2000).

2.3 Sample collection

The samples were collected by staff of the North Canterbury Catchment Board and staff from the Environmental Quality Section of Environment Canterbury. Sampling was carried out from a boat with the surface water collected by leaning over the side of the boat and the water at depth collected using a modified 2L Van-Dorn sampler. All water collected was stored in specially prepared bottles provided by the laboratory undertaking the analyses, and kept cooled in chilli bins until delivery to the laboratory.

In the field the water temperature was measured using a field meter and general observations on the weather (air temperature, cloud cover, wind direction, wind strength) were recorded at the time of sampling.

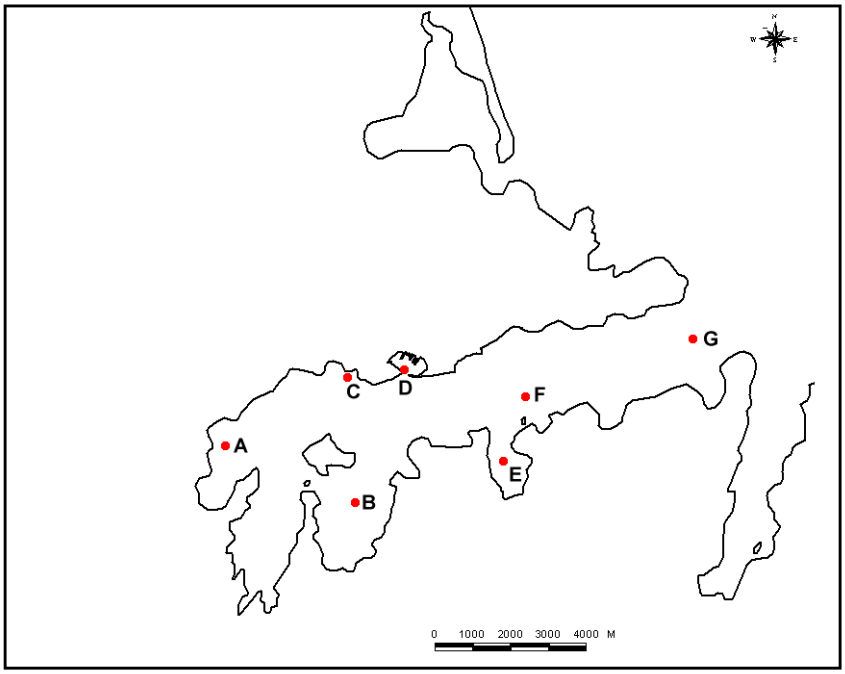


Figure 2.1 Water Quality monitoring sites in Greater Lyttelton Harbour/Whakaraupō

A = Governors Bay B = Charteris Bay C = Corsair Bay D = port entrance E = Purau F = Ripapa G = harbour entrance

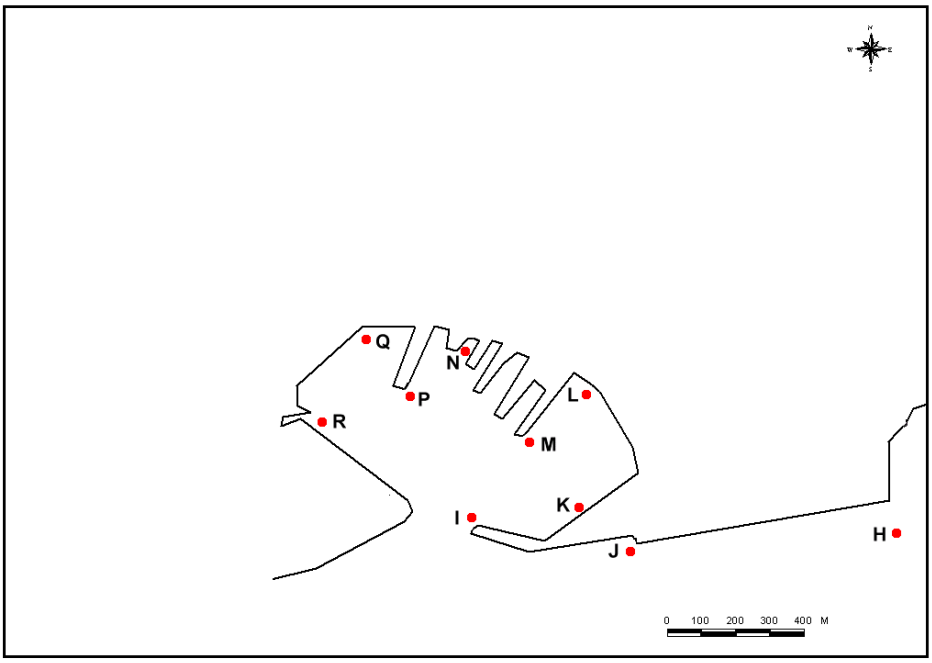


Figure 2.2 Water Quality monitoring sites in the Port of Lyttelton, Lyttelton Harbour/Whakaraupō

H = Sticking point I = end of Z berth J = Cashin Quay K = Gladstone pier
L = Fox II mooring M = end of no.2 wharf N = Between no. 5 & 6 wharf P = end of no. 7 wharf
Q = between fishing boats & yachts R = Cattle jetty

2.4 Sample analyses

The collected water samples were analysed for a range of chemical determinands as listed in Table 2.1. Laboratory analysis of the 1988 samples were carried out by the North Canterbury Catchment Board, analysis of the 1992-1993-1994 samples were carried out by the Cawthron Institute and analysis of the 1999-2000 and 2002-2003 samples were carried out by Environment Canterbury. The details of analytical methods are given in Appendix II.

Table 2.1 Chemical determinands (nutrients)

Nitrate and nitrite nitrogen (NNN)
Total ammonia nitrogen (NH3N)
Dissolved inorganic nitrogen (DIN) (=NNN+ NH3N)
Total organic nitrogen (TON)
Total nitrogen (TN)
Dissolved reactive phosphorus (DRP)
Total phosphorus (TP)

2.5 Data analyses

Microsoft Excel 2000, Statistica (version 6) and Systat (version 9) were used for the production of summary statistics, charts, box plots and all statistical analyses (Statsoft, 2001; SPSS, 1999).

To determine if there was a significant difference in the concentration of each nutrient between sites in greater Lyttelton Harbour in each sampling period, and between sites in the Port of Lyttelton in 1999-2000, the non-parametric Wilcoxon signed rank test was used. The data from greater Lyttelton Harbour were separated into three sets, with the data sets consisting of surface water (seven sites), 3.5 m deep water (four sites) and 6.5 m deep water (three sites). Because sampling at sites in the Port of Lyttelton in 1999-2000 primarily consisted of sampling surface water with only two sites sampled at depth, all of these data were incorporated into one data set. Using the Wilcoxon signed rank test (Systat V9), between-site comparisons for each data set were carried out for each nutrient.

To determine if there was a significant difference in the concentration of each nutrient with water depth, the non-parametric Wilcoxon signed rank test (Systat V9) was used. Statistical analyses were performed on data from greater Lyttelton Harbour sites where more than one water depth was sampled and were performed on the data from each sampling period.

To determine if there was a significant difference in the concentration of each nutrient at each site in greater Lyttelton Harbour over time, Kruskal-Wallis ANOVA and Wilcoxon two-tailed sign test analyses were used. At sites where more than one water depth was sampled, the data were separated into depth data sets. The Kruskal-Wallis ANOVA (Systat V9) was performed on the data sets from each site to determine if there was a significant difference in the concentration of each nutrient over time. Where there was a statistically significant difference, the Wilcoxon two-tailed sign test (Systat V9) was applied to determine between which sampling periods the difference/s occurred.

To determine if the nutrient concentrations in Lyttelton Harbour water are cause for ecological concern, the concentrations of DIN, TN, DRP and TP at each site were compared to the 'trigger levels' concentrations for 'slightly disturbed marine water', as listed in the ANZECC (2000) guidelines. In addition the N:P ratio for each site was calculated using the DIN and DRP values.

Where concentrations of nutrients were less than the analytical limits of detection, the results were reported as 'less than' the detection limit. These non-detect data were converted to a value equal to half the detection limit for the purposes of data analyses.

3 Results

3.1 Variation between sites

3.1.1 Greater Lyttelton Harbour/ Whakaraupō

Was there a significant difference in the concentration of each nutrient between sites in greater Lyttelton Harbour in each sampling period?

3.1.1.1 Surface samples

The data for each nutrient for each sampling period are presented in box and whisker plots (Figures 3.1-3.6). The results of the Wilcoxon two-tailed sign test, used to determine if, over each sampling period, there was a significant difference in the concentration of each nutrient between sites, are presented in Appendix III.

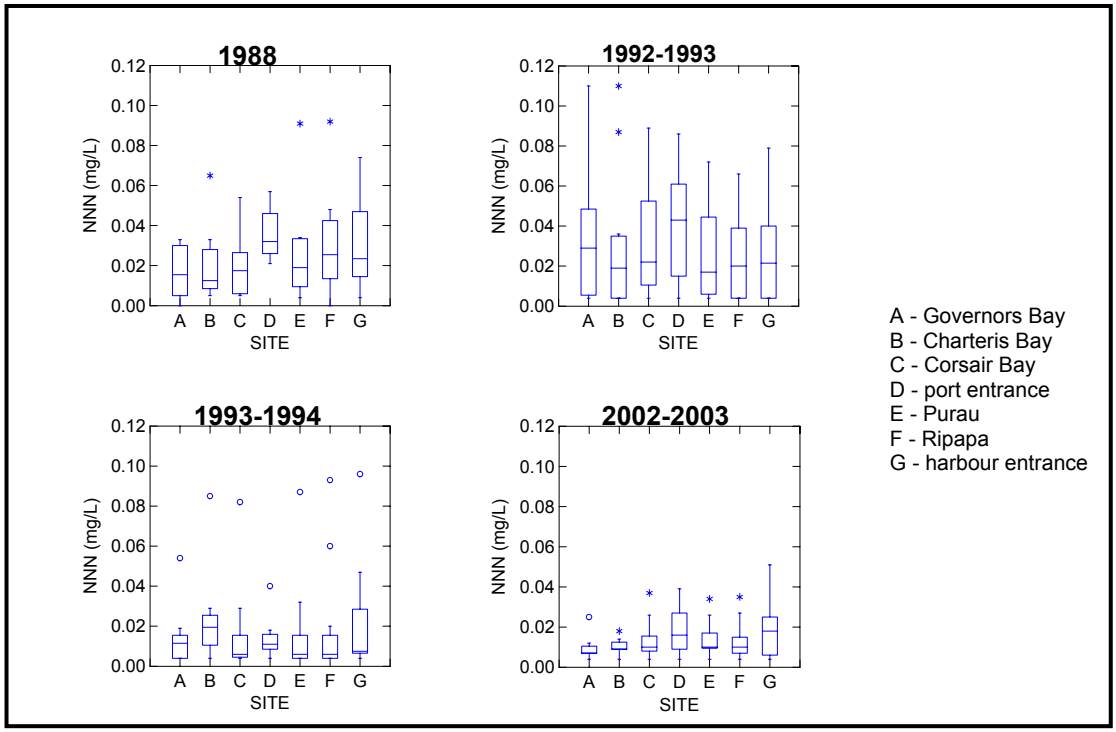


Figure 3.1 Nitrate-nitrite nitrogen (mg/L) in surface water at greater Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

Note: horizontal bar = median, box = interquartile range, whisker ends = 5% and 95%iles, * and o indicate outlier and extreme values respectively

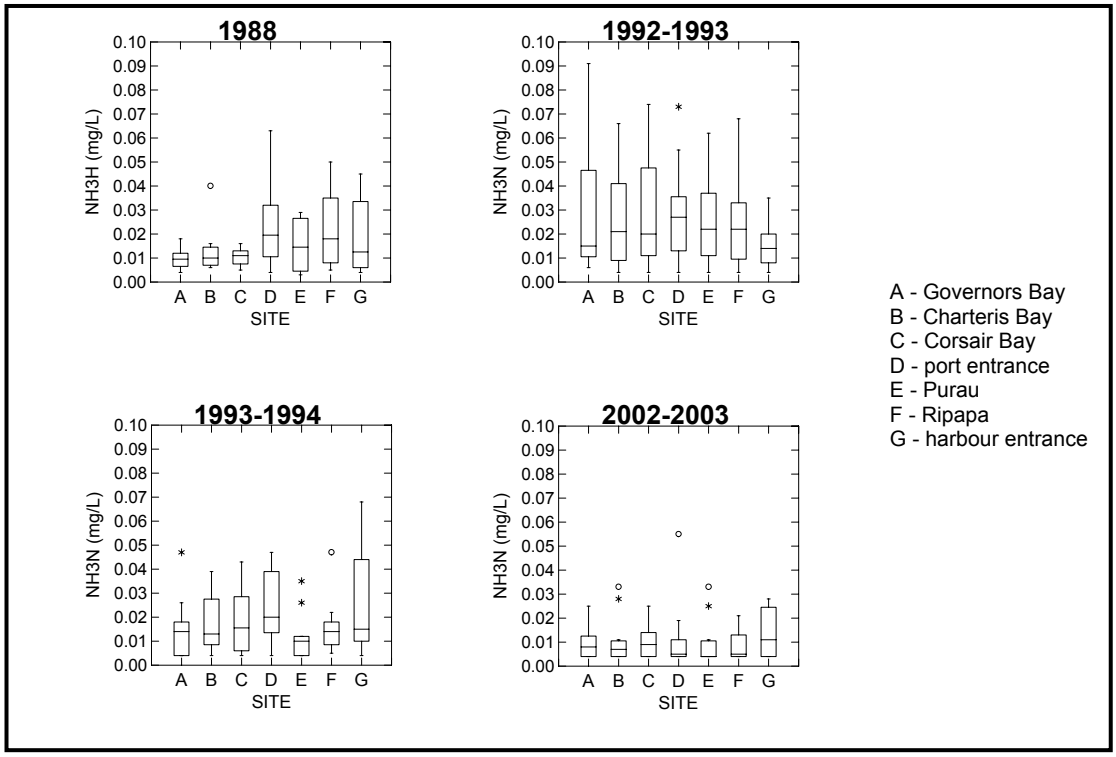


Figure 3.2 Ammonia nitrogen (mg/L) in surface water at greater Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

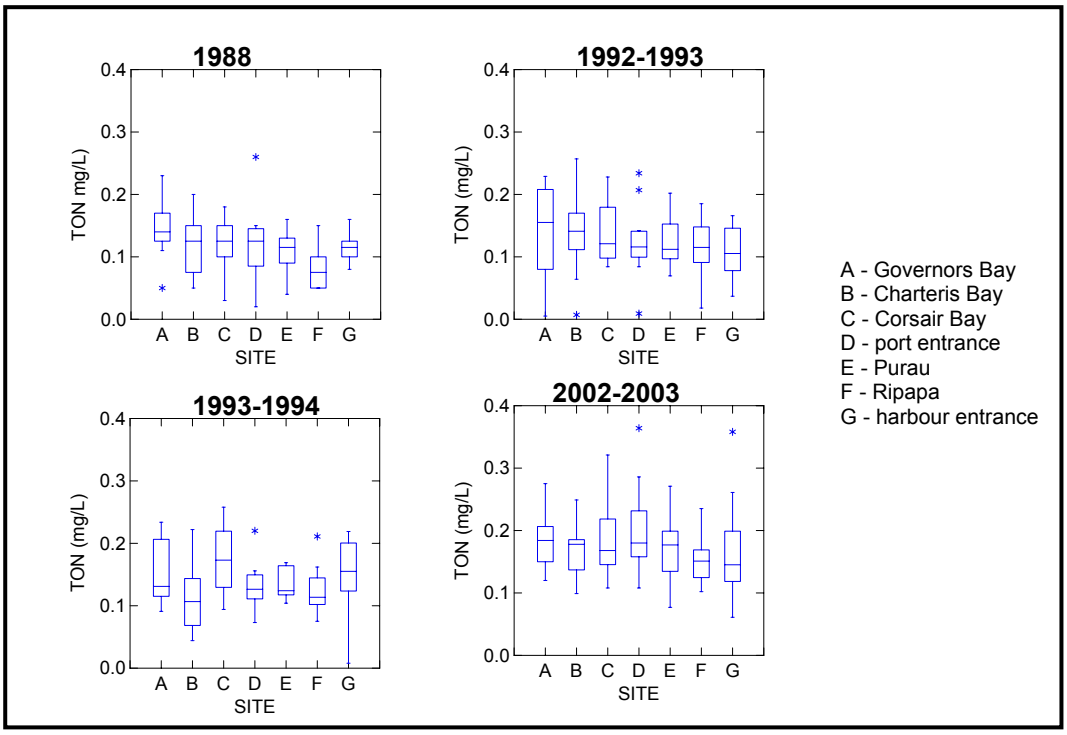


Figure 3.3 Total organic nitrogen (mg/L) in surface water at Greater Lyttelton Harbour/ Whakaraupō sites, 1988-2003

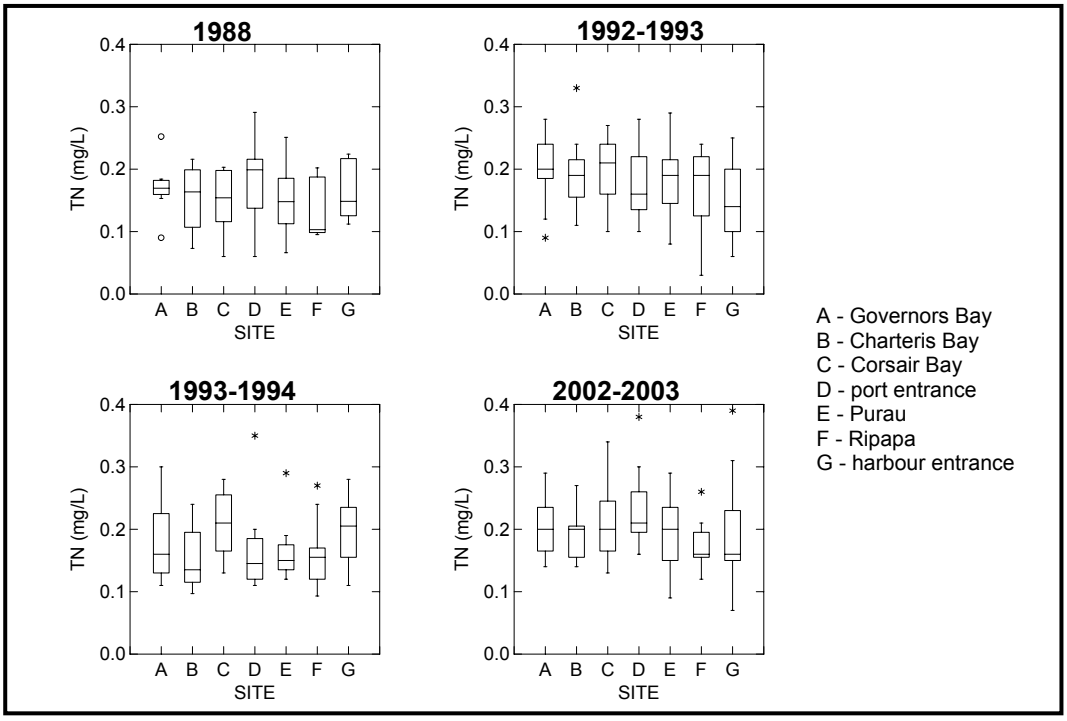


Figure 3.4 Total nitrogen (mg/L) in surface water at Greater Lyttelton Harbour/Whakaraupō sites, 1988-2003

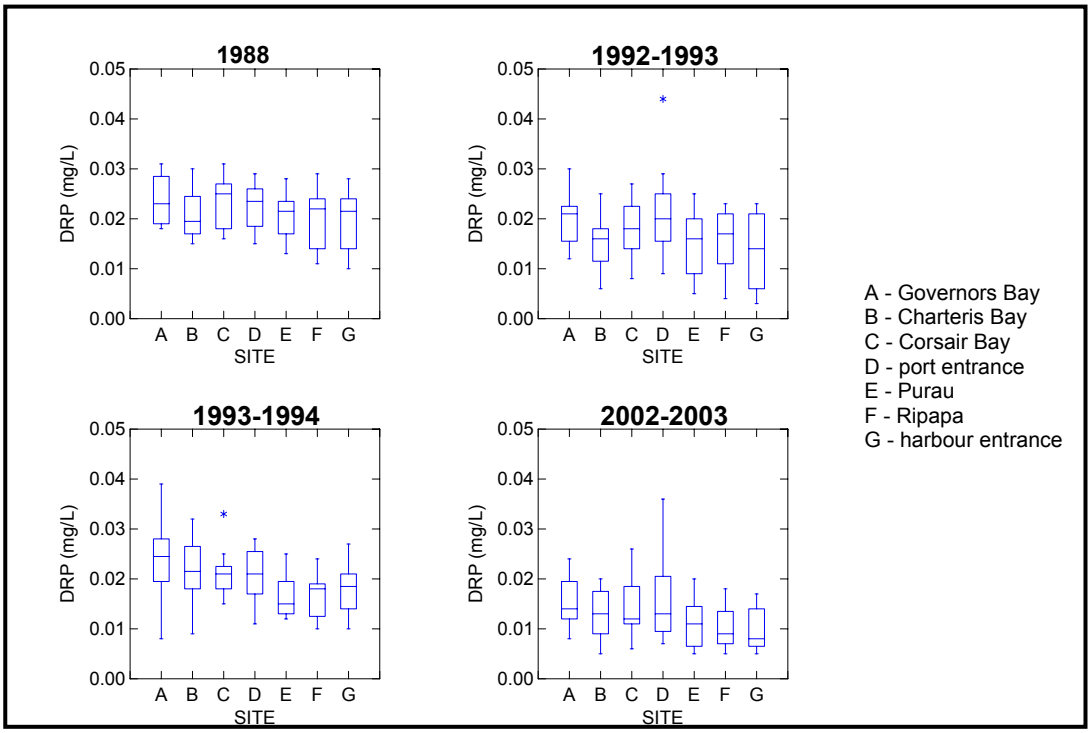


Figure 3.5 Dissolved reactive phosphorus (mg/L) in surface water at greater Lyttelton Harbour/ Whakaraupō sites, 1988-2003

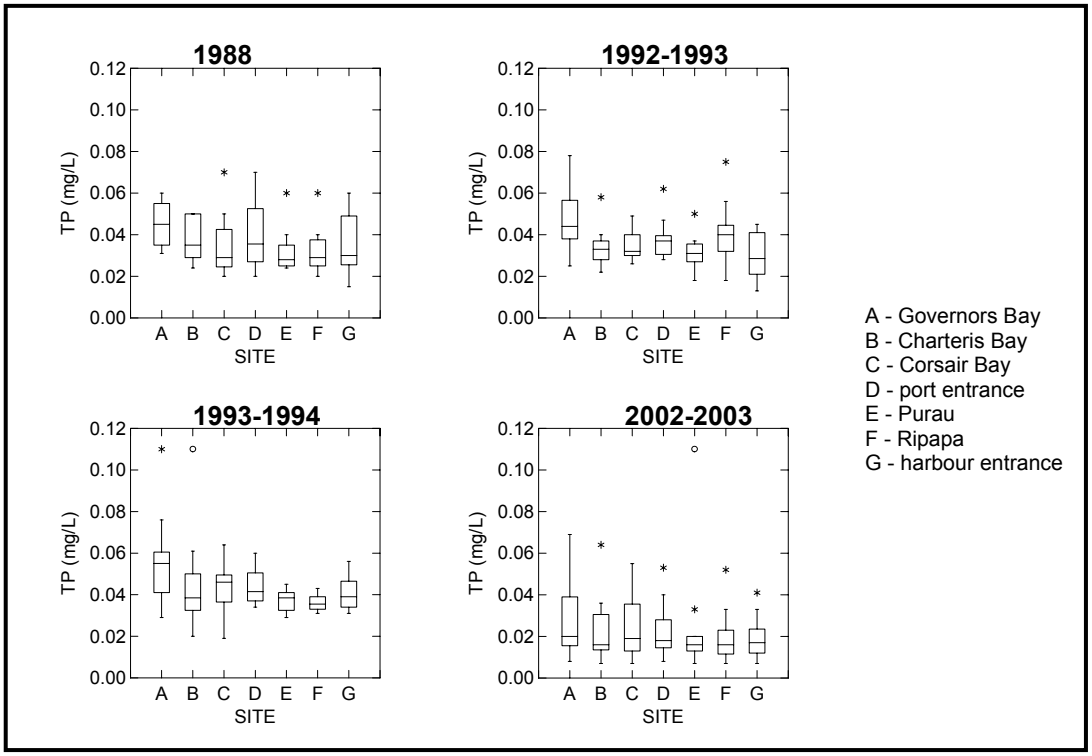


Figure 3.6 Total phosphorus (mg/L) in surface water at greater Lyttelton Harbour/Whakaraupō sites, 1988-2003

Nitrate and nitrite nitrogen (NNN)
In general NNN concentrations were significantly higher at the port entrance than at sites further into the harbour i.e. Governors Bay, Charteris Bay and Corsair Bay, and sites in the outer harbour i.e. Purau, Ripapa and the harbour entrance. Significant differences in NNN concentration also occurred between inner harbour sites over different sampling periods with higher concentrations in Charteris Bay than in Governors Bay in 1993-1994 and higher concentrations in Corsair Bay than in Governors Bay in 2002-2003.

Ammonia nitrogen (NH3N)
NH3N concentrations were significantly higher at the port entrance than at Corsair Bay, Purau and the harbour entrance over one or more sampling periods. There were also significant differences in NH3N concentration between outer harbour sites over different sampling periods with higher concentrations at Ripapa than at Purau and the harbour entrance in 1988 and higher concentrations at the harbour entrance than at Ripapa in 2002-2003. Significant differences in NH3N concentration also occurred between outer and inner sites over different sampling periods with higher concentrations at Ripapa than in Corsair Bay in 1988 and higher concentrations in Charteris Bay and Corsair Bay than at Purau in 1993-1994.

Total organic nitrogen (TON)
TON concentrations were significantly higher in Governors Bay and Corsair Bay than in Charteris Bay and Ripapa over one or more sampling periods. TON concentrations in Corsair Bay were also significantly higher than in Purau and the port entrance in 1993 -1994 and concentrations at the harbour entrance were significantly higher than at Ripapa in 1988 and higher than in Charteris Bay in 1993-1994.

Total nitrogen (TN)
TN concentrations were significantly higher in Governors Bay, Charteris Bay and Corsair Bay than the harbour entrance in 1992-1993 whereas in 1993-1994 TN concentrations at the harbour entrance were significantly higher than in Charteris Bay. Concentrations at the harbour entrance were also significantly higher than those at Ripapa in 1988 and higher than those at Purau in 1993-1994 while concentrations in Governors Bay and Corsair Bay were higher than those at Ripapa in both 1992-1993 and 2002-2003.

Dissolved reactive phosphorus (DRP)
DRP concentrations were significantly higher in Governors Bay than at many of the other sites in 1992-1993 and 2002-2003 and higher in Governors Bay than in Charteris Bay and Corsair Bay in 1998. DRP concentrations were also higher in Governors Bay than at Purau and Ripapa in 1993-1994. Concentrations at Corsair Bay were higher than those at Purau, Ripapa and the harbour entrance in 1992-1993, 1993-1994 and 2002-2003 and concentrations at Charteris Bay were higher than those at Purau and Ripapa in 1993-1994 and 2002-2003. DRP concentrations at the port entrance were significantly higher than those at Purau, Ripapa and the harbour entrance over all sampling periods.

Total phosphorus (TP)
TP concentrations in Governors Bay were significantly higher than at all other sites in 1993-1994, higher than in Charteris Bay, Corsair Bay and the port entrance in 1992-1993 and higher than in Charteris Bay, Ripapa and at the harbour entrance in 2002-2003. In 1993-1994 TP concentrations in Corsair Bay were higher than those at Ripapa and those at the port entrance higher than at Purau and Ripapa. There was no significant difference in TP concentration between sites in 1998.

3.1.1.2 3.5 metre deep samples

Sampling at 3.5 m deep was undertaken at the port entrance, Purau, Ripapa and the harbour entrance. The data for each nutrient for each sampling period are presented in box and whisker plots (Figures 3.7-3.12). The results of the Wilcoxon two-tailed sign test are presented in Appendix IV.

Over each sampling period except 1988, differences in the concentration of one or more nutrients at 3.5 m deep consisted of higher concentrations at the port entrance than at the other three sites. In addition, in 1993-1994 there were higher concentrations of the nitrogen-based nutrients at the harbour entrance than at the other three sites.

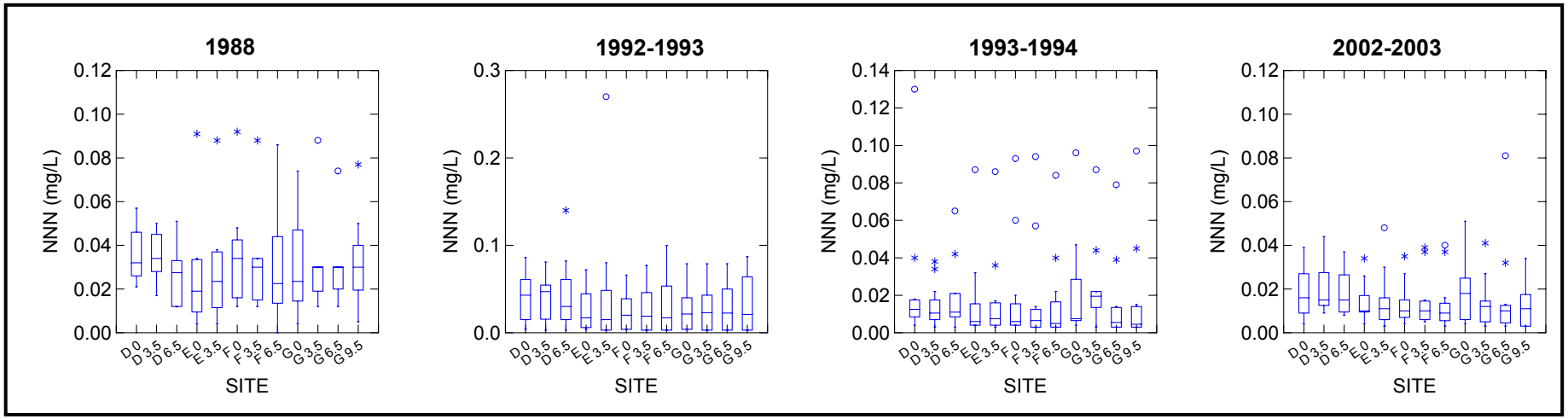


Figure 3.7 Nitrate-nitrite nitrogen (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

D- port entrance, E – Purau, F – Ripapa, G – harbour entrance
0, 3,5, 6,5, 9.5 – Depth in metres

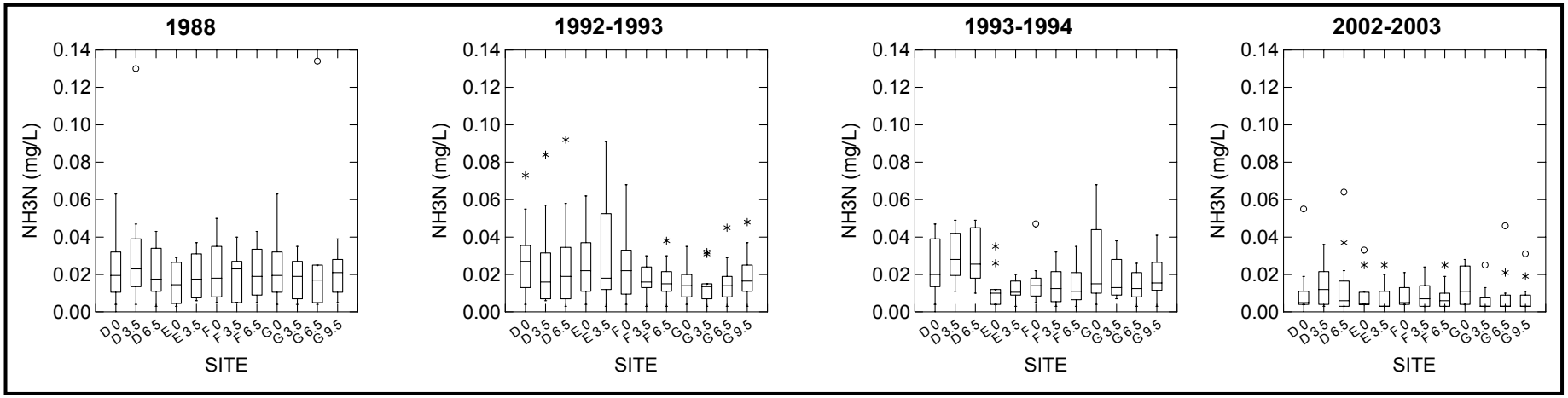


Figure 3.8 Ammonia nitrogen (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 – 2003

D- port entrance, E – Purau, F – Ripapa, G – harbour entrance
0, 3,5, 6,5, 9.5 – Depth in metres

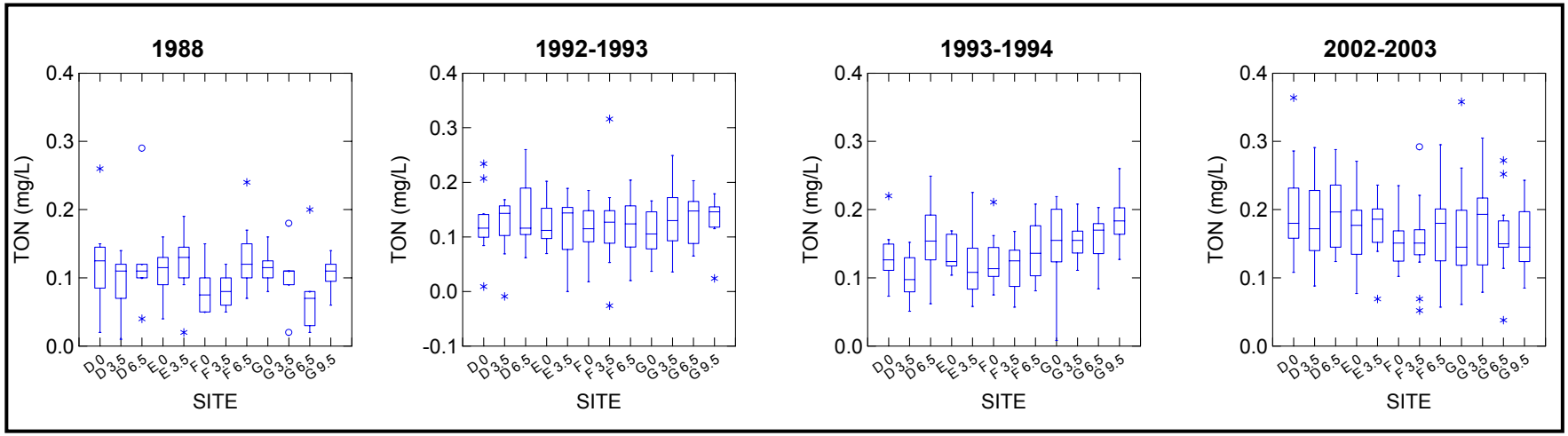


Figure 3.9 Total organic nitrogen (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

D – port entrance, E – Purau, F – Ripapa, G – harbour entrance

0, 3.5, 6.5, 9.5 - Water depth in metres

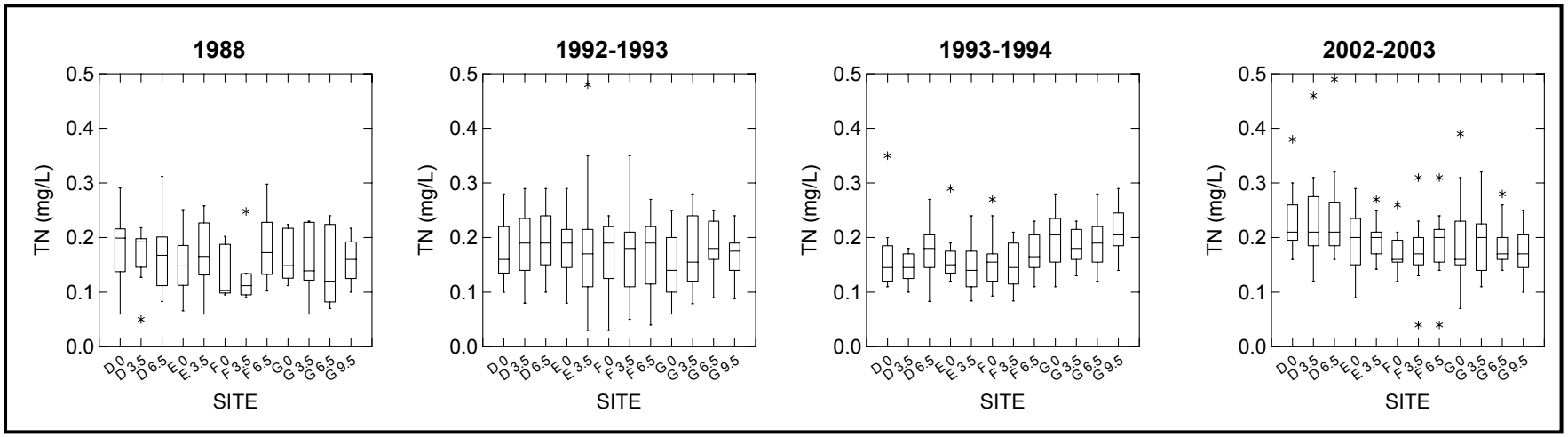


Figure 3.10 Total nitrogen (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

D – port entrance, E – Purau, F – Ripapa, G – harbour entrance

0, 3.5, 6.5, 9.5 - Water depth in metres

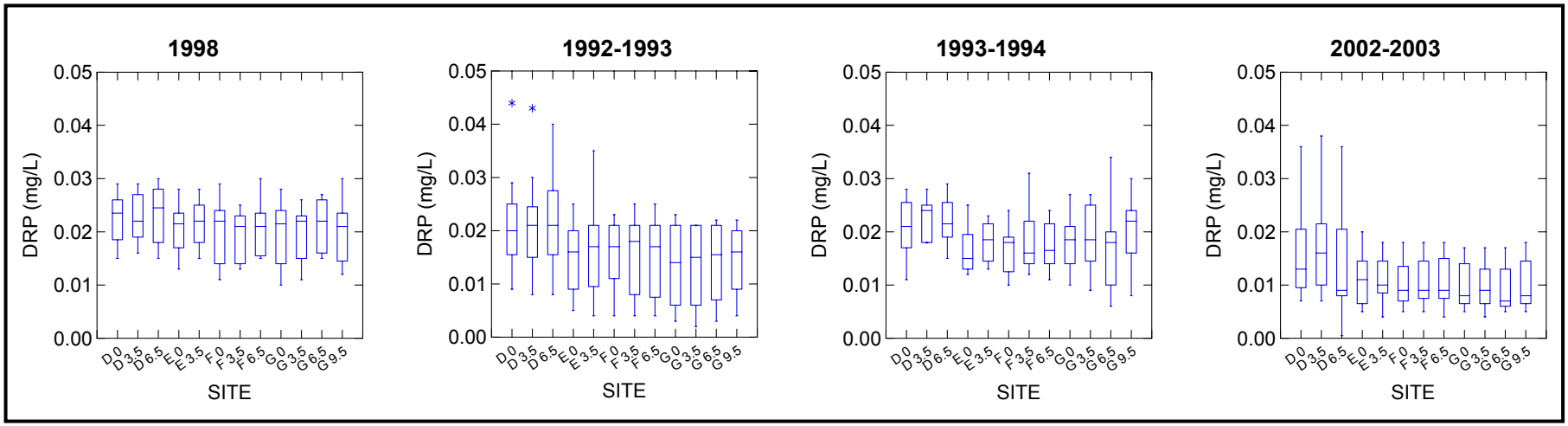


Figure 3.11 Dissolved reactive phosphorus (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

D – Port entrance, E – Purau, F – Ripapa, G – harbour entrance

0, 3.5, 6.5, 9.5 – water depth in metres

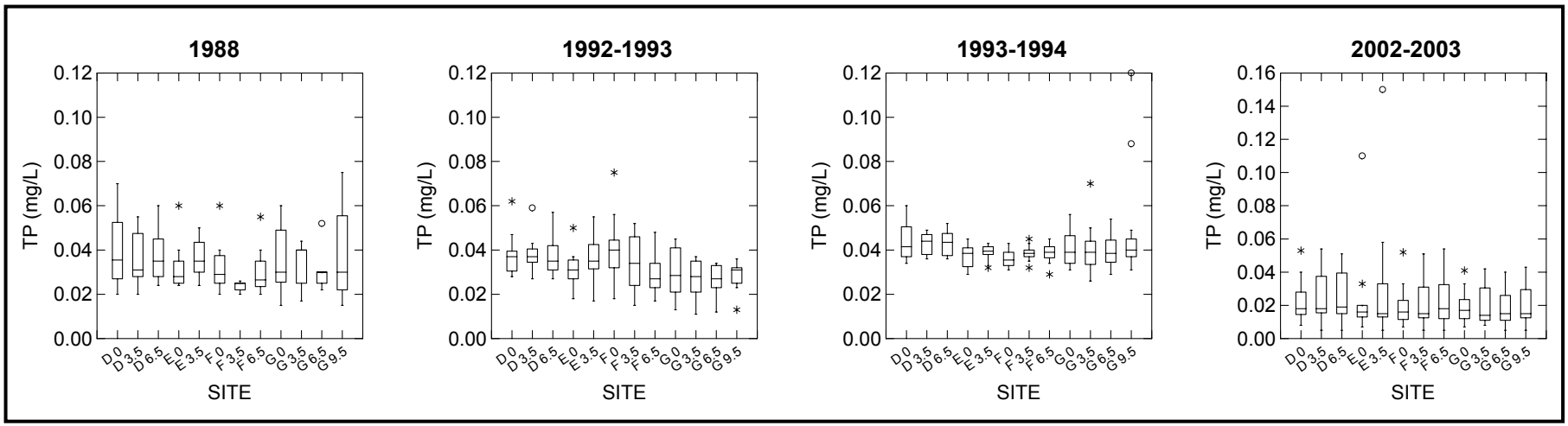


Figure 3.12 Total phosphorus (mg/L) at different depths at four Lyttelton Harbour/Whakaraupō sites, 1988 - 2003

D – Port entrance, E – Purau, F – Ripapa, G – harbour entrance

0, 3.5, 6.5, 9.5 – water depth in metres

3.1.1.3 6.5 metre deep samples

Sampling at 6.5 m deep was undertaken at the port entrance, Ripapa and the harbour entrance. The data for each nutrient for each sampling period are presented in box and whisker plots (Figures 3.7-3.12). The results of the Wilcoxon two-tailed sign test are presented in Appendix IV.

Over each sampling period except 1988, differences in the concentration of nutrients at 6.5 m deep consisted of higher concentrations at the port entrance than at the other sites.

3.1.2 Port area (surface and 8 metre deep samples)

Was there a significant difference in the concentration of each nutrient between sites in the Port of Lyttelton?

The data for each nutrient are presented in box and whisker plots (Figure 3.13). The results of the Wilcoxon two-tailed sign test are presented in Appendix V.

There was a significant difference in the concentration of all nutrients between some of the sites.

Nitrate and nitrite nitrogen (NNN)

NNN concentrations at Sticking Point, the Fox II mooring, between wharves 5 and 6 and between the fishing boats and yachts were significantly higher than at many of the other sites in the port area.

Ammonia nitrogen (NH3N)

NH3N concentrations at Cashin Quay were significantly higher than at Z point and in the surface water at the end of wharf no.7.

Total organic nitrogen (TON)

TON concentrations at Z point, Cashin Quay, the Fox II mooring, and wharf no.2 surface and deep were significantly higher than at the cattle jetty.

Total nitrogen (TN)

TN concentrations at the Fox II mooring, between wharves 5 and 6 and between the fishing boats and yachts were significantly higher than at than at some of the other sites in the port area.

Dissolved reactive phosphorus (DRP)

DRP concentrations at the Fox II mooring, wharf no.2 deep, between wharves 5 and 6 and between the fishing boats and yachts were significantly higher than at some of the other sites in the port area including Cashin Quay. The DRP concentrations at Cashin Quay were also significantly lower than at Sticking Point, Z point, Gladstone wharf, wharf no. 7 deep and the cattle jetty.

Total phosphorus (TP)

TP concentrations between the fishing boats and yachts were significantly higher than at the Fox II mooring and at wharf no.7 surface and deep.

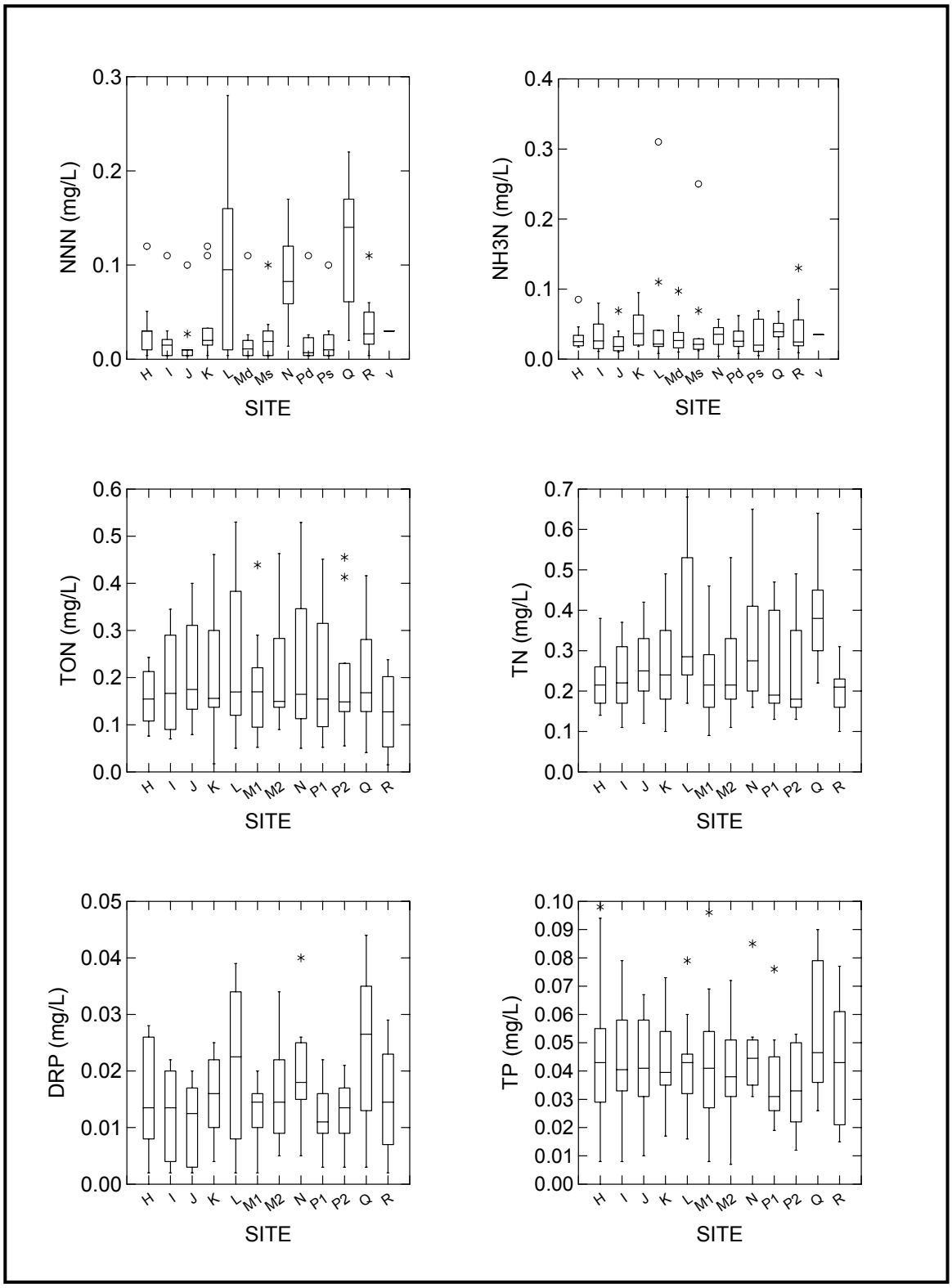


Figure 3.13 Nutrient concentrations (mg/L) at sites in the port area 1999-2000

H = Sticking point
I = end of Z berth
J = Cashin Quay
K = Gladstone pier
L = Fox II mooring
M = end of no.2 wharf
N = Between no. 5 & 6 wharf
P = end of no. 7 wharf
Q = between fishing boats & yachts
R = Cattle jetty

M1 = surface at end of no.2 wharf
M2 = 8 m deep at end of no.2 wharf
P1 = surface at end of no.7 wharf
P2 = 8 m deep at end of no.7 wharf

3.2 Variation within sites

3.2.1 Variation with water depth

Was there a significant difference in the concentration of each nutrient with depth at each of four sites in greater Lyttelton Harbour?

At the port entrance, Purau, Ripapa and the harbour entrance samples were collected at two or more water depths. The data for each nutrient at each water depth over each sampling period are presented in Figures 3.7-3.12. The Wilcoxon two-tailed sign test was used to determine if, over each sampling period, there was a significant difference in the concentration of each nutrient with water depth. The results of this are presented in Table 3.1.

At each site there was a significant difference in the concentration of at least one nutrient with water depth. However, at each site the significant difference in concentration of a nutrient with water depth changed over time.

3.2.2 Variation over time

Was there a significant difference in the concentration of each nutrient at each site in greater Lyttelton Harbour over time?

3.2.2.1 Surface samples

The concentration of each nutrient in surface water at each greater Lyttelton Harbour site over time is presented in Figures 3.14 – 3.15. The data presented in Figures 3.14 –3.15 include the monthly data collected in 1988, 1992-1993, 1993-1994 and 2003 and the data (mean concentration from sampling (monthly?) over a full year) collected by Millhouse in 1976 (from Millhouse, 1977). The results of the Kruskal-Wallis ANOVA, used to determine if there was a significant difference in the concentration of each nutrient at each site over time (between 1988 and 2003), are presented in Table 3.2 while the results of the Wilcoxon two-tailed sign test used to determine between which sampling periods any differences occurred, are presented in Appendix VI.

Table 3.1 Significant differences in the concentration of nutrients with depth at four sites in Lyttelton Harbour/Whakaraupō

0, 3,5, 6,5 and 9.5 - depth in metres
* significant difference between depths at p<0.05
** significant difference between depths at p<0.01
Blank cells - no significant difference in the concentration of any nutrients with depth

	Port entrance	Purau	Ripapa	Harbour entrance
1988		**NH3N** 3.5 > 0 *	**TN** 6.5 > 0 *	
1992-1993	**TON** 6.5 > 0 *			**NH3N** 0 > 3.5 * **NH3N** 6.5 > 3.5 * **TN** 6.5 > 0 * **TON** 3.5 > 0 ** **TON** 6.5 > 0 * **TON** 9.5 > 0 *
1993-1994	**NH3N** 3.5 > 0 ** **NNN** 0 > 3.5 * **TN** 6.5 > 3.5 * **TON** 6.5 > 3.5 **			**NH3N** 9.5 > 6.5 * **NNN** 0 > 6.5 ** **NNN** 0 > 9.5 * **NNN** 3.5 > 6.5 ** **NNN** 3.5 > 9.5 * **TN** 6.5 > 3.5 * **TON** 9.5 > 3.5 *
2002-2003	**DRP** 3.5 > 0 * **DRP** 3.5 > 6.5 *	**NH3N** 0 > 3.5 *	**TP** 3.5 > 0 *	**NH3N** 0 > 3.5 ** **NH3N** 0 > 6.5 * **NH3N** 0 > 9.5 * **NNN** 0 > 3.5 *

Table 3.2 Comparison of the concentration of each nutrient at each site over time

ns - no significant difference in concentration over time
* - significant difference over time at p<0.05
** - significant difference over time at p<0.01

SURFACE WATER	NNN	NH3N	TON	TN	DRP	TP
Governors Bay	ns	ns	ns	ns	*	**
Charteris Bay	ns	ns	ns	ns	**	*
Corsair Bay	ns	ns	ns	ns	*	*
Port entrance	*	ns	*	*	ns	**
Purau	ns	ns	ns	ns	*	**
Ripapa	ns	ns	*	ns	**	**
Harbour entrance	ns	ns	ns	ns	**	**
3.5 m DEEP	**NNN**	**NH3N**	**TON**	**TN**	**DRP**	**TP**
Port entrance	*	ns	**	*	ns	*
Purau	ns	*	*	ns	**	ns
Ripapa	ns	ns	ns	ns	*	*
Harbour entrance	ns	*	ns	ns	**	**
6.5 m DEEP	**NNN**	**NH3N**	**TON**	**TN**	**DRP**	**TP**
Port entrance	ns	ns	*	ns	ns	*
Ripapa	ns	ns	ns	ns	*	*
Harbour entrance	ns	ns	ns	ns	*	**

Ripapa and the port entrance were the only sites where there was a significant difference in one or more of the nitrogen based nutrients over time (1988 –2003) (Figure 3.14). At Ripapa the TON concentration was significantly higher in 2002-2003 than in 1988. At the port entrance NNN concentration was significantly higher in 1988 than 2002-2003, TON concentration was significantly higher in 2002-2003 than in 1988 and 1993-1994 and TN concentration was significantly higher in 2002-2003 than in 1993-1994.

A seasonal difference in concentration occurred for NNN. This difference consisted of higher concentrations in mid to late winter and lower concentrations in spring and summer. Such a seasonal difference in NNN concentrations was obvious in 1988, 1992-1993 and 1993-1994 but not in 2002-2003.

DRP and TP concentrations were significantly different over time (1988-2003) at all sites except the port entrance (DRP only) and generally consisted of slightly lower concentrations in 2002-2003 than in one or more of the other sampling periods (Figure 3.15). In Corsair Bay there were also significantly lower concentrations of DRP in 1992-1993 than in 1998 and 1993-1994, at Purau there were significantly lower concentrations of DRP in 1993-1994 than in 1988 and at the harbour entrance there were significantly lower concentrations of TP in 1992-1993 than in 1993-1994.

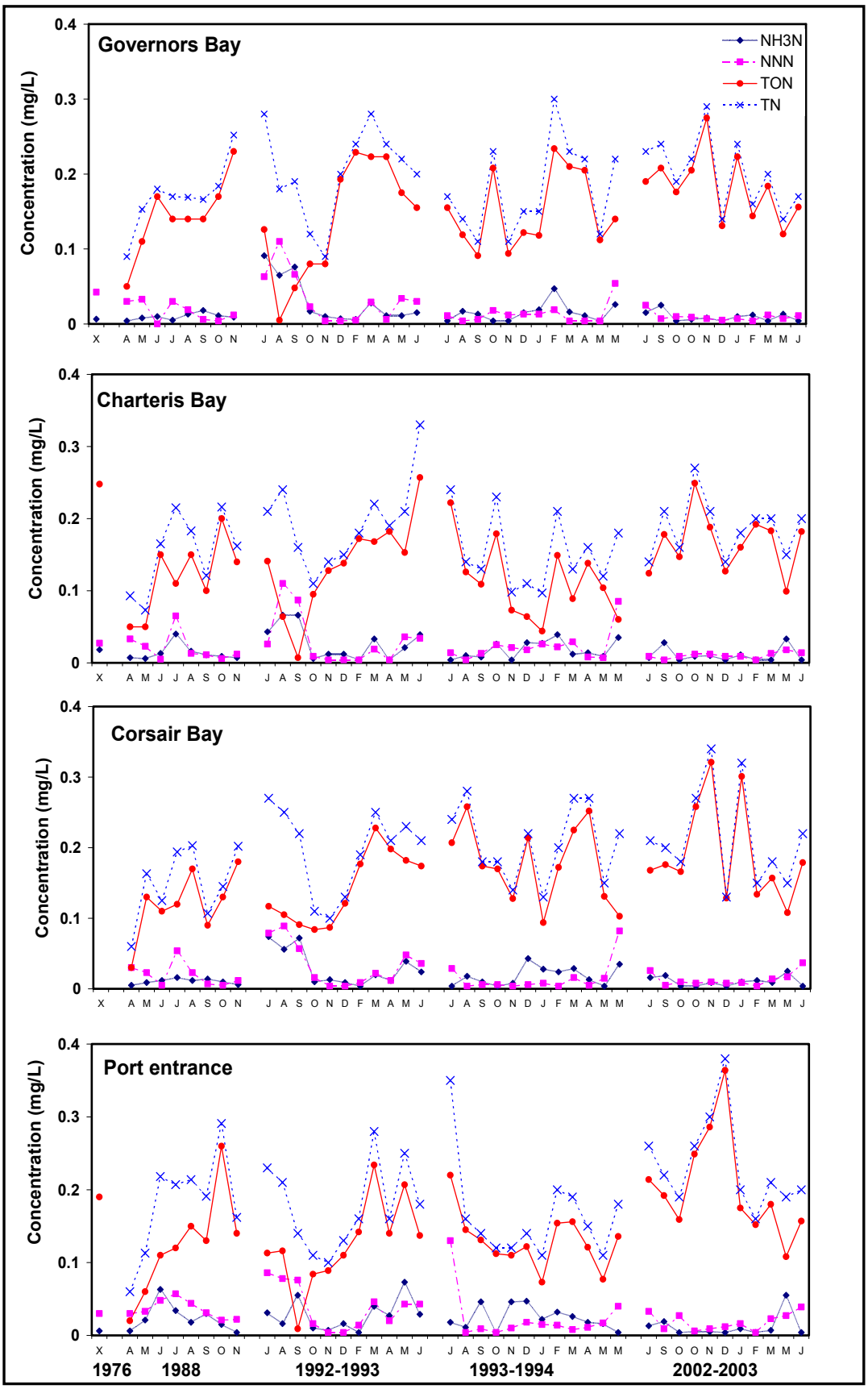


Figure 3.14 Concentration (mg/L) of nitrogen based nutrients in surface water at greater Lyttelton Harbour/Whakaraupō sites over time

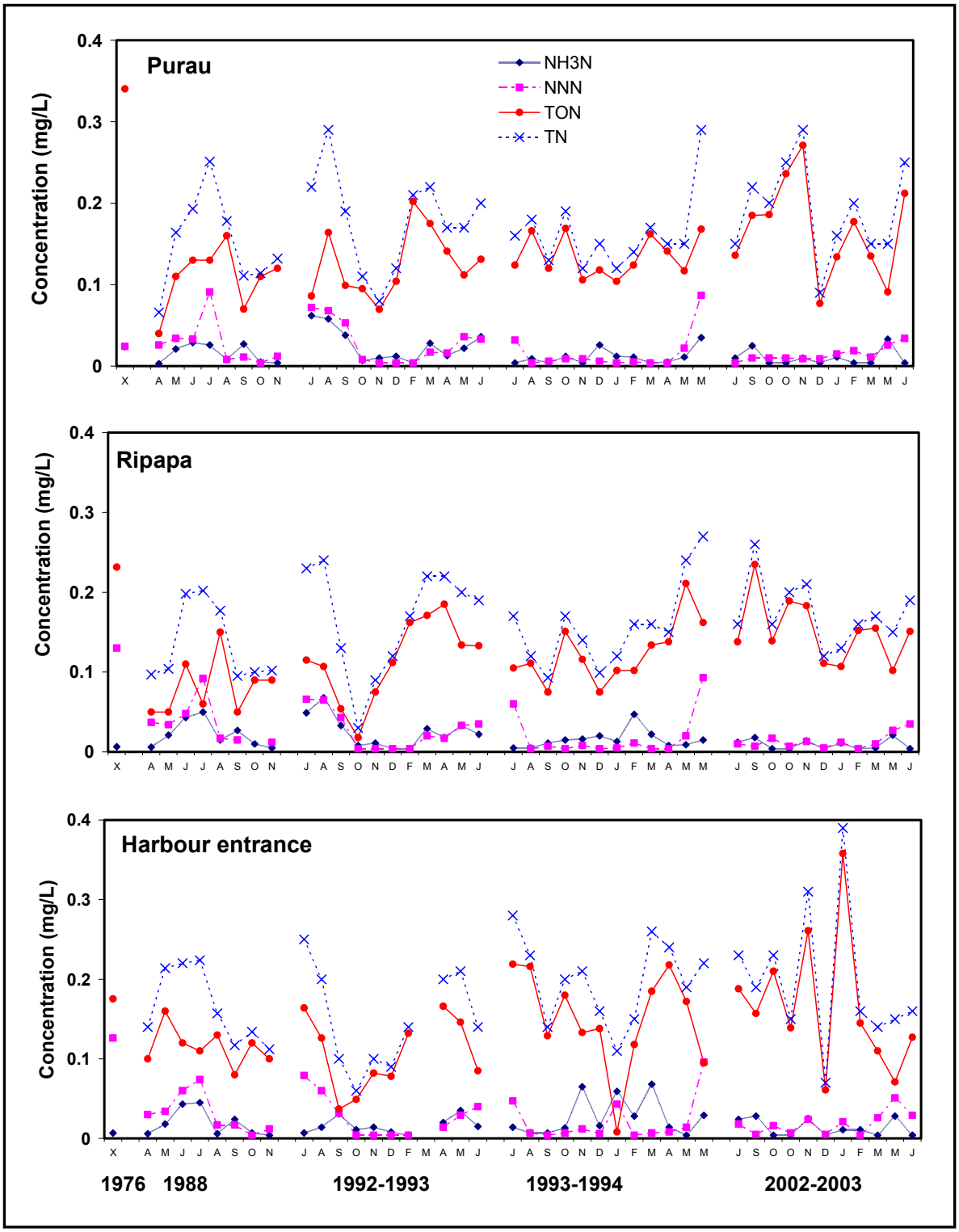


Figure 3.14 continued: Concentration (mg/L) of nitrogen based nutrients in surface water at greater Lyttelton Harbour/Whakaraupō sites over time

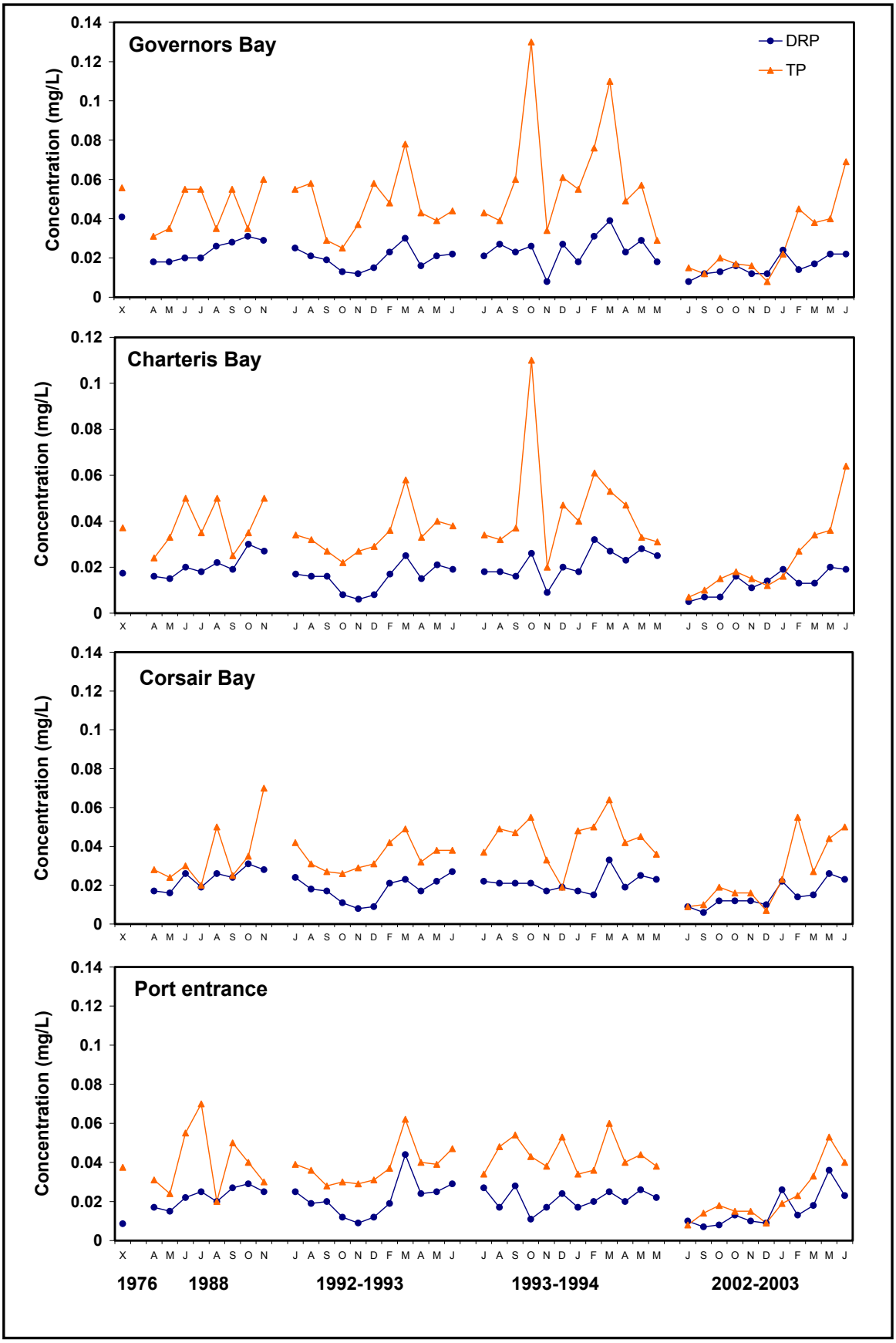


Figure 3.15 Concentration (mg/L) of phosphorus based nutrients in surface water at greater Lyttelton Harbour/Whakaraupō sites over time

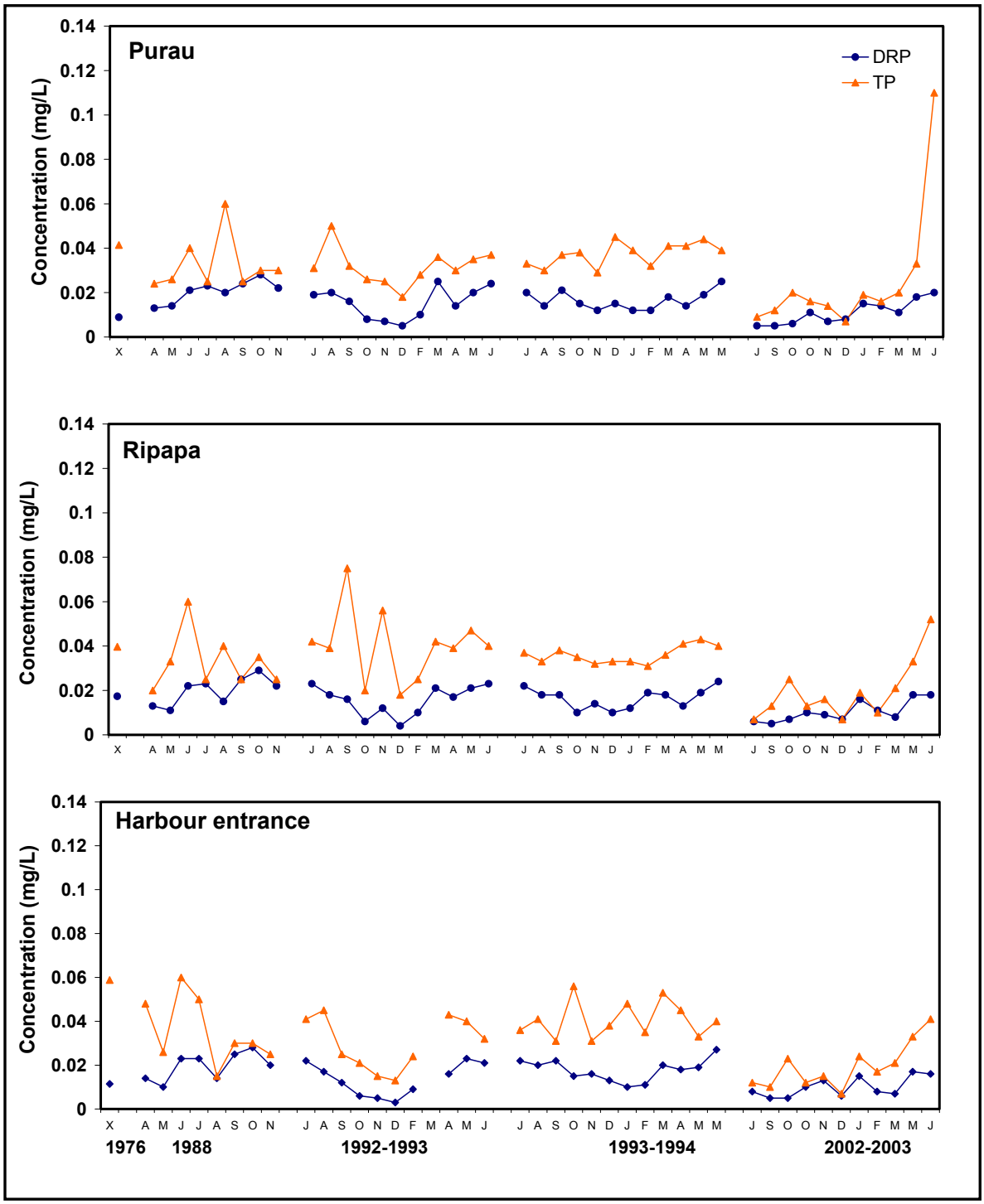


Figure 3.15 (continued) Concentration (mg/L) of phosphorus based nutrients in surface water at greater Lyttelton Harbour/Whakaraupō sites over time

A comparison of the nutrient concentrations over time (1988 and 2003) with those in 1976 (analytical methodology not described) (Millhouse, 1977) reveals that:

- The mean TON concentration at Governors Bay and Purau in 1976 was higher than any recorded TON concentration at these sites between 1988 and 2003.
- The mean TON concentration at Charteris Bay and Ripapa in 1976 was higher than all but one or two recorded concentrations at these sites between 1988 and 2003.
- The mean NNN concentration at Ripapa and the Harbour entrance in 1976 was higher than any recorded NNN concentration at these sites between 1988 and 2003.
- The mean DRP concentration at Governors Bay in 1976 was higher than all but one recorded concentration at this site between 1988 and 2003.
- The mean TP concentration at the Harbour entrance in 1976 was higher than all but two recorded concentrations at this site between 1988 and 2003.

3.2.2.2 3.5 metre deep samples

The results of the Kruskal-Wallis ANOVA for each nutrient are presented in Table 3.2 and the results of the Wilcoxon two-tailed sign test are presented in Appendix VII.

The significant differences in DRP and TP concentrations over time at all 3.5 m deep sites except Purau (TP) were comparable to those in the surface water at these sites i.e. generally lower concentrations in 2002-2003 than in one or more of the other sampling periods. In addition, TP concentrations were significantly higher in 1993-1994 than in 1988 at Ripapa and significantly higher in 1993-1994 than in 1992-1993 at the harbour entrance. At 3.5 m at Purau there was no significant difference in TP concentration over time.

Significant differences in the concentration of one or more of the nitrogen-based nutrients over time occurred at the port entrance, Purau and the harbour entrance. TON concentrations were significantly higher in 2002-2003 than in one or more of the other sampling periods at both the port entrance and Purau, NH3N concentrations were significantly lower in 2002-2003 than in 1992-1993 at Purau and than in 1993-1994 at the harbour entrance and NNN and TN concentrations at the port entrance were significantly lower in 1993-1994 than in one or more of the other sampling periods.

3.2.2.3 6.5 metre deep samples

The results of the Kruskal-Wallis ANOVA for each nutrient are presented in Table 3.2 and the results of the Wilcoxon two-tailed sign test are presented in Appendix VIII.

The significant differences in DRP and TP concentrations over time at 6.5 m deep at three sites were comparable to those in the surface water and 3.5 m deep water at these sites i.e. generally lower concentrations in 2002-2003 than in one or more of the other sampling periods. In addition, TP concentrations were significantly higher in 1993-1994 than in 1992-1993 at all three sites. At the port entrance TON concentration was significantly higher in 2002-2003 than in 1992-1993.

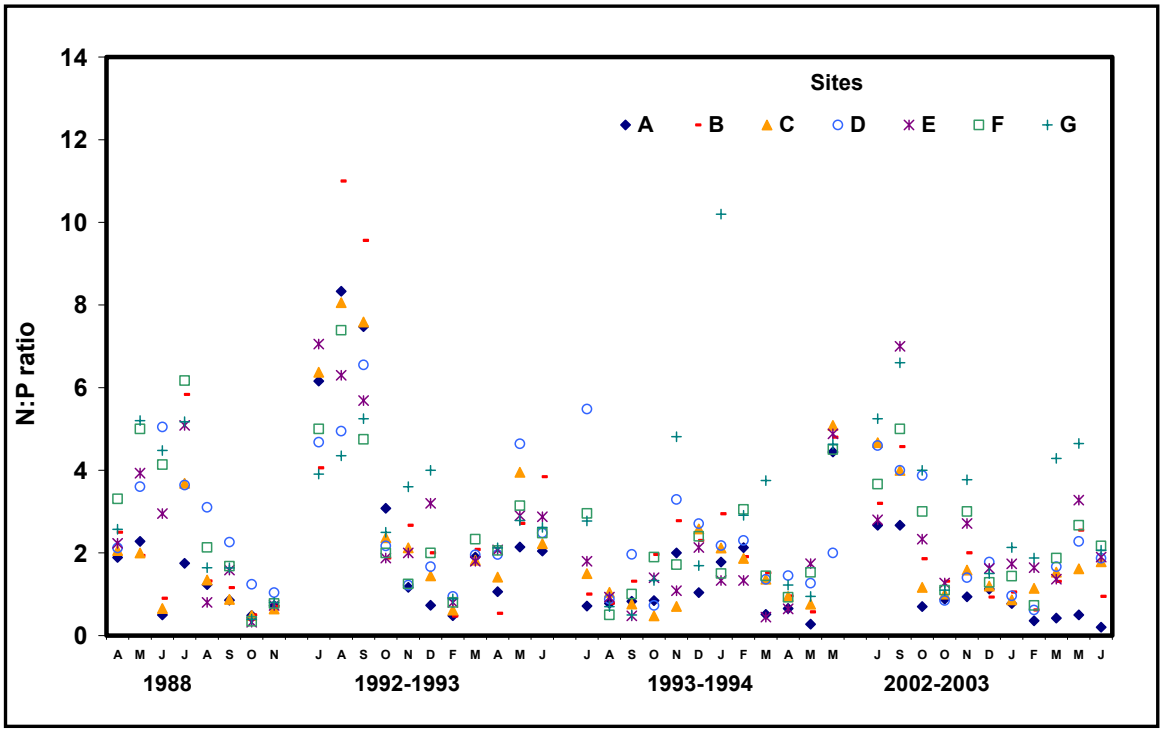


Figure 3.16 N:P ratio in surface water at greater Lyttelton Harbour/Whakaraupō sites over time

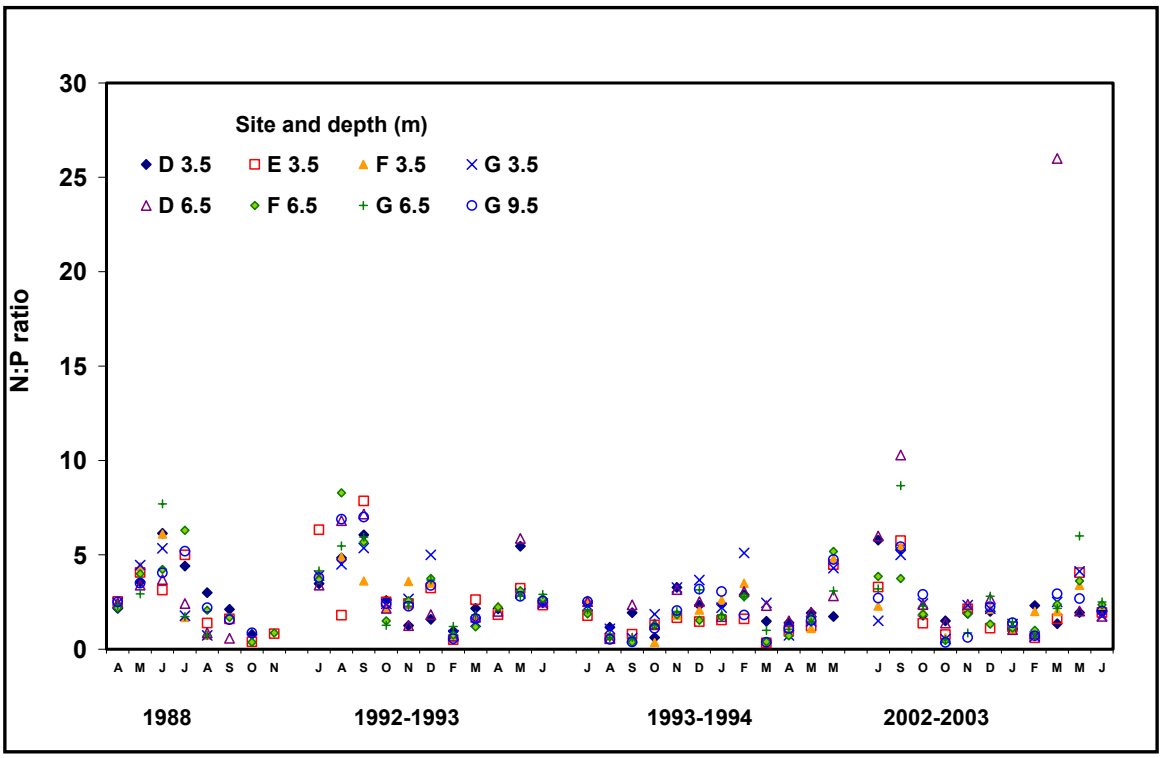


Figure 3.17 N:P ratio in water sampled at various depths at greater Lyttelton Harbour/Whakaraupō sites over time

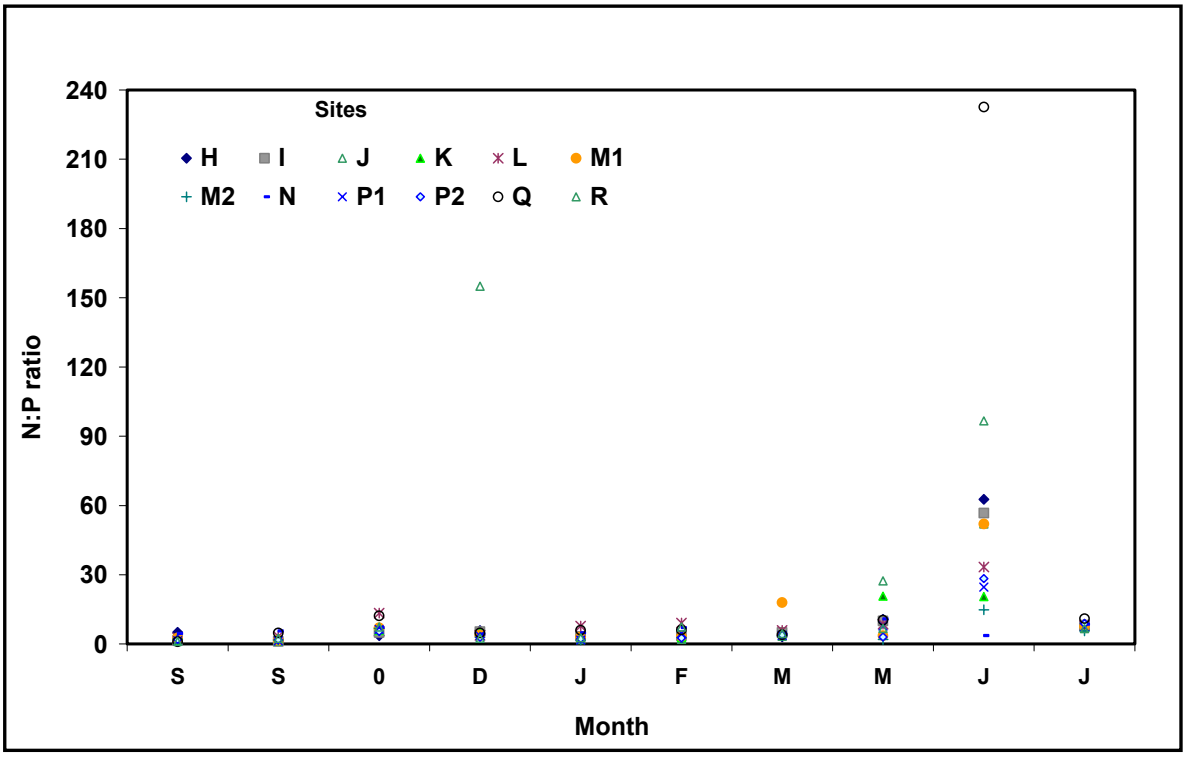


Figure 3.18 N:P ratio in water from sites in the Port of Lyttelton in 1999-2000.

3.3 Are the nutrient concentrations in Lyttelton Harbour/ Whakaraupō water of ecological concern?

3.3.1 Comparison with guideline values

In the ANZECC (2000) Guidelines, trigger values in 'slightly disturbed marine water' are given for DIN (= NO_x (≡NNN) + NH_4^+ (≡NH3N)), TN, FRP (≡DRP) and TP. The guideline trigger values are the concentrations below which there is a low risk that adverse biological effects will occur. While concentrations above the trigger values do not necessarily mean that adverse effects will occur, the potential is there for adverse effects, i.e. eutrophication.

To compare the DIN, TN, DRP and TP concentrations obtained in this study to the ANZECC (2000) guideline trigger values, the range in concentrations of each nutrient and the percentage of samples in which the guideline value was exceeded at each water depth at each site, was calculated. These data are presented in Table 3.3. The highest concentration of DIN and TN occurred in the Port of Lyttelton and the highest concentration of DRP and TP occurred in Governors Bay. The trigger values for each nutrient were exceeded at all sites and water depths sampled. The highest percentage of samples exceeding the guideline values for DIN, TN and TP were collected in the Port of Lyttelton while for DRP they were in samples from Governors Bay. A high percentage of the samples collected at the Port entrance also contained DIN, TN, DRP and TP concentrations in excess of the trigger values. For DRP and TP there was a general trend of a decrease in the percentage of samples exceeding the trigger value with increasing distance down the harbour i.e. from the inner to outer harbour.

Table 3.3 The range in concentrations and the percentage of samples exceeding the ANZECC guideline values for nutrients DIN (= NNN+NH3N) TN, DRP and TP) at each water depth at each site in greater Lyttelton Harbour/Whakaraupō and over all sites in the Port of Lyttelton

n=number of samples

ANZECC (2000) trigger values: DIN - 0.02 mg/L, TN - 0.12 mg/L, DRP - 0.01mg/L, TP - 0.025 mg/L

Site	n	DIN		TN		DRP		TP	
		Range(mg/L)	%	Range(mg/L)	%	Range(mg/L)	%	Range(mg/L)	%
Surface water									
Governors Bay	42	0.008-0.175	50	0.09-0.3	86	0.008-0.069	95	0.008-0.13	71
Charteris Bay	42	0.008-0.176	57	0.073-0.33	83	0.005-0.032	83	0.007-0.11	74
Corsair Bay	42	0.01-0.153	60	0.06-0.34	90	0.006-0.033	88	0.007-0.07	74
Port entrance	42	0.008-0.148	79	0.06-0.38	76	0.007-0.044	86	0.008-0.07	76
Purau	42	0.008-0.134	52	0.066-0.29	79	0.005-0.028	79	0.007-0.11	67
Ripapa	42	0.008-0.142	64	0.03-0.27	69	0.004-0.029	71	0.007-0.075	64
Harbour entrance	41	0.008-0.125	66	0.06-0.39	80	0.003-0.028	67	0.007-0.06	61
Port	100	0.014-0.93	89	0.09-0.68	95	0.002-0.044	67	0.008-0.098	86
3.5m water									
Port entrance	41	0.01-0.178	85	0.05-0.46	83	0.007-0.043	85	0.005-0.059	80
Purau	42	0.006-0.324	52	0.03-0.48	76	0.004-0.035	76	0.005-0.15	76
Ripapa	39	0.006-0.128	56	0.04-0.35	67	0.004-0.031	74	0.005-0.052	64
Harbour entrance	38	0.006-0.123	60	0.06-0.32	82	0.002-0.027	66	0.008-0.07	63
6.5m water									
Port entrance	40	0.01-0.143	88	0.083-0.49	88	0.0005-0.04	83	0.005-0.06	78
Ripapa	42	0.006-0.126	55	0.04-0.31	81	0.004-0.03	76	0.005-0.055	62
Harbour entrance	38	0.006-0.208	53	0.07-0.28	82	0.003-0.034	66	0.005-0.052	63
9.5m water									
Harbour entrance	41	0.005-0.124	63	0.088-0.29	90	0.004-0.03	70	0.004-0.12	63

3.3.2 N:P ratios

The N:P ratio was calculated for all samples. The results are presented in Figures 3.16-3.18.

The N:P ratio in all surface samples on all sampling occasions at all sites in greater Lyttelton Harbour was less that 16:1, i.e. N was the nutrient limiting primary productivity (i.e. phytoplankton growth). This was also the case for the water sampled at depth (3.5, 6.5 and 9.5 m) except at 6.5m at the Port entrance (D) in March 2003 where a ratio of 26:1 occurred. At 26:1 primary productivity would have been P limited. In general the N:P ratio was higher in the winter than in the spring and summer months.

The N:P ratio indicates that primary productivity in water from the surface and at depth at sites in the Port of Lyttelton was generally N limited; however, at Cashin Quay in December 1999, Cashin Quay and Gladstone Wharf in May 2000 and at almost all sites in early June (8th) 2000 the ratio indicates P limitation.

4 Discussion

The water within Lyttelton Harbour consists of tidal exchange water from Pegasus Bay in combination with water from the freshwater streams and three sewage outfalls that discharge into the harbour. Overall, the calculated volume of Lyttelton Harbour at low water on a spring tide is 230 x 10^6 m^3 of water (Spigel, 1993). The freshwater inflow from streams is not significant in terms of water volume, so no long-term salinity gradients exist in the harbour and even after major storm events the salinity gradients are small (Spigel, 1993). The volume of input for the sewage outfalls consists of:

- Lyttelton (Sticking Point) outfall - the maximum permissible discharge volume is 8640 m^3 per day with average dry weather flows expected, at the time the consent was granted, to be 1129 m^3 per day (Royds Consulting, 1992)
- Governors Bay outfall - the maximum permissible discharge volume is 600 m^3 per day with the average dry weather flows expected to be 200 m^3 per day.

- Diamond Harbour outfall (Pauaohinekotou Heads) - to date has been consented to discharge 2000 m^3/day. However, a renewal of the resource consent, for a maximum permissible discharge of 2850 m^3 per day with the average dry weather flows expected to be 875 m^3 per day, is in progress (MWH, 2003).

There are no known measurements of the residence time of water within the harbour. However, Spigel (1993) stated "calculations give grounds for the belief that significant replacement of harbour water (with Pegasus Bay water) does occur over a tidal cycle".

The mixing of water within Lyttelton Harbour is driven by tidal and wind driven circulation patterns and long-term equilibrium mixing processes (Spigel, 1993). It has been noted that the mixing of water in the inner harbour is more restricted and tidal 'excursions' are smaller than in the outer half of the harbour (Spigel, 1993). Within the harbour the general circulation of the water is asymmetric and tidally driven, and water does not simply flow up and down the harbour. It has been found that the tide appears to flood more strongly on the south side of the harbour and ebb more strongly on the north side (Garner and Ridgeway, 1955). Also deduced, but not directly measured, are large scale tidal 'gyres' that flow clockwise on the ebb tide and counter-clockwise on the flood tide in the outer half of the harbour (Curtis, 1985). However the 'gyres' do not influence the water circulation patterns within the inner harbour (Curtis, 1985), where the current flows are parallel to the harbour longitudinal axis. Water circulation within each of the smaller bays of the harbour has not been investigated.

Each Lyttelton Harbour water source contains nutrients. However, the concentrations of these nutrients vary, not only between the different water sources but also over time for a specific source. For example, there is a difference in the concentration of total nitrogen (TN) and total phosphorus (TP) between the water in the Purau, Cass Peak and Allandale streams and in each stream the concentrations of nutrients are variable over time (Appendix IX). The in-stream nutrient concentrations are attributed to land use within the catchment. In addition, urban stormwater with its associated nutrient load is discharged into many of the Lytttelton harbour streams. Sewage discharges are also contributors of nitrogen and phosphorus compounds to the harbour. Consequently, nutrient concentrations in the Harbour are likely to vary over time at each site and differ between sites.

In greater Lyttelton Harbour, significant differences occurred in the surface water concentrations of NNN, NH3N, TON, TN and DRP between at least two of the seven sites in each sampling period and for TP significant differences occurred between at least two of the seven sites sampled in 3 of the 4 sampling periods. For NH3N, TON and TN concentrations there was no obvious pattern, while for NNN, DRP and TP there was a pattern of significant differences between sites over all sampling periods. These patterns consisted of:

- Generally higher concentrations of NNN at the port entrance than at other sites
- Generally higher concentrations of DRP and TP at inner harbour sites (Charteris Bay, Governors Bay and Corsair Bay) and the port entrance than at outer harbour sites (Harbour entrance, Purau and Ripapa).

These results suggest that there is NNN, DRP and TP input into or near to the port entrance and DRP and TP input/s into the inner harbour. Nutrient concentration data from three streams discharging into Lyttelton Harbour (Appendix IX) reveals that TP and TN concentrations in the Cass Peak and Allandale streams that discharge into the head of the harbour were higher than that in the Purau stream which discharges into the outer harbour. Thus the generally higher concentrations of DRP and TP at inner harbour sites could be as a result of the inputs from the inner harbour streams; however this does not appear to be the case for TN concentrations in the inner harbour. Such differences in nutrient concentration with location in the harbour was also found by Millhouse (1977) who concluded that the Harbour "appears to divide into three distinct segments" (the harbour mouth, the central body of the harbour and the inner harbour), with generally higher nutrient (Kjeldahl N and TP) concentrations in the inner harbour than in the other two harbour segments.

Within the Port of Lyttelton, significant differences occurred in the surface water concentrations of NNN, NH3N, TON, TN, DRP and TP between some of the sites, with generally higher concentrations of NNN, TN, DRP and TP at the Fox II mooring, between wharves 5 and 6 and between the fishing boats and the yachts than at

the other sites. This is highly suggestive of site-specific sources of nutrients within the port. Higher concentrations of each nutrient occurred within the port area than in greater Lyttelton Harbour and the range (variation) in concentration of each nutrient was also greater at sites within the port area than at sites in greater Lyttelton Harbour. This high variation in the concentration of each nutrient at the sites in the port area is an indication of ever changing (over the year of sampling) water quality, which could be as a result of the water mixing and circulation patterns in combination with irregular nutrient inputs at various locations, within the port area. From time to time notable fertiliser spills have occurred in the port area as a result of boat unloading activities at various wharves (J. Jones, Ecan, *pers. comm.*), and wind-borne and other small non-notified fertiliser inputs into the port cannot be discounted. In addition, stormwater from Lyttelton township and the working area of the port is discharged into the sea in the port area.

The variability in nutrient concentrations within the port is also reflected in the concentrations of NNN, TON and TN at the port entrance over time. Of all the greater Lyttelton Harbour sites, it was only at the port entrance that NNN, TON and TN concentrations were significantly different over time. This is suggestive that either irregular nitrogen-based nutrient inputs occur near to the port entrance or that the outflow of nutrient enriched water from the port area affects this site.

Over time the surface water concentrations of DRP and TP were significantly different at all greater Lyttelton Harbour sites except the port entrance. The difference over time generally consisted of lower concentrations in 2002-2003 than in one or more of the other sampling periods. In 2002-2003 the DRP and TP concentrations did increase over the course of this sampling period with the concentrations at the end of the period being comparable to those recorded in other sampling periods. It is not possible to determine why there were low DRP and TP concentrations harbour wide over a period in 2002-2003.

For all nutrients there was no apparent overall trend of a decrease or increase in concentration in surface water in greater Lyttelton Harbour between 1988 and 2003. However, the TON concentrations at Governors Bay, Charteris Bay, Purau and Ripapa, the NNN concentrations at Ripapa and the Harbour entrance, the DRP concentrations at Governors Bay and the TP concentrations at the Harbour entrance between 1988 and 2003 were all lower than the mean concentration for these nutrients at these sites in 1976 (Millhouse, 1977). At first sight this comparison with the 1976 data appears suggestive of a decrease in the concentration of some nutrients between 1976 and 1988; however for the for following reasons this may not the case:

- The differences did not occur at all sites
- There was no trend with respect to location in the harbour, for example TON concentrations were higher in 1976 at two inner harbour sites and two outer harbour sites but not at the site in between.

The higher concentration of these nutrients in 1976 than in 1988 at some sites could result from the localised input of nutrients into the harbour in 1976, with the dilution and flushing processes of the harbour enough to dilute the nutrients such that the high concentrations did not extend to all sampling sites within greater Lyttelton Harbour. The concept of localised inputs of these nutrients is supported by the large standard deviation (suggestive of a wide range i.e. from very low to very high concentrations at a site over the period of sampling) for the 1976 nutrient concentrations.

The concentrations of the nutrients at sites in greater Lyttelton Harbour and the Port of Lyttelton were compared to the ANZECC (2000) trigger levels for 'slightly disturbed marine water'. When concentrations are below the trigger levels the risk of adverse biological effects is low while at concentrations above the trigger level there is the potential for adverse biological effects (ANZECC, 2000). The adverse biological effects of nutrient over-enrichment include:

- the excessive growth of aquatic plants (phytoplankton, cyanobacteria, algae, seagrasses) i.e. eutrophication. Eutrophication can result in changes in the structure and functioning of marine ecosystems, reduced biodiversity, an increase in harmful algal blooms and impact on fisheries, aquaculture, recreation and tourism (Rosenberg, 1985; ANZECC, 2000; EEA, 2001).
- possible changes in the relative abundance of phytoplankton species without an overall increase in primary productivity (NRC, 2001).

It is important to note that to date marine trigger values have not yet been developed for New Zealand and in the guidelines it suggests the

comparison of New Zealand values to those for south-east Australia. As a consequence the guideline values, which are for the low-nutrient (oligotrophic) waters of south-east Australia, are conservative for the nutrient concentrations in New Zealand coastal waters which are higher than for those on which the guidelines were based. For example the median concentrations of NNN, NH3N, TN and DRP recorded at Amberley Beach in 2000-2001 were 0.042, 0.04, 0.19 and 0.009 mg/L respectively. The ANZECC (2000) guideline values for NNN, NH3N, TN and DRP are 0.005, 0.015, 0.12 and 0.01 mg/L respectively. The nutrient concentrations recorded in Lyttelton Harbour are comparable to those in Pegasus Bay (i.e. Waimari and Amberley beaches) and are not high in comparison to nearshore coastal waters elsewhere in New Zealand (P.Gillespie, *pers.comm*.). However a comparison of the nutrient concentrations recorded in this study with the ANZECC (2000) guideline values highlights the difference in nutrient concentrations between sites in the harbour and is a conservative indication of if and where there is the potential for adverse effects i.e. enhanced plant growth.

The concentrations of DIN, TN, DRP and TP in water from the surface and at depth at sites in greater Lyttelton Harbour and the Port of Lyttelton frequently exceeded the ANZECC (2000) trigger levels for 'slightly disturbed marine water' (south-east Australia). The percentage of samples in which the DIN, TN and TP concentrations exceeded the ANZECC (2000) trigger values was higher within the port area than in greater Lyttelton Harbour. This indicates that adverse effects i.e. enhanced aquatic plant growth, is more likely to occur within the port than elsewhere in the harbour. The green seaweeds *Enteromorpha* sp. and *Ulva* sp. (sea lettuce) have been found to be prevalent in the intertidal zone at sites within the port (Handley *et al.,* 2000; Fenwick, 2003). The growth of both these seaweeds typically increases with an increase in nutrient concentrations and large amounts of sea lettuce for example can cause a problem, as has been the case in the past in the Avon-Heathcote Estuary. Another concern is that the nutrient concentrations within the port could enhance the growth of the invasive seaweed *Undaria pinnifida* in this area. *Undaria pinnifida* thrives on a hard substrate in sheltered areas i.e. within bays/harbours/ports, and typically grows to a large size in the colder months and dies back in summer. The presence of this seaweed results in a change in the ecological balance of the biological communities of the hard substrate. In addition there is the potential for the nutrient concentrations within the port to enhance the growth of any future plant pest species that are inadvertently introduced into the area.

Phytoplankton growth is generally limited and regulated by the dissolved inorganic nitrogen (DIN) concentration. To assess the potential for enhanced phytoplankton growth, which could result in an algal bloom, it is necessary to evaluate the concentrations of DIN. In a recent study of the potential for nutrient-rich wastewater to stimulate algal blooms it was found that a mean DIN concentration of 0.07-0.14 mg/L over 72 hours resulted in an increase in chlorophyll-a concentration (a measure of the quantity of phytoplankton present) to around 0.002 mg/L (Zeldis and Gall, 1999). A chlorophyll-a level of 0.005 mg/L has been found to cause physical discolouration of surface waters (Eppley *et al*., 1977) and a level of 0.015 mg/L is associated with eutrophication (Harris *et al*., 1996). In this study the maximum DIN concentration at all sites and water depths was higher than 0.07 mg/L and at many sites it was also higher than 0.14 mg/L. However, a DIN concentration of higher than 0.07 mg/L occurred in less than 17 percent of the samples at all sites except those in the Port of Lyttelton and at the port entrance. Within the port 50 percent of the samples and at the port entrance 24 percent of samples had a DIN concentration higher than 0.07 mg/L. Given the percentage occurrence of these DIN concentrations there is a greater likelihood of enhanced phytoplankton growth in the port area than at sites in greater Lyttelton Harbour.

Although high nutrient concentrations can lead to excessive growth of aquatic plants, the relative availability of nitrogen and phosphorus i.e. the N:P ratio, the flushing, light regime and temperature and for phytoplankton the availability of other chemicals such as silica and iron are also important (ANZECC, 2000; NRC, 2001).

The N:P ratio in water from the surface and at depth at all sites on all sampling occasions in greater Lyttelton Harbour, except at 6.5m at the Port entrance in March 2003 and at sites in the Port on most sampling occasions in 1999-2000, was less than 16:1, which indicates that N was the nutrient limiting phytoplankton growth. This is in agreement with the widely accepted fact that nitrogen is generally the critical limiting nutrient for phytoplankton growth in the marine environment (NRC, 2001; Rosenberg, 1985; Valiela, 1995). However, at a number of sites and on a number of

occasions in the port the N:P ratio was greater than 16:1 which means that phytoplankton growth was limited by P rather than N. A ratio of greater than 16:1 resulted from either a high concentration of DIN (from either a high concentration of NH3N or NNN) or a low concentration of DRP or a combination of both. The high NH3N or NNN concentrations are indicative of irregular nutrient inputs at various locations, within the Port of Lyttelton.

Optimal nutrient conditions for phytoplankton growth, that is an N:P ratio of 16:1 did not occur during the period of sampling. Nonetheless, phytoplankton blooms have occurred in Lyttelton Harbour in the past (M.Main, Environment Canterbury, *pers.comm.*). Of note is that excessive aquatic plant growth has been reported in Church Bay (P. Pritchard, *pers. comm.*) and while local Church Bay residents attribute this to sewage discharge from the Diamond Harbour outfall no water quality data are yet available to support this claim. Under the sampling regime used in this study, the water in many of the smaller bays of Lyttelton Harbour was not sampled and consequently the nutrient status in these bays is unknown. Even if optimal nutrient conditions were to occur in Lyttelton Harbour, given the generally high water turbidity, light would likely be a major limiting factor for a phytoplankton bloom.

5 Conclusions

Lyttelton Harbour is a 15 km long body of water with a growing human population living in the harbour surrounds and a busy commercial port located about midway down the northern side of the harbour. As a consequence there are three sewage outfalls, septic tank outflows, stormwater discharges, occasional accidental spills from operational activities in the port area, agricultural runoff and stream flows that all add nutrients to the harbour water.

Monitoring of the nutrient status of sites in greater Lyttelton Harbour water between 1988 and mid 2003 shows that the only patterns, with respect to differences in nutrient concentrations between sites, consisted of generally higher concentrations of DRP and TP at inner harbour sites and the port entrance than at outer harbour sites, and generally higher NNN concentrations at the port entrance than at other sites. Over time there has been no overall trend of a decrease or increase in nutrient concentrations. This indicates that in this time period any increase in nutrient inputs into the harbour via sewage and stormwater runoff (a likely consequence of an increasing human population in the harbour surrounds), has not resulted in an increase in nutrient concentrations in the water of Lyttelton Harbour.

Year-long monitoring at sites within the Port of Lyttelton shows that within this area nutrient concentrations were higher, and the range in concentration of each nutrient was larger than at sites in greater Lyttelton Harbour. The large variation in nutrient concentration is suggestive of irregular nutrient inputs at various locations, within the port area. Continued monitoring of the nutrient status of the Port of Lyttelton is recommended. As the nutrient concentrations in the Port are comparatively high at times, enhanced aquatic plant growth is more likely to occur within the port than elsewhere in the harbour. Thus annual monitoring of the intertidal algae *Ulva* sp. and *Enteromorpha* sp., and the invasive seaweed *Undaria pinnifida* within and just outside the port area and at other Lyttelton Harbour sites is recommended.

Nutrient concentrations at sites in greater Lyttelton Harbour and the Port of Lyttelton frequently exceeded the ANZECC (2000) guideline trigger levels. Given the percentage number of samples with concentrations exceeding the guideline concentrations, and in particular the DIN concentrations, the indications are that there is a greater likelihood of enhanced phytoplankton growth in the port area than at sites in greater Lyttelton Harbour. The Port of Lyttelton is a working port facility and therefore the natural state of the marine environment, including water quality, is somewhat compromised. Needless to say all possible measures should be in place to minimise discharges/inputs that have the potential to cause an increase in the seawater concentration of nutrients.

Nitrogen is generally the critical limiting nutrient for primary productivity in the marine environment and this was the case at all sites in greater Lyttelton Harbour and at sites in the port on most sampling occasions in 1999-2000. However, at a number of sites and on a number of occasions in the port primary productivity was P limited. This variation in the nutrient limiting primary productivity indicates that the nutrient status in the Port of Lyttelton is dynamic.

6 Future investigations and monitoring

The current monitoring programme, i.e. every 5 years, represents the minimum desirable frequency for the continued monitoring of the nutrient status of greater Lyttelton Harbour. In future it would be advisable to measure the chlorophyll-a concentration at all sites and water depths in addition to the concentration of the nutrients measured to date so that nutrient status can be related to primary productivity.

It is recommended that in addition to the current monitoring programme, water quality, including chlorophyll-a monitoring, be carried out in Church Bay, Rapaki Bay and Cass Bay within the inner harbour and at a number of sites within the Port of Lyttelton.

It is recommended that annual monitoring for the presence and abundance of the algae *Ulva* sp. and *Enteromorpha* sp. in the intertidal region, and the invasive algae *Undaria pinnifida* in the shallow subtidal region, be undertaken at sites in and adjacent to the Port of Lyttelton and at other sites in Lyttelton Harbour.

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Appendix I: Details of the sampling sites and sampling depths at each site in Lyttelton Harbour/Whakaraupō

Site I.D.	Site Label	Site Description	Depth (m)	Grid Reference NZMS 260 map series
CRC300651	A	Governors Bay - mid bay	0-0.5	M36:8237-3118
CRC300661	B	Charteris Bay - mid bay	0-0.5	M36:8573-2968
CRC300632	C	Corsair Bay -mid bay	0-0.5	M36:8560-3305
CRC300680	D1	Inner Harbour entrance	0-0.5	M36:8707-3321
CRC304532	D2	Inner Harbour entrance	3.5	
CRC304533	D3	Inner Harbour entrance	6.5	
CRC300673	E1	Purau Bay - mid bay	0-0.5	M36:8965-3083
CRC304531	E2	Purau Bay - mid bay	3.5	
CRC302585	F1	NE of Ripapa Island	0-0.5	N36:9031-3249
CRC304529	F2	NE of Ripapa Island	3.5	
CRC304530	F3	NE of Ripapa Island	6.5	
CRC302587	G1	Lyttelton Harbour entrance	0-0.5	N36:9465-3403
CRC304526	G2	Lyttelton Harbour entrance	3.5	
CRC304527	G3	Lyttelton Harbour entrance	6.5	
CRC304528	G4	Lyttelton Harbour entrance	9.5	
CRC304041	H	end of Sticking Pt. breakwater	0-0.5	M36:8850-3300
CRC304042	I	end of Z berth near Lighthouse	0-0.5	M36:8725-3311
CRC304043	J	Cashin Quay container terminal	0-0.5	M36:8769-3305
CRC304044	K	Gladstone Pier docking area	0-0.5	M36:8755-3315
CRC304045	L	beside Fox II mooring	0-0.5	M36:8759-3350
CRC304046	M1	end of No.2 wharf	0-0.5	M36:8740-3335
CRC304047	M2	end of No.2 wharf	8	
CRC304048	N	between no.5 and no.6 wharf	0-0.5	M36:8721-3360
CRC304049	P1	end of No.7 wharf	0-0.5	M36:8705-3350
CRC304050	P2	end of No.7 wharf	8	
CRC304051	Q	between fishing boats and yachts	0-0.5	M36:8691-3356
CRC304052	R	beside cattle jetty	0-0.5	M36:8680-3340

Appendix II: Details of analyses included in the water quality monitoring programme

Determinand	Analysis provider	Method	Time Period	Detection Limit	Units
Nitrate/nitrite nitrogen (NNN)	NCCB Laboratory	Water and Soil Publication No.38	1988	0.001	mg/L
	CIN Laboratory	APHA 418C Cawthron method	1992-1993- April 1994	0.005	mg/L
	CIN Laboratory	Cd reduction APHA reagents Buffer = NH4Cl/EDT	- May 1994	0.005	mg/L
	Ecan laboratory	APHA 4500 NO_3 - F (19th ED, 1995)	1999-2004	0.001	mg/L
Total amjmonia-nitrogen (NH3N)	NCCB Laboratory	Water and Soil Publication No.38	1988	0.005	mg/L
	CIN Laboratory	Limnology and Oceanography Cawthron method	1992-1993- May 1994	0.005	mg/L
	Ecan laboratory	APHA 4500 NH3-F - modified (19th ED, 1995)	1999-2004	0.005	mg/L
Dissolved inorganic nitrogen (DIN)	Calculation (NNN + NH3N)				mg/L
Total organic nitrogen (TON)	Calculation (TN-DIN)				mg/L
Total Kjeldahl nitrogen (TKN)	NCCB Laboratory	DSIR Ilam TKN Method as at 27/11/85	1988	0.05	mg/L
Total nitrogen (TN)	Calculation (TKN + NNN)		1988		mg/L
	CIN Laboratory	Photo-oxidation then NNN Cawthron method	1992-1993- May 1994		mg/L
	Ecan laboratory	APHA 4500-N C modified (19th ED, 1995)	1999-2004	0.08	mg/L
Dissolved reactive phosphorus (DRP)	NCCB Laboratory	Water and Soil Publication No.38	1988	0.001	mg/L
	CIN Laboratory	APHA 424F modified Cawthron method	1992-1993- May 1994	0.003 - 0.001	mg/L
	Ecan laboratory	APHA 4500-P B, E modified (19th ED, 1995)	1999-2004	0.003	mg/L
Total phosphorus (TP)	NCCB Laboratory	Water and Soil Publication No.38	1988	0.005	mg/L
	CIN Laboratory	APHA 424 C3 Persulphate Digest Cawthron method	1992 - 1993 -Jan.1994	0.008	mg/L
	CIN Laboratory	APHA 424 C1 Perchloric acid Digestion Cawthron	Feb 1994-May 1994	0.008	mg/L
	Ecan laboratory	APHA 4500-P B (19th ED, 1995)	1999-2004	0.008	mg/L

Appendix III: Comparison of nutrient concentration in surface water between all sites in greater Lyttelton Harbour/Whakaraupō results from the two-tailed Wilcoxon Signed Rank Test

* - significant difference between sites at p<0.05
** - significant difference between sites at p<0.01
blank cells indicate there was no significant difference

1988		Higher concentration						
		Governors	Charteris	Corsair	Port	Purau	Ripapa	Entrance
Lower Concentration	Governors				NNN *			
	Charteris	DRP *			NNN *			
	Corsair	DRP *			NNN * NH3N *		NH3N *	
	Port							
	Purau				NH3N * DRP *		NH3N *	
	Ripapa	TON *	TON *	TON *	DRP *	TON *		TN * TON *
	Entrance				DRP *		NH3N *	

1992-1993		Higher concentration						
		Governors	Charteris	Corsair	Port	Purau	Ripapa	Entrance
Lower Concentration	Governors							
	Charteris	DRP ** TP **		DRP *	DRP ** TP **			
	Corsair	TP **			DRP *			
	Port	TP *						
	Purau	DRP ** TP **		NNN * DRP *	NNN ** DRP *			
	Ripapa	TN * DRP *		NNN * TON * DRP * TN *	NNN ** DRP *			
	Entrance	TN * DRP *	TN *	TN * DRP *	NNN * NH3N * DRP *			

1993-1994		Higher concentration						
		Governors	Charteris	Corsair	Port	Purau	Ripapa	Entrance
Lower Concentration	Governors		NNN **					
	Charteris	TON * TP **		TON ** TN *				TON * TN *
	Corsair	TP *						
	Port	TP *		TON * TN *				TN *
	Purau	DRP * TP **	NH3N * DRP *	NH3N * TON * TN * DRP *	NH3N * DRP ** TP *			TN *
	Ripapa	DRP * TP **	DRP *	TON * DRP * TP *	DRP ** TP *			
	Entrance	TP *		DRP *	DRP *			

2002-2003		Higher concentration						
		Governors	Charteris	Corsair	Port	Purau	Ripapa	Entrance
Lower Concentration	Governors			NNN *	NNN *			
	Charteris	DRP * TP*			NNN *			
	Corsair				NNN *			
	Port							
	Purau	DRP **	DRP *	DRP **	DRP **			
	Ripapa	TON * TN * DRP ** TP*	DRP **	TN * DRP **	TON * TN * DRP **			NH3N *
	Entrance	DRP ** TP*	DRP *	DRP **	DRP *			

Appendix IV: Comparison of nutrient concentration between 3.5 m deep sites and between 6.5m deep sites in greater Lyttelton Harbour/Whakaraupō - results from the two-tailed Wilcoxon Signed Rank Test

* - significant difference between sites at p<0.05
** - significant difference between sites at p<0.01
blank cells indicate no significant differences

3.5 metre sites

1988		Higher value			
		Port	Purau	Ripapa	Entrance
Lower	Port				
	Purau				
	Ripapa		TP *		
	Entrance	NH3N *			

1992-1993		Higher value			
		Port	Purau	Ripapa	Entrance
Lower value	Port				
	Purau	DRP **			
	Ripapa	NNN ** DRP *			
	Entrance	DRP ** TP **			

1993-1994		Higher value			
		Port	Purau	Ripapa	Entrance
Lower value	Port				NNN * TN ** TON **
	Purau	NH3N ** DRP *			NH3N * NNN * TN * TON *
	Ripapa	NH3N ** DRP *			NNN * TN * TON *
	Entrance	NH3N *			

2002-2003		Higher value			
		Port	Purau	Ripapa	Entrance
Lower value	Port				
	Purau	NNN * NH3N * DRP **			
	Ripapa	NNN ** NH3N * TN * TON * DRP ** TP *			
	Entrance	NNN * NH3N * DRP **	DRP *	DRP **	

6.5 metre sites

1988		Higher value		
		Port	Ripapa	Entrance
Lower	Port			
	Ripapa	TP *		
	Entrance		TON *	

1992-1993		Higher value		
		Port	Ripapa	Entrance
Lower value	Port			
	Ripapa	NNN ** TP * DRP **		
	Entrance	TP * DRP *		

1993-1994		Higher value		
		Port	Ripapa	Entrance
Lower value	Port			
	Ripapa	NH3N * DRP **		
	Entrance	NH3N * TP ** DRP *	TP *	

2002-2003		Higher value		
		Port	Ripapa	Entrance
Lower value	Port			
	Ripapa	NH3N * TP *		
	Entrance	NH3N * DRP *	DRP *	

Appendix V: Comparison of nutrient concentration between sites in the Port of Lyttelton in 1999-2000 - results from the two-tailed Wilcoxon Signed Rank Test

* - significant difference between sites at p<0.05
** - significant difference between sites at p<0.01
blank cells indicate not significant differences

1999-2000	Higher Concentration											
Lower Concentration	St. Point	Z	Cashin	Gladstone	Fox II	2 Wharf	2 Wharf 8m	5/6 Wharf	7 Wharf	7 Wharf 8m	Fish/yacht	Cattle Jetty
St. Point					TN *			NNN * TN * DRP *			NNN * TN * DRP *	
Z	NNN *			NH3N * DRP *	NNN * TN * DRP *		DRP *	NNN * DRP *			NNN * TN * DRP *	DRP *
Cashin	NNN * DRP *	NNN * DRP *		NNN * DRP *	NNN * TN * DRP *	NNN *	DRP *	NNN * DRP *		DRP *	NNN * TN * DRP *	DRP *
Gladstone					TN *			TN * DRP *			NNN * TN * DRP *	
Fox II											TP *	
2 Wharf	NNN *				NNN * TN * DRP *			NNN * TN * DRP *			NNN * TN * DRP *	
2 Wharf 8m	NNN *				NNN *			NNN *			NNN * TN *	
5/6 Wharf												
7 Wharf	NNN *			NH3N *	NNN * DRP *		DRP *	NNN * DRP *			NNN * TN * DRP * TP *	NNN *
7 Wharf 8m	NNN *			NNN *	NNN * TN *		DRP *	NNN * TN * DRP *			NNN * NH3N * TN * DRP * TP *	
Fish/yacht												
Cattle Jetty		TON *	TON *		TON * TN *	TON *	TON *	NNN * TN * DRP *			NNN * TN * DRP *	

Appendix VI: Comparison in nutrient concentration in surface water at each greater Lyttelton Harbour/Whakaraupō site over time results of the two-tailed Wilcoxon Signed Rank Test

* - significant difference at $p<0.05$
** - significant difference at $p<0.01$
blank cells indicate that there was no significant difference

Governors Bay

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		**	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994	*			
2002-2003	*	*	**	

Charteris Bay

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

Corsair Bay

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993	*		**	
1993-1994				
2002-2003	*		**	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*	*	*	

Purau

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994	*			
2002-2003	*		**	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*			

Ripapa

TON	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				*
1992-1993				
1993-1994				
2002-2003				

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*	*	**	

Harbour entrance

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993			*	
1993-1994				
2002-2003	*	*	**	

Port entrance

NNN	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*			

TON	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				*
1992-1993				
1993-1994				*
2002-2003				

TN	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				*
2002-2003				

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*	*	**	

Appendix VII: Comparison in nutrient concentration at 3.5 m deep at four sites in greater Lyttelton Harbour/Whakaraupō over time results of the two-tailed Wilcoxon Signed Rank Test

* - significant difference at p<0.05
** - significant difference at p<0.01
blank cells indicate that there was no significant differences

Port entrance

NNN	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994	*	*		*
2002-2003	*			

TON	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				*
1992-1993				*
1993-1994				*
2002-2003				

TN	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994		*		**
2002-2003				

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*	*	**	

Ripapa

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988			*	
1992-1993				
1993-1994				
2002-2003	*	*	*	

Purau

NH3N	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003		*		

TON	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				*
1992-1993				
1993-1994				*
2002-2003				

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		*	

Harbour entrance

NH3N	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003			*	

DRP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993				
1993-1994				
2002-2003	*		**	

TP	Higher concentration			
Lower conc.	1988	1992-1993	1993-1994	2002-2003
1988				
1992-1993			*	
1993-1994				
2002-2003	*	*	*	

Appendix VIII: Comparison in nutrient concentration at 6.5 m deep at three sites in greater Lyttelton Harbour/Whakaraupō over time results of the two-tailed Wilcoxon Signed Rank Test

* - significant difference at p<0.05
** - significant difference at p<0.01
blank cells indicate that there was no significant difference

Port entrance

TON		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993				*
	1993-1994				
	2002-2003				

TP		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993			*	
	1993-1994				
	2002-2003	*	*	**	

Ripapa

DRP		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993				
	1993-1994				
	2002-2003	*		*	

TP		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993			*	
	1993-1994				
	2002-2003			*	

Harbour entrance

DRP		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993				
	1993-1994				
	2002-2003	*		*	

TP		Higher concentration			
		1988	1992-1993	1993-1994	2002-2003
Lower conc.	1988				
	1992-1993			**	
	1993-1994				
	2002-2003	*	*	**	

Appendix IX: Concentration of TN and TP in three permanently flowing streams discharging into Lyttelton Harbour/Whakaraupō

Nutrient	Stream	Sampling	Range in concentration (mg/L)	Mean concentration (mg/L)	Standard Deviation
TP	Purau	1988-1989	0.016 - 0.094	0.03	0.02
TP	Cass Peak	1988-1989	0.046 - 0.365	0.11	0.095
TP	Allandale	1988-1989	0.072 - 0.68	0.22	0.18
TN	Purau	1988-1989	0.23 - 3.56	0.69	0.97
TN	Cass Peak	1988-1989	0.28 - 2.48	1.03	0.73
TN	Allandale	1988-1989	0.86 - 4.65	2.16	1.21

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