Status of Fanga'uta Lagoon, Tonga: Monitoring of water quality and seagrass communities 1998-2000

Photo.

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Summary

Past studies have suggested that Fanga'uta Lagoon is in poor condition and conditions are further declining. Public have been making request for information because they notice that the quality and quantity of marine resources are declining. This study was an designed to examine these issues by identifying patterns in changes through time, through sections of the lagoon and at different sites (locations) in a range of water quality, water chemistry and seagrass community indicators.

We examined a total of 28 indicators of ecosystem health over 5 sampling times between December 1998 and July 2000. At each sampling time we took measurements at 30 sites spread out through six sections of the Fanga'uta system. The variables for water quality included salinity, temperature, dissolved oxygen (DO), acidity/alkalinity (pH), clarity, depth and faecal coliforms. Measurements for water chemistry included nitrate, nitrite, ammonia, dissolved inorganic nitrogen (DIN) and phosphate. Percentage cover for seagrass communities included looking at, *Halodule*, *Halophila* species and seagrass with epiphytes and the algae *Caulerpa*, *Halimeda* species.

The results indicated that the Lagoon was worst during times in November/December 1998 through to February 1999, but appears to have improved slightly since than. There is was a general trend for decreasing in water clarity, not only in this study but in all previous studies since 1981. Levels of nitrate, phosphate & faecal coliforms measured have all exceeded Australian standards for seafood, recreational use and risk of algal blooms, at least at one time during this study. The eastern side of the lagoon is generally in better condition than the western side. Sites with the biggest problems and changes are sites 8, 12, 21, 24 and 27. Of these sites 8 and 12 showed the greatest deterioration during the study. Sites 21, 24,and 27 showed the greatest change, but some of these were improvements. The most problems with high nutrient levels were recorded at the following sites: Pea – sites 2 & 5; Fanga'uta – sites 7, 8 & 9; Fanga Kakau – sites 11 – 15; Mouth – sites 16 – 20; Mu'a – sites 21, 24 & 25; and Vaini – sites 26 & 27.

The recommendations for immediate and longer term actions to be taken with regard to the Lagoon are as follows:

1. It is recommended that a management plan for the lagoon be developed and implemented to improve conditions and ensure sustainable use of the area.
2. Major problems tended to be common in the western side of the lagoon in Pea, Fanga'uta and Fanga Kakau. Look for sources of problem. Chasing up sewage sources in urban and industrial areas would be worth while.
3. Any site identified as unusual or with high readings of nutrients or poor conditions should be investigated further. At this stage, this includes Fanga'uta S8 and FK S12. These sites have indicated possible problems.
4. Faecal coliforms at Vaini require attention – it is recommended that sources be identified.
5. Monitoring should continue indefinitely to get long term data on change and seasonal patterns. In addition to identifying problem areas.
6. Surveys should be run consistently during the months of Jan, April, July and October of each year, at least initially to investigate seasonal patterns. Quality of data collection needs to be improved.
6. Seafoods should be tested immediately to see if they are fit for human consumption & further recommendations be made to the public after that.

7. The public needs to be informed about the importance of international standards for recreational use and seafood consumption, and the fact that conditions in the lagoon have exceeded the allowable levels.

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1 Introduction

1.1 Background and rationale

Tonga's Development Plan 6 (GOT 1991) has a major goal for protecting the environment for the health of the people of Tonga. The communities living around the lagoon raised an alarm that their lagoon resources were declining and that shellfish & fish were safe to eat. They also were concerned that the lagoon depth was decreasing and that there were problems with shore erosion emerging. Initially, their concerns were around the problem of climate change – sealevel rise. Over the past 10 years. Also concerns for recreational activities (swimming, fishing). People also complained about the risk of pollution from the hospital and activities nearby. There have also been concerns raised about the loss of mangroves around the fringes of the lagoon through traditional and non-traditional uses. Urbanisation around the fringes of the lagoon for last 15 years.

In an attempt to deal with these problems a range of by-laws have been implemented. In the 1940's the Havelu area was declared a national park by the then Prime Minister (Honourable Ata). The land from mean high water mark (MHWM) and 50m inland is controlled by the Minister of Lands, Survey & Natural Resources. Under the Fish & Birds Preservation Act 1974 – protected fish through banning commercial fishing in the lagoon and also protected mangroves. This was reopened 1981 because the law was not enforced. Awareness of the problem was present, EPACS has been trying to reach out to the community through publication of educational materials, Replanted mangroves about 10 years ago – awareness over last 10 years. There was also an enhancement programmes by fisheries – farming of mullet. Prawn trawling was banned around 1974.

These ad hoc approaches did not work. There is now an urgent need to develop an integrated management plan for the lagoon and its surrounds if we are going to be able to prevent further damage and address the concerns of the public. The basis of such a plan is good data on the condition of the lagoon and how it changes through time. This monitoring programme has been designed to meet this need.

1.2 Aims

The overall aim of this programme was to quantify the conditions in the lagoon using indicators of water quality and ecosystem health and how those might have changed through time in different parts of the lagoon. These measurements could then be further used to identify existing and possible emerging problems in the lagoon upon which a management plan could be based. Specifically, we aimed to:

- Describe patterns in different sections of the lagoon;
- Describe the amount of variation at Locations within sections of the lagoon to identify problem locations;
- To identify changes through time, including seasonal patterns and longer term changes; and
- Assess what these patterns might mean in relation to health of the lagoon.

1.3 Literature Review

Fanga'uta lagoon is a rare lagoon type in the Pacific Region, so there are few studies of similar lagoons either in Tonga or elsewhere. There have, however, been several studies done in Fanga'uta in Tonga and in Erakor lagoon in Vanuatu that can provide context for this study. These studies are summarised below.

In 1981, Zann et al. (1984) carried out an ecological study in Fanga'uta Lagoon. Water clarity was 1.5-2m in the area between Fanga Kakau and Mu'a and up to 1.1m in Pea where turbidity was higher during windy periods (see Figure 1). The tidal range in Fanga'uta was approximately 1m with current drive of up to 2.6 kts with a tide lag of 3-4 hours. About 4% of the lagoon volume was exchanged by tides per day. Corals were present in the lagoon at <1% cover as patch reefs in the entrance (Mouth Section). Fanga'uta Lagoon was dominated by extremely productive soft substratum communities.

Zann et al. (1984) reported that the lagoon was already undergoing large changes by 1981. In the two decades before 1981, the lagoon supported a mullet fishery (yielding about 187 tonnes per year), but this had gone into decline, resulting in closure to commercial fishing in 1975. This was reopened in 1981. The lagoon was shallowing, mangroves were being cleared and there was a decline in the mussel fishery. It was noticed that there were problems with the lagoon resources connected with development pressures, particularly land reclamation for building. Nutrient levels were increasing with an N:P ratio of 130.

By 1987 to 1988, further changes in the lagoon were recorded. Naidu et al. (1991) reported sewage-related problems in the lagoon. There were relatively high nutrients (nitrate & phosphate) concentrations, sufficient to have detrimental effects on coral growth. Fanga'uta Lagoon had exceeded international standards for phosphate and nitrate concentrations which would cause reductions in calcification rate and significant algal growth problems. Further declines in mullet and edible mussels were recorded, with the mussels not only having declined in numbers but also have disappeared from some locations of the lagoon. Possible problems with trace metals were indicated and dredging of the lagoon appears to have affected the tidal height and the normal circulation of the lagoon. Recommendations for long term, locally-based monitoring were made at that time.

2. Methods

2.1 Study area

The study was carried out in Fanga'uta Lagoon system, located at the northern end of Tongatapu Island, Kingdom of Tonga (21^{o}S/175^{o}E). The system is an enclosed tropical lagoon divided into two major arms and covers an area of 27km2, and a depth that varies from 1.4-6m (Naidoo et al 1991). There are two entrance channels into the lagoon which bring in seawater during tides, and in 1981, a study found that 26,000m3 per day of freshwater flows into the lagoon from runoff and diffuse subsurface springs (Zann 1984). The lagoon is in an area of uplift (Zann 1984) and may have been uplifted somewhere between 40 and 200 years ago. The water residence time is in the order of 23 days at the southwestern end of the lagoon (Zann 1984). It is a soft-bottom, shallow lagoon system, dominated by seagrass beds and bordered by 8 species of mangroves (Ellison 1998). In 1983 of 58km of Fanga'uta shoreline, 44-45 are covered by mangrove tidal forests (Zann 84).

2.2 Survey design

The lagoon was divided into 6 sections for the study to examine large scale patterns. The sections were: Pea, Fanga'uta and Fanga Kakau in the western arm, Vaini and Mu'a in the east, and the Mouth (Figure 1). Five Locations, were randomly selected within each Section of the lagoon to provide good representative sampling for each of the sections (Table 1). These locations were labelled uniquely through the lagoon as Sites 1-30. Between 5 and 10 replicates, depending on variable, were sampled at each Site. The overall design for the sampling programme is shown in Figure 2. This survey design was repeated through time, with 5 surveys being completed to date. The survey dates covered by this report were:

Survey 1 - Dec 1998
Survey 2 - July 1999
Survey 3 - Jan/Feb 2000
Survey 4 - April 2000
Survey 5 - July 2000

With an extra Water Chemistry and Faecal coliform survey as follows:

Feb99 - Feb 1999

Figure 1: The six Sections and 30 sampling Sites in Fanga'uta Lagoon.

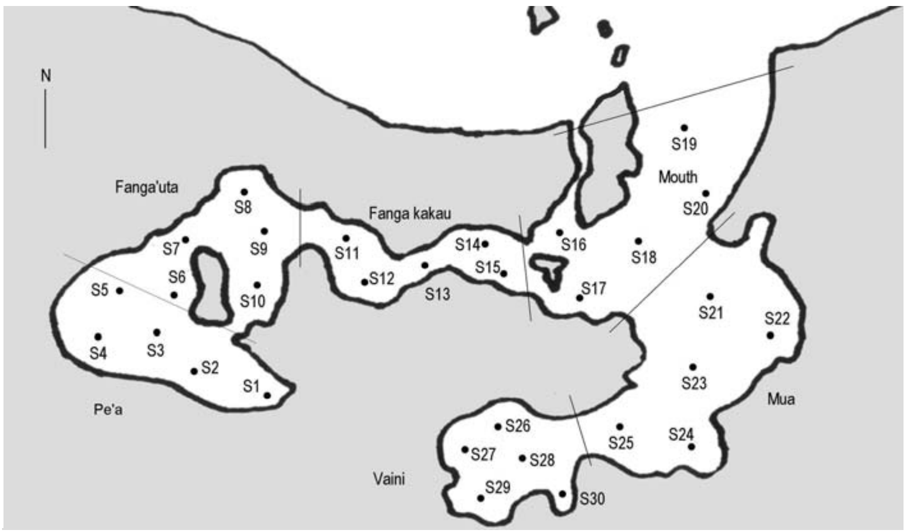
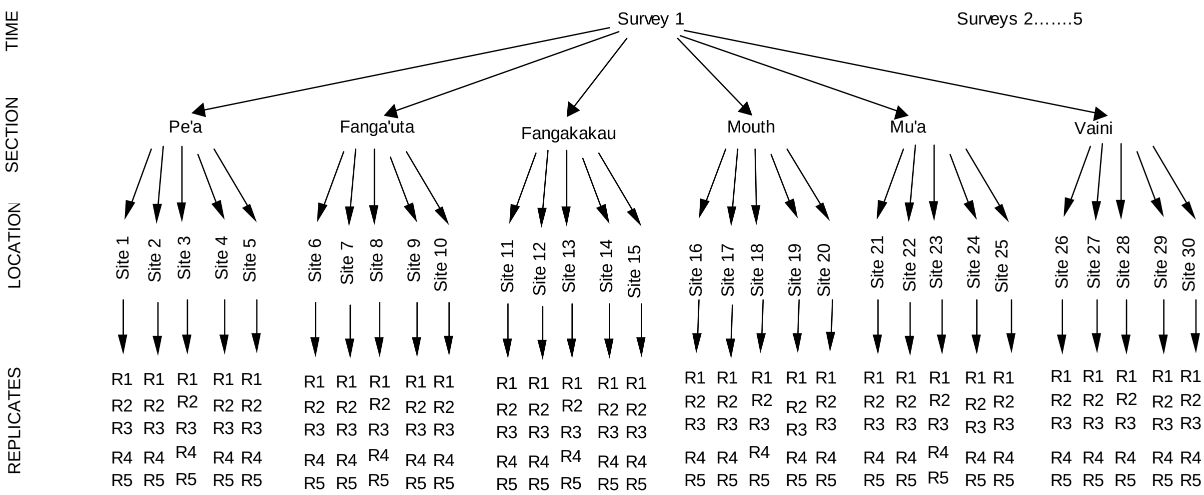


Table 1: Latitude and longitude coordinates for all survey Sites.

Location Name	Latitude (S)	Longitude (E)	Location Name	Latitude (S)	Longitude (E)
S1	21,10,71	175,11,92	S16	21,09,28	175,09,17
S2	21,10,78	175,12,47	S17	21,09,84	175,09,04
S3	21,10,25	175,13,03	S18	21,09,63	175,08,61
S4	21,10,56	175,13,45	S19	21,08,44	175,08,16
S5	21,10,23	175,13,40	S20	21,08,90	175,07,99
S6	21,09,86	175,12,88	S21	21,10,01	175,07,72
S7	21,09,39	175,12,93	S22	21,10,22	175,07,04
S8	21,08,97	175,12,27	S23	21,10,31	175,08,12
S9	21,09,35	175,12,23	S24	21,11,33	175,07,74
S10	21,09,89	175,12,21	S25	21,10,79	175,08,34
S11	21,09,26	175,11,30	S26	21,11,13	175,10,02
S12	21,09,91	175,11,07	S27	21,11,48	175,10,16
S13	21,09,57	175,10,53	S28	21,11,33	175,09,75
S14	21,09,35	175,09,90	S29	21,11,66	175,09,83
S15	21,09,79	175,09,75	S30	21,08,03	175,09,22

Figure 2: Sampling design tree for the study.

This figure shows the structure of the Monitoring Programme for variables with 5 replicates. Water Chemistry samples and Seagrass surveys had 2 and 10 replicates, respectively.



2.2 Indicators used

Three classes of indicators were selected and monitored during this study. These were:

- Water quality – physical measures and faecal coliforms
- Water chemistry - nutrients
- Seagrass communities - % cover by seagrasses, epiphytes of seagrasses and algae.

For water quality, we examined 7 variables, including salinity, temperature, pH, dissolved oxygen, turbidity, depth and faecal coliforms (Table 2). A total of 5 indicators of water chemistry were monitored. These included phosphate and several forms of nitrogen. For seagrass communities, a total of 10 indicators was used, including cover by species of seagrasses, percent cover of the seagrasses by epiphytes, algae and other fauna.

Table 2: Description of units, times, dates, position in the water and numbers of replicates for all indicator variables measured during the study.

Position refers to location of the sample in the water column; Surf=10cm below the surface; Bott=15-20cm up from the bottom; Diff = difference between surface and bottom which was calculated either as Surface – Bottom (S-B) or Bottom – Surface (B-S). Differences were usually calculated for Surface – Bottom because it was expected that temperature, DO, pH and Clarity would be greater in surface waters, implying a +ve gradient. For Salinity, it was expected that surface waters might be less saline, so the direction of a +ve gradient was reversed.

Variable	Units	Surveys	Dates	Position	Replicates
Water Quality					
. Salinity	ppt	1-5	Dec98, Jul99, Feb00, Apr00, Jul07	Surf, Bott, Diff = (B-S)	5 each
. Temperature	C	1-5	Dec98, Jul99, Feb00, Apr00, Jul08	Surf, Bott, Diff = (S-B)	5 each
. Dissolved Oxygen (DO)	mg/L	1-5	Dec98, Jul99, Feb00, Apr00, Jul09	Surf, Bott, Diff = (S-B)	5 each
. pH		1-5	Dec98, Jul99, Feb00, Apr00, Jul10	Surf, Bott, Diff = (S-B)	5 each
. Clarity (Turbidity Tube)	cm	1-5	Dec98, Jul99, Feb00, Apr00, Jul11	Surf, Bott, Diff = (S-B)	5 each
. Secchi disc	m	1-5	Dec98, Jul99, Feb00, Apr00, Jul12	-	5
. Depth	m	1-5	Dec98, Jul99, Feb00, Apr00, Jul13	-	5
. Faecal coliforms	#/100ml	1-5, Feb99	Dec98, Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1-3
Water Chemistry					
. Nitrate	µmol/L	2-5, Feb99	Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1
. Nitrite	µmol/L	2-5, Feb99	Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1
. Ammonia	µmol/L	2-5, Feb99	Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1
. DIN Dissolved Inorganic Nitrogen		2-5, Feb99	Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1
. Phosphate	µmol/L	2-5, Feb99	Feb99, Jul99, Feb00, Apr00, Jul00	Surf	1
Seagrass Communities					
. *Halodule uninervis*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Halophila ovalis*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Cymodocea*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Syringodium*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Total seagrass	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Seagrass with epiphytes	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Caulerpa racemosa*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Caulerpa taxifolia*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Caulerpa webbiana?*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Caulerpa serrulata*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Total Caulerpa*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Acanthophora spicifera*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Hypnea spp.*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Algal turf	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Udotea*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Sargassum*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Halimeda*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Blue-green algal mat	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Total % algae	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Sponges	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *P. damicornis*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Porites sp.*	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Faviids	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Oysters	%	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Holothurians	# per sqm	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Starfish	# per sqm	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. Anemone	# per sqm	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10
. *Cassiopea medusae*	# per sqm	1-5	Dec98, Jul99, Feb00, Apr00, Jul00	-	10

2.3 Survey methods

2.3.1 Water Quality

Measurements of pH, temperature, salinity and DO, were taken using two probes (TPS Ltd, Brisbane, Australia - WP 84 and WP 91). Measurements were taken at two different levels in the water using a 5m long probe cable. Measurements were taken at 10cm depth and approximately 20cm off the bottom. At times when a long probe cable was not available, water samples were collected from near the bottom by a diver using water sampling bottle. These were brought to the surface and measured immediately. Water clarity was measured using two techniques. Surface and bottom clarity were measured separately using a turbidity tube. This is a 0.95m long perspex tube, with an internal diameter of 29mm, sealed at one end and marked with a black circle on its bottom. Water was poured into the tube, while looking down the column from the top and the height of water measured when the black circle at the bottom was no longer visible. Turbidity was also measured using a secchi disk. Depth at each Site was measured using a drop line made of measuring tape and dive weight.

Two replicate water samples for faecal coliform counts were collected at each Site. Samples were collected in 150ml plastic sample containers from 10cm below the surface of the water. These were stored in an esky on ice until they could be delivered to the lab for analysis. Analyses were done by either TWB or MoH. APHA-AWWA-WPCF 1995. Faecal coliforms were analysed using the membrane filtration technique at TWB and the most probably number (MPN) method at MoH (Morrison 1999).

2.3.2 Water Chemistry

A single one litre water sample was collected from each Site for chemical analysis. These were placed in an esky on ice before being frozen for later analysis. Laboratory analysis of the samples was carried out by MAF using standard methods APHA-AWWA-WPCF 1995. For ammonia this was the indophenol blue method, for phosphate, the molybdenum blue method, and for nitrite, production of a red azo compound. Nitrate used the same method as nitrite, after it had been reduced using a cadmium column.

2.3.3 Seagrass communities

For seagrass communities, ten replicate 1m2 quadrats were used to estimate the percentage cover by seagrasses and algae. The quadrats were divided into 81 points of intersection using string. A diver randomly-placed the quadrat on the lagoon floor and recorded the presence of seagrasses and other variables under each point. Of the total the total count for seagrasses, those points which also had epiphytes were also recorded. Epiphytes are defined as any algae or other organisms covering the blades of the seagrass >5mm. The counts out of 81 were later converted to percentage cover for analysis.

2.4 Statistical methods

Data were recorded in a Microsoft Excel. Not all data were analysed, for example, rare species were omitted, individual species were pooled, secchi measurements often were limited by depth, giving a non-numeric result, so were not analysed here – clarity measurements using a turbidity tube were used instead. Faecal coliforms were counted in between 1 and 3 replicates per site and were also not analysed using ANOVA – these were examined form graphs.

Data were imported into Statsoft Statistica 4.5 for analysis. Data were analysed separately in individual ANOVAS. The data for each variable were first tested for normality and for homogeneity of variances, using normality plots, plots of means vs. variances ("trumpet plot") and Cochran's test. If data were found to be heterogenous, they were transformed to either $\sqrt{(x+1)}$ or $\ln(x+1)$ and the transformed data used in the ANOVA. If transformation did not stabilise the data we proceeded to analyse the original data.

Data were analysed using a 3 factor ANOVA for Water Quality and Seagrass variables, with main effects being Time, Section and Location (Table 3), and interaction terms being Time * Section and Time * Location(Section). Water Chemistry variables were analysed by 2-F ANOVA, using Locations as replicates to analyse the Time and Section factors. The probability level for all analyses (ANOVAs and Cochran's Tests) was set at $p=0.05$. Results of the ANOVAs were interpreted from the F-tests and graphs of means +/- SE (Standard Errors).

Table 3: Summary of the ANOVA design used for analysing 3-Factor survey results

Most Water Quality variables were analysed only for Surveys 2-5, with the exception of Turbidity, Depth and Seagrass variables which were analysed for surveys 1-5. Water Chemistry variables were analysed for Feb99 and Surveys 2-5 using a 2-Factor ANOVA because there were no replicates at the level of Location. This meant that the factors Location(Section) and Time*Location(Section) could not be analysed for Water Chemistry variables. Faecal coliforms were not analysed by ANOVA at all and were interpreted directly from graphs.

Factor	DF (5 replicate design)	Denominator of F-test	Fixed / Random	Nesting
Time	3	Time * Location(Section)	Fixed	
Section	5	Location(Section)	Fixed	
Location(Section)	24	Residual	Random	Nested in Section
Time * Section	15	Time * Location(Section)		
Time * Location(Section)	72	Residual		
Residual	480			
Total	599			

3. Results

3.1 Water quality

A total of 16 variables were analysed using a ANOVAs, while one additional variable, Faecal coliforms was interpreted only from graphs due to missing data.

14 of the variables resulted in a Time*Section interaction, while all analysed variables had significant interactions between Time and Location(Section) (Table 4 and Appendix 7.1). This means that looking at the main factors of Time, Section and Location in isolation is insufficient, and the results need to be interpreted in combinations of Time and Section or Location. This means changes through time are dependent on which section of the lagoon and which Location was being surveyed.

Salinity

Surface and bottom salinities varied between 14 and 32 ppt over the period of the survey. Salinities in Pea and Fanga'uta were generally lower than in the remaining sections of the lagoon (Appendix 7.2.1). Salinities were lower overall during survey 4 (Apr00), with the largest range between surveys being recorded at Fanga Kakau and the Mouth. Surface salinities were particularly low during Survey 4 (Apr00) at Sites 9 and 10 in Fanga'uta and Site 15 in Fanga Kakau.

Difference in Salinity between surface and bottom waters varied among surveys and sites, but not across Sections of the lagoon. The largest differences in salinity occurred during Survey 4 (Apr00) at Pea Site 1, Mu'a Site 21 and Vaini Site 26. There were also higher differences in salinities recorded at Fanga'uta Site 8. The salinity gradient tended to be positive throughout the study, changing to negative in Survey 3 (Jan00) in most sections of the lagoon.

Temperature

Both interaction terms were significant for all three temperature variables (Table 4). There was an overall pattern for surface and bottom temperatures to start low in Survey 2 (Jul99), rise through Surveys 3 and 4 (Jan00 and Apr00) and drop during Survey 5 (Jul00). At Pea, Fanga'uta and Fanga Kakau (the western arm of the lagoon), surface temperature rose from around 24^{o}C in Survey 2 (Jul99) to a high of up to 31^{o}C during Survey 3 (Jan00), dropping back down to 24^{o}C by Survey 5 (Jul00). At Pea surface temperature stayed about the same in surveys 3 and 4, while at Fanga'uta and Fanga Kakau mean temperatures dropped about 2 degrees.

At Mouth, Mu'a and Vaini, in the eastern arm of the lagoon, surface and bottom temp rose from 24^{o}C in Survey 2 (Jul99), up to 31^{o}C in Survey 3 (Jan00) and then dropped slowly and evenly by about 3^{o}C over the subsequent 2 surveys. In these sections of the lagoon during the final survey, temperatures were higher (26^{o}C) than those found during Survey 2 or at the other sections of the lagoon during Survey 5.

In Pea and Mu'a , the difference between surface and bottom temperatures (S-B) were greatest during Survey 4 (Apr00), while in Fanga Kakau, the greatest difference was in survey 5 (Jul00) and was negative (bottom waters warmer than top). In Pea there were significant positive temperature gradients at sites 1, 2, 3 and 5 during survey 4 (Apr00) and at Mu'a at Site 24. In Fanga Kakau there was a negative temperature gradient at S12 during Survey 5

(Jul00). The Mouth and Vaini sections showed the least stratification in temperature throughout the study.

Dissolved Oxygen (DO)

Time*Section and Time*Site(Section) were both significant for surface DO (Table 4 and Appendix 7.2.1). The surface DO readings varied between 6.5 and 9.4 mg/L. Surface DO varied through time in different ways in different sections of the lagoon. The only relatively consistent pattern was that surface DO tended to be highest during Survey 5 (Jul00). There was a tendency for surface DO to increase over the period of the study at Vaini at all sites except S27 where it stayed constant.

In the western side of the lagoon system (Pea, Fanga'uta and Fanga Kakau) bottom DO tended to be higher in Survey 5 (Jul00) than in previous surveys. At Vaini we recorded a gradual increase in bottom DO over the entire study. There was a significantly lower bottom DO recorded at Site 8 of Fanga'uta, during Survey 4 (Apr00). Surface and bottom DO tended to follow similar patterns in terms of sites.

Difference in DO between surface and bottom waters (S-B) did not significantly vary in the eastern lagoon sections (Mouth, Mu'a, Vaini). On the western side of the lagoon, Pea and Fanga Kakau started high, decreased during Surveys 3,4 (Jan00 and Apr00) and ended high in Survey 5 (Jul00).

pH

Both interaction terms were significant indicating that changes through time were dependent on both section of the lagoon and individual sites. For Pea, Fanga'uta, Mouth, Mu'a, surface pH tended to oscillate around the value of 8 with the lowest reading in Survey 4 (Apr00), particularly at Fanga'uta and Mouth. In Fanga'uta Sites 9 and 10 show a similar pattern of decreasing pH between Surveys 3 and 4 (Jan00 and Apr00). In Fanga Kakau Sites 12, 13 and14 had lower surface pH than Sites 11 and 15. At Vaini, there was a tendency for surface pH to decrease over time. This was largely driven by a decline over surveys 4 and 5 (Apr00 and Jul00) at sites 26-28. Bottom pH showed similar patterns to surface pH, except for a very low pH at Site 21 during Survey 4 (Apr00).

The difference in pH between surface and bottom waters (S-B) was low almost everywhere. The exception was at S21 at Mu'a where during Survey 4 (Apr00) a large difference of 4 pH units was recorded between surface and bottom waters.

Clarity

Surface and bottom water clarity varied through time differently in the sections of the lagoon and at different sites (both interaction terms are significant) (Table 4, Appendix 7.2.1). In all sections of the lagoon water clarity tended to decrease significantly over the time of all surveys. This was especially noticeable at the Mouth section where water clarity dropped from 100cm to only 45cm between surveys 1 and 5 (Dec98 – Jul00). Pea was an exception, with surface turbidity remaining very poor and relatively constant at 30-40cm through the study. Bottom waters at Pea showed a marked increase in clarity during Survey 5.

Most sections of the lagoon had clearer surface than bottom waters over all surveys. Pea and Fanga'uta followed this general pattern except during Survey 5 (Jul00) where surface waters were recorded as more turbid than bottom waters (inverted clarity/turbidity gradient).

Depth

Pea, Fanga'uta and Mouth were the shallowest sections of the lagoon, being between 0.5 and 1.3m deep. The depth of these sections did not vary significantly over the study. Fanga Kakau, Mu'a and Vaini were generally deeper, with depths between 0.6 and 1.6m. There was a general tendency for their depths to decrease through time.

Faecal coliforms

There were elevated faecal coliform counts during February 1999 at all sections of the lagoon except at Mouth and Mu'a. Elevated counts were recorded at Fanga'uta S8, Fanga Kakau Sites 11, 13, 14 and 15, Pea Sites 2 and 5 and at Vaini Sites 26-28. In July 99, two additional sites in Vaini had relatively high faecal counts, these were S27, S30. In July 2000, Pea also had elevated Faecal coliforms.

Table 4: Summary of ANOVA results for Water Quality variables.

The significance level used was p = 0.05, where * indicates a significant effect and "NS" indicates no significant difference among the levels of the factor(s) being tested. Note that the results of an ANOVA for Faecal coliforms are not included here because of either no or unequal replication. These results were interpreted exclusively from graphs. S=Surface, B=Bottom, D=Difference.

Factor	Salinity			Temperature			DO			pH			Clarity			Depth
	S	B	D	S	B	D	S	B	D	S	B	D	S	B	D	-
Time	*	*	*	*	*	*	*	*	*	*	*	NS	*	*	*	*
Section	*	*	NS	NS	NS	*	NS	NS	*	*	*	NS	*	*	*	*
Site(Section)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Time * Section	*	*	NS	*	*	*	*	*	*	*	*	NS	*	*	*	*
Time * Site(Section)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

3.2 Water chemistry

Nitrate

Nitrate levels were elevated during February 1999 in all sections of the lagoon. Nitrate levels fluctuated greatly in Pea, Fanga'uta and Vaini throughout the study. Lowest levels were recorded at the Mouth and during Surveys 2 and 5 at Vaini. Nitrate levels were lowest for all sections of the lagoon at Survey 5 (Jul00).

Nitrite

Nitrite levels were highest in the western arm of the lagoon and at Vaini compared with the Mouth and Mu'a. Levels were highest in Feb99, Jul99 and Jan00 and declined over the study to low levels in Surveys 4 and 5 (Apr00 and Jul00).

Ammonia

Ammonia levels were generally low except at Mouth and Fanga'uta, where at Survey 3 (Jan00) levels were elevated to 25 and 14 μmol/L, respectively. Vaini and Mu'a had consistently low levels of ammonia throughout the study.

Dissolved Inorganic Nitrogen (DIN)

Levels were generally low, with fluctuations that varied between 0 and 24 μmols/L over the period of the study. In Fanga'uta, levels were higher during Feb 99 and Jan00. At the Mouth levels were highest during survey 3 (Jan00).

Phosphate

Phosphate levels are high during Survey 2 (Jul99) in all sections of the lagoon, with the highest readings in Pea, Fanga Kakau, Mouth, Mu'a and Vaini. Levels were low at this time in Fanga'uta.

Table 5: Summary of ANOVA results for Water Chemistry variables.

Note that these results are 2-Factor ANOVAs using the single reading obtained at each site to form 5 replicates for the analysis. The significance level used was p = 0.05, where * indicates a significant effect and "NS" indicates no significant difference among the levels of the factor(s) being tested.

Factor	Nitrate	Nitrite	Ammonia	DIN	Phosphate
Time	*	*	*	*	*
Section	NS	*	NS	NS	NS
Time * Section	NS	*	NS	NS	NS

3.3 Seagrasses communities

Halodule uninervis

Cover by *Halodule* varied between 0 and 40% during the study. Section and Time*Location(Section) were significant in the ANOVA for this seagrass (Table 6, Appendix 7.2.3). There are significant differences in cover by this seagrass in the different sections of the lagoon. The lowest cover by *Halodule* was found at the Mouth and Mu'a, with intermediate cover being recorded at Fanga'uta and Fanga Kakau. Highest cover by *Halodule* was recorded from Pea and Vaini throughout most of the study.

Halophila ovalis (Gk: Lover of salt)

Significant interactions were found between Time*Section and Time*Location(Section) (Table 6, Appendix 7.2.3). Cover by *Halophila* varied between 0 and 45% throughout the study. There was very low cover by *Halophila* at Mouth and Fanga Kakau throughout the study. In Pea and Vaini *Halophila* cover gradually increased over the period of the study, with temporarily elevated cover during Surveys 2 and 3 (Jul99 and Jan00) for Pea and Survey 2 for Vaini. In Mu'a the pattern was slightly different with very low cover during Survey 1 (Dec98), an increase by Survey 2 (Jul99) and a further increase between Surveys 4 and 5 (Apr-Jul00).

Total seagrass cover

Both interaction terms were significant for total seagrass cover which varied between 0 and 42% (Table 6 and Appendix 7.2.3). There is no change in cover by seagrasses at the Mouth throughout the study, with cover staying near zero. Pea has relatively high cover at 40% which does not vary much over the study. At Fanga'uta, Fanga Kakau, Mu'a and Vaini, cover by seagrasses tended to fluctuate slightly over the period of the study, dropping to near zero by Survey 5 (Jul00) (It is likely that the low cover recorded in Survey 5 are in error). Fanga'uta had the highest cover recorded Survey 3 (Jan 00).

Cover of seagrasses with epiphytes

Both interaction terms were significant and epiphyte cover reached up to 73% at Pea during this study (Table 6, Appendix 7.2.3). Cover by epiphyte is generally low at Mouth and Mu'a, where the highest cover is found during survey 1 at the Mouth and survey 3 at Mu'a respectively. At the sections of the lagoon there is a general trend of decreasing cover by epiphytes over the period of the study.

Caulerpa

Significant results were obtained for both interaction terms. *Caulerpa* is very rare in Pea. Every other section of the lagoon displays different patterns of cover by this algae. There is an overall decrease in cover by *Caulerpa* at Fanga'uta, Fanga Kakau and Vaini over the period of the study. Fanga'uta, Fanga Kakau and Vaini are very similar in terms of changes in *Caulerpa* cover through time. In Fanga'uta, cover of *Caulerpa* starts off at around 10%, increases to 25% by Survey 3 (Jan00), and then drops to zero in Survey 4 (Apr00) and Survey 5 (July00). In Fanga Kakau, cover begins at 5%, drops during Survey 2 (Jul99), increasing again in Survey 3 (Jan00), and then drops to zero in Surveys 4 and 5.

At Mouth and Mu'a there is an overall increase in cover by *Caulerpa*, with the highest cover for the study being recorded at the Mouth in Survey 5 (July 00).

Halimeda
Significant results were obtained for both interaction terms. *Halimeda* is not very common in the western arm of Fanga'uta lagoon. In the eastern 3 sections of the lagoon there is a slight tendency of increase by cover of *Halimeda* over the period of the study. The greatest change was observed in Vaini, between Surveys 4 (April 00) and Survey 5 (July 00) cover increased from 0 to 45%. Result from Survey 5 (July 00) at Vaini is suspected to be mis-identified with *Halodule*.

Table 6: Summary of ANOVA results for seagrass communities

Full results of analyses, with transformations if required, are available in Appendix 7.1. The significance level used was p = 0.05, where * indicates a significant effect and "NS" indicates no significant difference among the levels of the factor(s) being tested.

Factor	% Halodule	% Halophila	% Total seagrass	% Seagrass with epiphytes	% Caluerpa	% Halimeda
Time	NS	*	*	*	*	*
Section	*	*	*	*	NS	NS
Site(Section)	*	*	*	*	*	*
Time * Section	NS	*	*	*	*	*
Time * Site(Section)	*	*	*	*	*	*

3.4 Locations in the lagoon identified as subject to the most change

The five sites with the largest number of signals of change (Table 7) were:

Fanga'uta Site 8: In comparison to other sites of this section the differences in salinity, turbidity, faecal coliform, nitrate, DIN, phosphate, seagrass with epiphytes and Caulerpa increase at site 8 while DO decreases over the survey period.

Fanga Kakau Site 12: In comparison to other sites of this section the pH, ammonia, total seagrass with epiphytes and Caulerpa increases, while temperature gradient decrease and Halodule fluctuating during the this study.

Mu'a Site 21: Throughout the survey there were increases in salinity, DO, differences of pH, nitrite, clarity, as well as Halodule, Caulerpa and total seagrasses while decreases occur at the bottom of pH and depth.

Mu'a Site 24: In comparison to other sites of this section the Nitrite, phosphate, Halophila, total seagrass, epiphytes, and Caulerpa increases while clarity decrease over the survey period.

Vaini Site 27: In comparison to other sites of this section the pH, faecal coliform, nitrate, nitrite, Halophila, Caulerpa and Halimeda while epiphytes decrease over the survey period.

Table 7: Summary of Site-specific changes in variables through out this study.

A dot indicates that a variable changed significantly at least once through the 5 surveys at that site. Direction of change is not indicated here. Sites with a large number were examined more closely as potential problem areas for lagoon management.

SECTION	LOCATION	Surf Salinity	Bott Salinity	Δ Salinity	Surf Temp	Bott Temp	Δ Temp	Surf DO	Bott DO	Δ DO	Surf pH	Bott pH	Δ pH	Surf Turbidity	Bott Turbidity	Δ Turbidity	Depth	Faecal Coliforms	Nitrate	Nitrite	Ammonia	DIN	Phosphate	Halodule	Halophila	Total Seagrass	% Seagrass epiphytes	Caulerpa	Halimeda	Water Qual signals	Water Chem signals	Seagrass signals	Total signals
Pea	S1			●			●			●														●	●	●	●			3		4	7
	S2						●								●	●		●					●		●	●				4	1	2	7
	S3						●			●				●	●	●							●						●	5	1	1	7
	S4									●				●	●	●								●	●	●				4		3	7
	S5						●			●				●	●	●		●	●								●			6	1	1	8
Fanga'uta	S6															●									●	●		●		1		3	4
	S7															●			●			●	●		●	●	●			1	3	3	7
	S8			●				●	●							●		●	●			●	●				●	●		5	3	2	10
	S9	●													●				●					●	●	●		●		2	1	4	7
	S10	●													●									●	●	●				2		3	5
Fanga Kakau	S11																●	●						●		●	●			2		3	5
	S12						●				●	●					●	●			●			●		●	●	●		5	1	4	10
	S13										●	●						●				●		●		●		●		3	1	3	7
	S14										●	●					●	●										●	●	4		2	6
	S15	●																●								●			●	2		2	4
Mouth	S16							●	●			●		●	●						●	●						●		5	2	1	8
	S17													●	●								●					●		2	1	1	4
	S18													●	●													●	●	2		2	4
	S19							●		●	●	●		●		●	●										●			7		1	8
	S20							●	●		●	●		●		●	●						●					●		7	1	1	9
Mu'a	S21			●						●		●	●	●	●		●			●				●		●		●		7	1	3	11
	S22																		●	●								●	●		2	2	4

	S23							●	●											●								●		2	1	1	4
	S24						●								●		●			●			●		●	●	●	●		3	2	4	9
	S25									●					●					●				●	●				●	2	1	3	6
Vaini	S26			●							●	●						●	●					●		●				4	1	2	7
	S27										●	●						●	●	●					●		●	●	●	3	2	4	9
	S28										●	●					●	●						●		●		●	●	4		4	8
	S29																								●	●	●		●			4	4
	S30																●	●						●	●	●	●	●	●	2		6	8

3.5 Significant events in the lagoon identified during this study

The most important changes occurred at the lagoon over the whole period of the study for each of the variables were;

- There were problems with fish kill and a lot of foam during 24-26 November 1998 at the Fanga'uta Section of the lagoon.
- Site 16 at the Mouth decreased dramatically between Survey 1(Dec98) and Survey 2 (Jul99) during all subsequent Surveys (Table 8)
- Difference in surface and bottom clarity turned to a negative gradient during Survey 5 (Jul00), in Pea sites 2-5 and Fanga'uta sites 6-8.
- The pH dropped to a very low level during Survey 3 (Jan00) at Fanga Kakau at Sites 12-14 and during Survey 4 (Apr00) at Mu'a site 21
- Faecal coliforms: was very high in Feb 99 at the Pea Section from all sites, and at Fanga'uta, Site 8, and all sites at Fanga Kakau and at Vaini, Site 26 to Site 28. The highest coliform count was achieved at the Vaini Section during Survey 2 (Jul99) from Site S27 and Site30.
- There were high levels of nitrate in Feb99 from all Sections of the lagoon. At Vaini during Surveys 3 (Jan00) and Survey 4 (Apr00) were also high and was driven by Sites 26 and 27. During Survey 4 (Apr00) at Fanga'uta was also achieving high nitrate level and was driven by Site 9. The level was also high at Mu'a during Survey 2 (Jul99) at Site 22.
- There was a generally high nitrite level from Pea, Fanga'uta and Vaini.
- There was a significant increase in the ammonia level during Survey 3 (Jan00) at the Mouth Section at Site 16.
- There was an elevated Dissolve Inorganic Nitrogen (DIN) at the Mouth Section at Site 16 and at the Fanga'uta section during Survey 3 (Jan00).
- A significant elevation of phosphate levels were resulted from Pea at sites 3 – 5, at Fanga Kakau all sites, at Mouth at site 16 – 18, and Mu'a at sites 21 and site 24 and at Vaini at Sites 26 and 29 during Survey 2 (Jul99).

Table 8: Sites at which major events occurred in terms of elevated nutrients and changes in seagrass communities

	Pea	Fanga'uta	Fanga Kakau	Mouth	Mu'a	Vaini
Clarity	2,3,4,5	9,10		16 to 20	21, 24, 25	
Faecal	2, 5	8,	11-15			26-28, 30
Nitrate	5	7-9			22	26, 27
Phosphate	2,3	7,8		17, 20	24	
Total seagrass	1,2,4	6,7,9,10	11-13,15		21,24,25	26,28-30
Epiphytes	1,5	7,8	11,12	19	24	27,29,30

4. Discussion

4.1 General overall patterns of change

It appears that the lagoon is divided into two main regions. The western region made up of Pea, FU, FK show signs of damage and increasing deterioration, with increases in nutrients, faecal coliforms, turbidity and salinity. This suggests problems with drainage over commercial and domestic areas of Nuku'alofa. Coliform problems could be coming from over flows with septic tanks and pig pens at Popua.

In the eastern region, including sections of Mu'a and Vaini, there were evidence of a slight recovery in the lagoon, with clarity, as well as Halodule, Caulerpa and total seagrasses.

4.2 Comparison with other studies since 1981

In 1981 water clarity in the lagoon varied between 0.3 and 1.1m in Pea (Zann, 1984). By 1987/9, Naidu et al. (1991) recorded an increase to 2.5m+ in the same section, but by 1992, Aalbersberg et al (1992) had shown the water clarity in this section of the lagoon had dropped to a maximum of 0.5m. In July 2000 in this study, the maximum water clarity at Pea was 0.42m. This overall decrease in clarity was worst in Pea, but also occurred in other sections of the lagoon. It is clear that problems with clarity have been going on for a long time.

There has been a tendency for salinity and pH to increase in all sections of the lagoon since studies from 1981 to date. A minimum of 25 ppth in Pea to a maximum of 40ppth in Mu'a was recorded and a minimum of 6 pH to 9.13 pH in Vaini. The low reading in salinity during this study may be due to a high rainfall compared to past years.

The overall results of Dissolved Oxygen (DO) have increased from 7 mg/L in Vaini (Naidu, et.al, 1991) to 11.62 in Mu'a of this study. This increase of DO along with the increase in clarity and total seagrasses suggest that the lagoon on the eastern side is recovering.

For all sections of the lagoon, depth resulted in a decrease over time. In studies by Zann (1981), depth was recorded at 6 m in Mu'a and further decreased in 1992 to 1.5 m (Aalbersberg, et.al, 1992). The depth from this study have additionally seen a significant drop in depth to 0.27 m. This suggests an accumulation of sediments over time from runoff, soil erosion or an increase in decaying of organic matter.

Faecal coliforms have increased in all sections of the lagoon since 1992 to date. This could be due to an increase in urban development.

There is a significant increase in nutrient levels (nitrate, nitrite, ammonia and phosphate) from studies carried out in1981-2000. However, results found in Naidu,et.al (1991) was disregarded due to it being incomprehensible compared to Zann (1981) and Aalbersberg, et.al (1992).

Table 9: Summary of maximum and minimum values and ANZECC standards obtained in the major studies in Fanga'uta and Erakor Lagoons.

		Fanga'uta Lagoon				Vanuatu	Australian Standards		
		1981 (Zann)	1988-1989 (Naidu et al 1991)	1992 (Aalbersberg et al 1992)	This study	Erakor 1998 (Kaly, 1998)	AS Recreation (ANZECC 1992	AS Seafood (ANZECC 1992)	AS Blooms (ANZECC 1992)
Clarity (m)	Pea	0.3-1.1	2.5m+	0.4-0.5m	0.28-0.42				
	Fanga'uta	-	1.5+-3.2	0.6-1+	0.28-0.52				
	Fanga Kakau	1.5-2.0	2.8+-3.2+	1+	0.3-0.7m	2.5-3.3	-	-	-
	Mu'a	1.5-2.0m	6+	1.5+	0.38-0.68m				
	Vaini	1.5-1.8+m	6+	0.5-1.0+	0.47-0.65m				
Salinity (ppth)	Pea	25	27-30	30-33	12.29-36ppt				
	Fanga'uta	-	28-34	34-36	16.3-37				
	Fanga Kakau	31	31-33	35-38	15.7-34.7	28.5-30.9	-	-	-
	Mu'a	33	31-34	34	20.6-40				
	Vaini	27	32-35	20	15-35				
DO (mg/l)	Pea	-	07-Sep	6.2-6.4	0.1-10.56				
	Fanga'uta	-	7.2-8	6.1-6.6	0.21-9.89				
	Fanga Kakau	-	7.2-9.1	6.2-6.3	6.16-11.39	-	-	-	-
	Mu'a	-	9	6-6.2	0-11.62				
	Vaini	-	7	6-6.4	0-11.27				
pH	Pea	-	7.6-8	7.7-7.9	6.44-9.01				
	Fanga'uta	-	7.5-8.5	7.7-7.9	6.56-8.83				
	Fanga Kakau	-	7.5-8	7.5-7.9	2.44-8.9	-	-	-	-
	Mu'a	-	7.8-8	7.9-8	2.36-8.79				
	Vaini	-	6-7.8	8-8.2	6.26-9.13				
Depth (m)	Pea	2.5	2.5	0.5-0.7	0.44-1.35				
	Fanga'uta	-	-	0.6-1.0	0.4-1.63				
	Fanga Kakau	3.2	3.2	0.8-2.0	0.4-4.1		-	-	-
	Mu'a	6	6	1.3-1.5	0.27-4.2				
	Vaini	2.8	2.8	1	0.42-2.5				
Faceal (colonies per 100ml)	Pea	-	-	0-7	0-50				
	Fanga'uta	-	-	0	0-240				
	Fanga Kakau	-	-	0	0-60	0-100	150	14	-
	Mu'a	-	-	0	0-58				
	Vaini	-	-	0-240	0-200				
Nitrate (ug/l)	Pea	0.11-0.17	4,800-8,800	19-52	0-466				
	Fanga'uta	-	4,400-8,800	14-22	0-489				
	Fanga Kakau	0.11-0.19	2,000-12,800	16-30	0-350.3	0-2,900	-	-	100
	Mu'a	0.4-0.7	6,200-7,500	6-8	0-252.96				
	Vaini	0.97-1.02	30-7,500	133-317	0-520.8				
Nitrite (ug/l)	Pea	-	50-80	0-2	0-34.04				
	Fanga'uta	-	30-70	0-2	0-27.14				
	Fanga Kakau	-	20-60	2-5	0-26.32	-	-	-	-
	Mu'a	-	0-70	2-5	0-9.66				
	Vaini	-	0-30	2-43	0-36.34				
Ammonia (ug/l)	Pea	-	1,100->3,000	85-190	2.5-237				
	Fanga'uta	-	1,000-1,800	<70-110	0-536				
	Fanga Kakau	-	1000-1800	<70	0-313	-	-	-	-
	Mu'a	-	1,000-1,500	<70	0-211				
	Vaini	-	1,100-1,600	<70	0-98				

Phosphate (ug/l)	Pea	0.08-0.12	240-600	5-25	0-4,291				
	Fanga'uta	-	240-2,000	<5-25	0-762				
	Fanga Kakau	0-0.05	200-3,300	2-21	0-4,305	0-190	-	-	15
	Mu'a	0.09-0.17	180-500	2-<5	0-3,365				
	Vaini	0.04-0.05	620->2,000	7-18	0-2,852				

4.3 Comparison with Erakor Lagoons, Vanuatu

The Erakor Lagoon system in Vanuatu is the most similar lagoon in the Pacific in which we can compare Fanga'uta Lagoon, and it appears to be in much better condition. Erakor (2.5 m – 3.3 m) was found to be much clearer than Fanga'uta (1.5 m – 2.0 m) since the very first study in 1981. The Salinity level and faecal coliform counts recorded tended to be much lower in Erakor than that of Fanga'uta Lagoon. Nitrate levels in Fanga'uta are much lower with higher phosphate levels than that of Erakor.

4.4 International standards for water quality

The faecal coliform counts (up to 240 colonies per 100 ml), nitrate levels (up to 520 μg/L) and phosphate levels (4,305 μg/L) have exceeded the international Australian standards for recreational use, seafood and algal blooms (ANZECC, 1992).

4.5 Problems with the data

Several problems were identified in the data collected. These are being rectified for future monitoring, but need to be identified for proper interpretation of results here. They are:

- The seagrass data during Survey 5 in Vaini are suspect. No Halimeda was recorded previously in Vaini, but very high % cover was recorded during Survey 5. Also the cover by seagrass dropped dramatically in this section of the lagoon at this time. It is possible that the species were misidentified.
- Water quality data collected during Survey 1 (Dec 98) were disregarded in analyses and interpretation (though they are shown in the graphs in Appendix 7.2). There was a problem with the probes being used at that time which may have affected readings on salinity, temperature, DO and pH. This was rectified by Survey 2.
- There were problems with identifying individual species of algae. Originally four species of Caulerpa were identified and censused. These were lumped in later surveys.
- There were problems with some survey techniques. It was important that divers and anchors should not interfere with water samples for nutrients and turbidity. It is not clear that this protocol was always observed.
- The depth readings may have been affected by inaccurate relocation of sites between surveys.
- There were problems and inaccuracies associated with censusing seagrasses in-situ. This was due to the generally poor visibility.

4.6 Conclusions

1. Worst times in lagoon were in Nov/Dec. 98 – Feb. 99 and it appeared to have improved a bit since than.
2. General trend for decreasing clarity not only in this study, but since all previous studies since 1981.

3. Levels of nitrate, phosphate & faecal coliforms have all exceeded Australian standards f or seafood, recreational use and risk of algal blooms, at least at one time during this study.
4. The eastern side of the lagoon is generally in better condition than the west. Sites with the biggest problems and changes are sites 8,12,21,24 and 27. Of these sites 8 and 12 showed the greatest deterioration during the study. Sites 21,24,and 27 showed the greatest changes, but some of these were improvements.
5. The most problems with high nutrient levels were recorded at the following sites:
   - Pea – sites 2 & 5
   - Fanga'uta – sites 7, 8 & 9
   - Fanga Kakau – sites 11 – 15
   - Mouth – sites 16 – 20
   - Mu'a – sites 21, 24 & 25
   - Vaini – sites 26 & 27

4.7 Recommendations

7. It is recommended that a management plan for the lagoon be developed and implemented to improve conditions and ensure sustainable use of the area.
8. Major problems tended to be common in the western side of the lagoon in Pea, Fanga'uta and Fanga Kakau. Look for sources of problem. Chasing up sewage sources in urban and industrial areas would be worth while.
9. Any site identified as unusual or with high readings of nutrients or poor conditions should be investigated further. At this stage, this includes Fanga'uta S8 and FK S12. These sites have indicated possible problems.
10. Faecal coliforms at Vaini require attention – it is recommended that sources be identified.
11. Monitoring should continue indefinitely to get long term data on change and seasonal patterns. In addition to identifying problem areas.
12. Surveys should be run consistently during the months of Jan, April, July and October of each year, at least initially to investigate seasonal patterns. Quality of data collection needs to be improved.
6. Seafoods should be tested immediately to see if they are fit for human consumption & further recommendations be made to the public after that.
7. The public needs to be informed about the importance of international standards for recreational use and seafood consumption, and the fact that conditions in the lagoon have exceeded the allowable levels.

5. Acknowledgments

This study was funded by AusAID through the TEMPP Project (1997-2001). The following Ministries and NGO supported this work and provided personnel for the team: Ministry of Lands, Survey and Natural Resources, Ministry of Health, Tonga Visitors Bureau, Tonga Water Board, Ministry of Fisheries, Ministry of Agriculture & Forestry (Vaini Division), Ministry of Marine & Ports, Ministry of Works. John Hibberd and Sylvia Hibberd supported all aspects of logistics for the programme. John Morrison provided training, assistance with water chemistry and past information on the lagoon. The following people assisted with parts of the monitoring work: 'Akapei Vailea (Geology), Timote Kaufusi (Tonga Water Board), Fine Tutu'u Lao (EPACS), Kasaline 'Ahoafi (EPACS), Havila Taukolo (MOW), Viliami Manu (Marine & Ports), Viliami Manu (Agriculture), Telefoni Pulu (MOW), Uepi Lea (MOH), Netatua Prescott (EPACS), Paula Taufa (EPACS). The EPACS labourers assisted with maintenance of equipment. Thanks to Sally Perry for assistance with data interpretation and some aspects of report writing.

6. Literature cited

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7. Appendices

7.1 ANOVA Results for all variables analysed

The significance level used was p = 0.05, where * indicates a significant effect and "NS" indicates no significant difference among the levels of the factor(s) being tested.

	DF Effect	MS	DF Error	MS Error	F	p-level	Sig
Surface Salinity - no transform, variances heterogeneous							
Time	3	3025.20	72	5.22	579.71	0.00	*
Section	5	780.60	24	9.12	85.57	0.00	*
Location(Section)	24	9.12	480	0.16	56.71	0.00	*
T*S	15	51.66	72	5.22	9.90	0.00	*
T*L(S)	72	5.22	480	0.16	32.44	0.00	*
Bottom Salinity - no transform, variances heterogeneous							
Time	3	2778.72	72	4.51	615.87	0.00	*
Section	5	759.27	24	7.70	98.60	0.00	*
Location(Section)	24	7.70	480	0.13	58.30	0.00	*
T*S	15	59.16	72	4.51	13.11	0.00	*
T*L(S)	72	4.51	480	0.13	34.16	0.00	*
Difference in Salinity (Bottom-Surface - if +ve, surface waters are less saline) - no transform, heterogeneous							
Time	3	6.84	72	0.94	7.26	0.00	*
Section	5	1.02	24	0.96	1.05	0.41	NS
Location(Section)	24	0.96	480	0.30	3.25	0.00	*
T*S	15	0.91	72	0.94	0.97	0.49	NS
T*L(S)	72	0.94	480	0.30	3.18	0.00	*
Surface Temperature - no transform, variances heterogeneous							
Time	3	1512.95	72	1.51	999.87	0.00	*
Section	5	6.12	24	3.34	1.83	0.14	NS
Location(Section)	24	3.34	480	0.02	196.39	0.00	*
T*S	15	19.22	72	1.51	12.70	0.00	*
T*L(S)	72	1.51	480	0.02	88.96	0.00	*
Bottom Temperature - no transform, variances heterogeneous							
Time	3	1478.97	72	1.42	1043.44	0.00	*
Section	5	6.76	24	3.38	2.00	0.12	NS
Location(Section)	24	3.38	480	0.02	217.19	0.00	*
T*S	15	18.31	72	1.42	12.92	0.00	*
T*L(S)	72	1.42	480	0.02	90.96	0.00	*
Difference in Temperature (Surface - Bottom, if +ve, surface is warmer) - no transform, variances heterogeneous							
Time	3	1.64	72	0.12	14.16	0.00	*
Section	5	0.43	24	0.10	4.47	0.01	*
Location(Section)	24	0.10	480	0.02	4.64	0.00	*
T*S	15	0.31	72	0.12	2.67	0.00	*
T*L(S)	72	0.12	480	0.02	5.65	0.00	*
Surface DO - no transform, variances heterogeneous							
Time	3	49.60	72	3.52	14.08	0.00	*
Section	5	3.90	24	8.33	0.47	0.80	NS
Location(Section)	24	8.33	480	0.24	34.57	0.00	*
T*S	15	14.31	72	3.52	4.06	0.00	*
T*L(S)	72	3.52	480	0.24	14.61	0.00	*
Bottom DO - no transform, variances heterogeneous							
Time	3	55.74	72	3.45	16.17	0.00	*
Section	5	13.30	24	7.06	1.88	0.13	NS
Location(Section)	24	7.06	480	0.36	19.63	0.00	*
T*S	15	10.10	72	3.45	2.93	0.00	*
T*L(S)	72	3.45	480	0.36	9.57	0.00	*

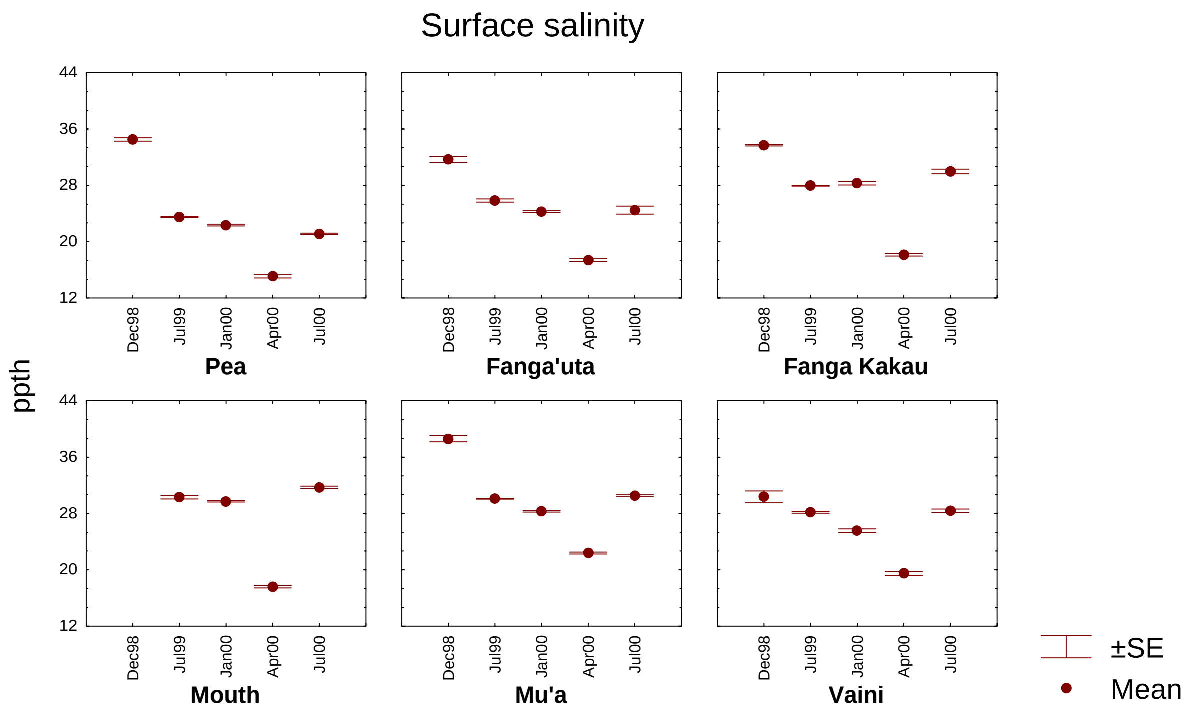
Difference in DO (Surface-Bottom, if +ve, surface has more oxygen) - no transform, variances heterogeneous							
Time	3	3.60	72	1.11	3.26	0.03	*
Section	5	6.21	24	1.33	4.66	0.00	*
Location(Section)	24	1.33	480	0.40	3.32	0.00	*
T*S	15	2.54	72	1.11	2.29	0.01	*
T*L(S)	72	1.11	480	0.40	2.75	0.00	*
Surface pH - no transform, variances heterogeneous							
Time	3	9.01	72	2.80	3.22	0.03	*
Section	5	13.24	24	2.10	6.30	0.00	*
Location(Section)	24	2.10	480	0.08	27.51	0.00	*
T*S	15	11.15	72	2.80	3.99	0.00	*
T*L(S)	72	2.80	480	0.08	36.61	0.00	*
Bottom pH - no transform, variances heterogeneous							
Time	3	14.93	72	3.95	3.78	0.01	*
Section	5	13.99	24	2.96	4.73	0.00	*
Location(Section)	24	2.96	480	0.11	26.50	0.00	*
T*S	15	12.07	72	3.95	3.05	0.00	*
T*L(S)	72	3.95	480	0.11	35.44	0.00	*
Difference in pH (surface-Bottom, if +ve, surface is more alkaline) - no transform, variances heterogeneous							
Time	3	1.44	72	1.13	1.28	0.29	NS
Section	5	1.11	24	1.17	0.95	0.47	NS
Location(Section)	24	1.17	480	0.08	15.48	0.00	*
T*S	15	0.83	72	1.13	0.73	0.74	NS
T*L(S)	72	1.13	480	0.08	14.90	0.00	*
Surface Turbidity - no transform, variances heterogeneous							
Time	4	8521.33	96	294.11	28.97	0.00	*
Section	5	28649.92	24	635.46	45.09	0.00	*
Location(Section)	24	635.46	600	31.96	19.88	0.00	*
T*S	20	1513.50	96	294.11	5.15	0.00	*
T*L(S)	96	294.11	600	31.96	9.20	0.00	*
Bottom Turbidity - no transform, variances heterogeneous							
Time	4	6214.04	96	340.97	18.22	0.00	*
Section	5	21881.29	24	764.74	28.61	0.00	*
Location(Section)	24	764.74	600	57.61	13.27	0.00	*
T*S	20	2387.88	96	340.97	7.00	0.00	*
T*L(S)	96	340.97	600	57.61	5.92	0.00	*
Difference in Turbidity (Surface-Bottom, if +ve, surface waters are clearer) - no transform, variances heterogeneous							
Time	4	2459.07	96	95.57	25.73	0.00	*
Section	5	1271.28	24	77.02	16.51	0.00	*
Location(Section)	24	77.02	600	39.15	1.97	0.00	*
T*S	20	419.37	96	95.57	4.39	0.00	*
T*L(S)	96	95.57	600	39.15	2.44	0.00	*
Depth - no transform, variances heterogeneous							
Time	4	6.11	96	0.55	11.15	0.00	*
Section	5	6.11	24	2.25	2.71	0.04	*
Location(Section)	24	2.25	600	0.06	37.63	0.00	*
T*S	20	1.13	96	0.55	2.06	0.01	*
T*L(S)	96	0.55	600	0.06	9.14	0.00	*
Nitrate - transformed sqrt(x+1)							
Time	4	7.31	120	0.11	68.18	0.00	*
Section	5	0.17	120	0.11	1.63	0.16	NS
T*S	20	0.12	120	0.11	1.16	0.30	NS
Nitrite							
Time	4	0.39	120	0.01	27.22	0.00	*
Section	5	0.09	120	0.01	6.39	0.00	*
T*S	20	0.03	120	0.01	2.02	0.01	*

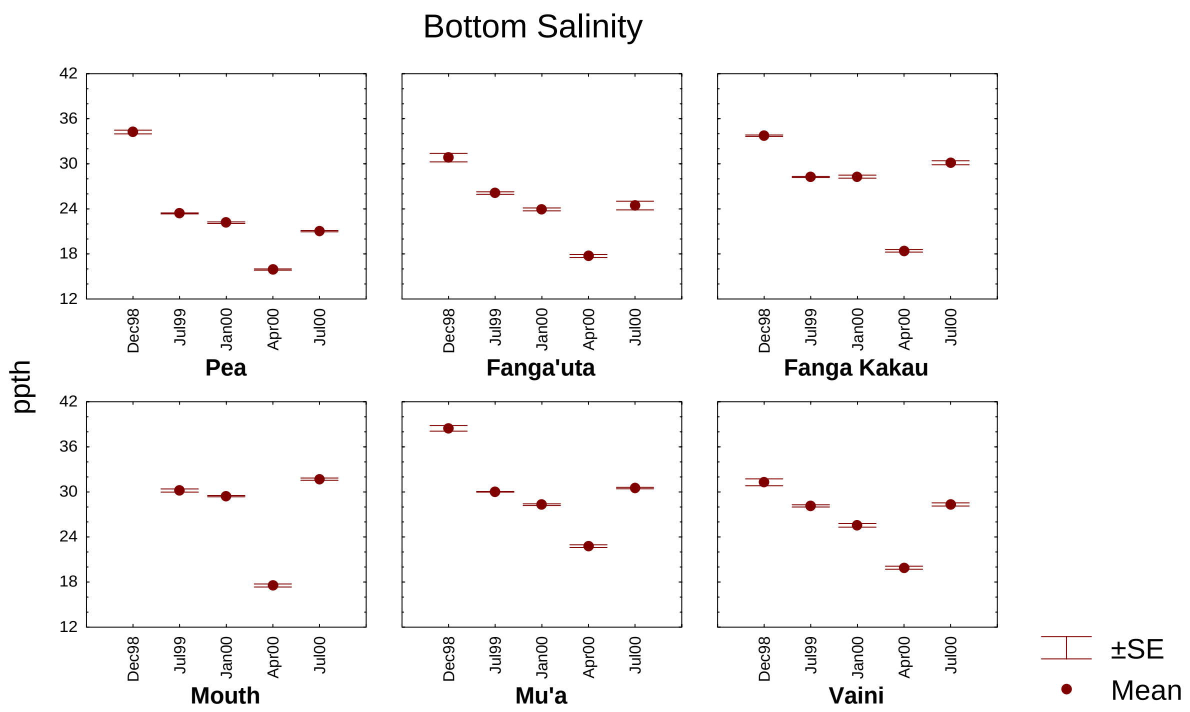
Ammonia - no transformation, variances heterogeneous							
Time	4	253.53	120	65.40	3.88	0.01	*
Section	5	59.22	120	65.40	0.91	0.48	NS
T*S	20	71.55	120	65.40	1.09	0.36	NS
Dissolved Inorganic Nitrogen (DIN) - no transformation, variances heterogeneous							
Time	4	248.68	120	25.70	9.68	0.00	*
Section	5	34.92	120	25.70	1.36	0.24	NS
T*S	20	30.11	120	25.70	1.17	0.29	NS
Phosphate - no transformation, variances heterogeneous							
Time	4	959.77	120	40.17	23.89	0.00	*
Section	5	49.74	120	40.17	1.24	0.30	NS
T*S	20	63.15	120	40.17	1.57	0.07	NS
Halodule - transformed ln(x+1)							
Time	4	17.96	96	10.30	1.74	0.15	NS
Section	5	131.94	24	27.15	4.86	0.00	*
Location(Section)	24	27.15	1350	0.99	27.31	0.00	*
T*S	20	13.13	96	10.30	1.27	0.22	NS
T*L(S)	96	10.30	1350	0.99	10.37	0.00	*
Halophila ovalis - transformed ln(x+1)							
Time	4	88.97	96	8.00	11.12	0.00	*
Section	5	70.34	24	18.31	3.84	0.01	*
Location(Section)	24	18.31	1350	0.75	24.32	0.00	*
T*S	20	13.29	96	8.00	1.66	0.05	NS
T*L(S)	96	8.00	1350	0.75	10.63	0.00	*
All Seagrasses - no transform, variances heterogeneous							
Time	4	35700.49	96	1609.98	22.17	0.00	*
Section	5	11785.33	24	2822.03	4.18	0.01	*
Location(Section)	24	2822.03	1350	137.69	20.50	0.00	*
T*S	20	4685.89	96	1609.98	2.91	0.00	*
T*L(S)	96	1609.98	1350	137.69	11.69	0.00	*
Epiphytes on Seagrasses - transformed to ln(x+1), variances heterogeneous							
Time	4	121.01	96	9.91	12.21	0.00	*
Section	5	96.07	24	14.36	6.69	0.00	*
Location(Section)	24	14.36	1350	1.43	10.05	0.00	*
T*S	20	19.73	96	9.91	1.99	0.01	*
T*L(S)	96	9.91	1350	1.43	6.94	0.00	*
Caulerpa spp. - no transform, variances heterogeneous							
Time	4	7445.79	96	2693.96	2.76	0.03	*
Section	5	9413.58	24	5342.77	1.76	0.16	NS
Location(Section)	24	5342.77	1350	314.46	16.99	0.00	*
T*S	20	7092.16	96	2693.96	2.63	0.00	*
T*L(S)	96	2693.96	1350	314.46	8.57	0.00	*
Halimeda spp. - transformed to ln(x+1), variances heterogeneous							
Time	4	17.72	96	4.93	3.60	0.01	*
Section	5	64.98	24	23.40	2.78	0.04	*
Location(Section)	24	23.40	1350	0.56	42.11	0.00	*
T*S	20	13.12	96	4.93	2.66	0.00	*
T*L(S)	96	4.93	1350	0.56	8.86	0.00	*

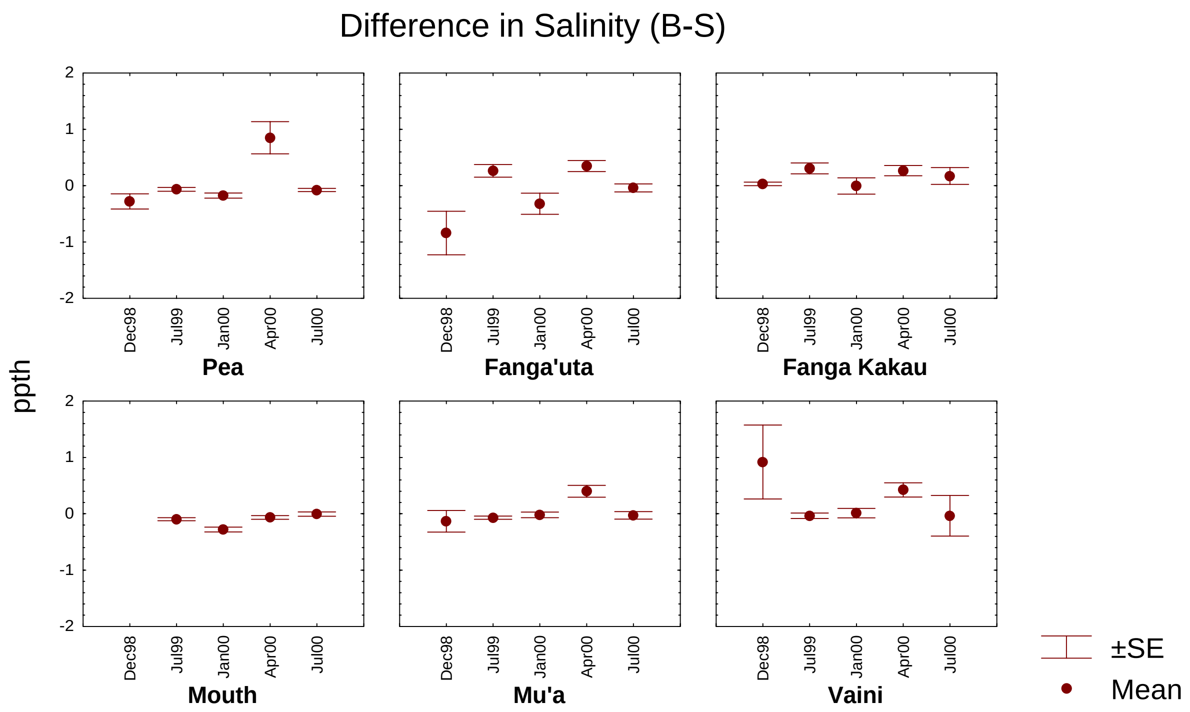
7.2 Graphs of Time vs Section of the lagoon for all variables analysed

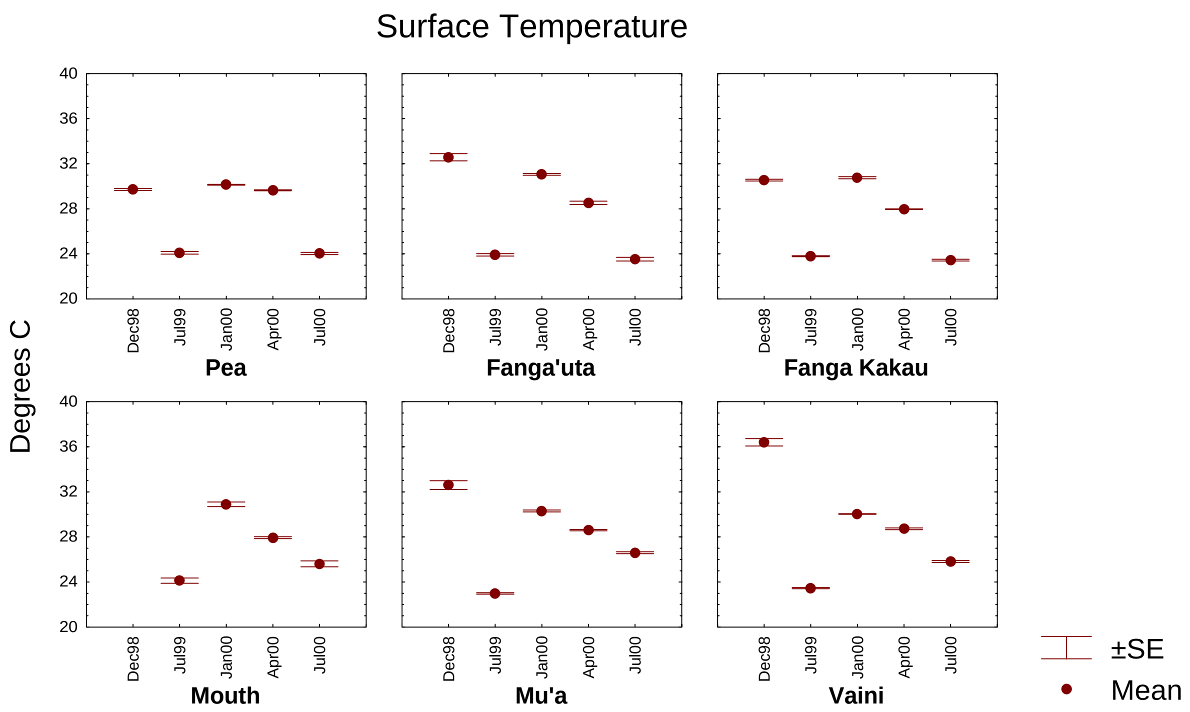
For all graphs, values plotted are means of values for each Survey time obtained across all Locations (Sites 1-30) separated for each Section of the lagoon +/-SE. Times are: Survey1=Dec98; Feb99; Survey2=July99; Survey3=Jan00, Survey4=April00; Survey5=July00. Note that data for water quality variables collected during Survey 1 in Dec 98 were ignored in analyses and not interpreted because of known problems with the sampling gear.

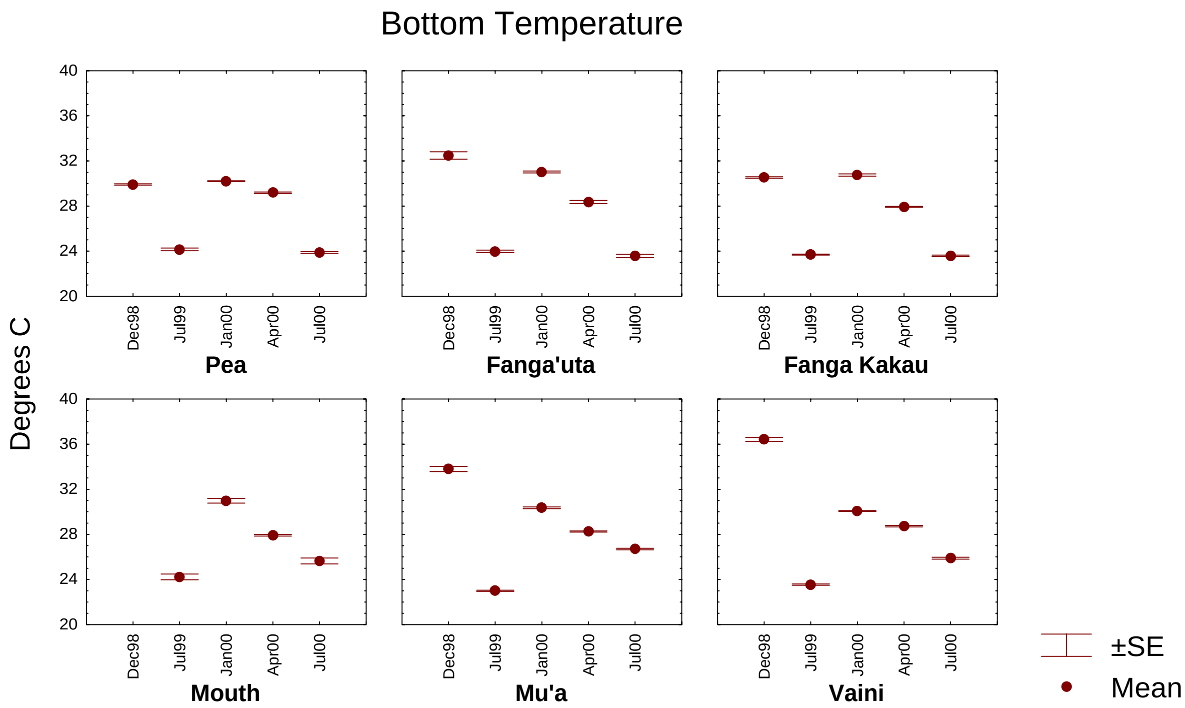
7.2.1 Water Quality variables

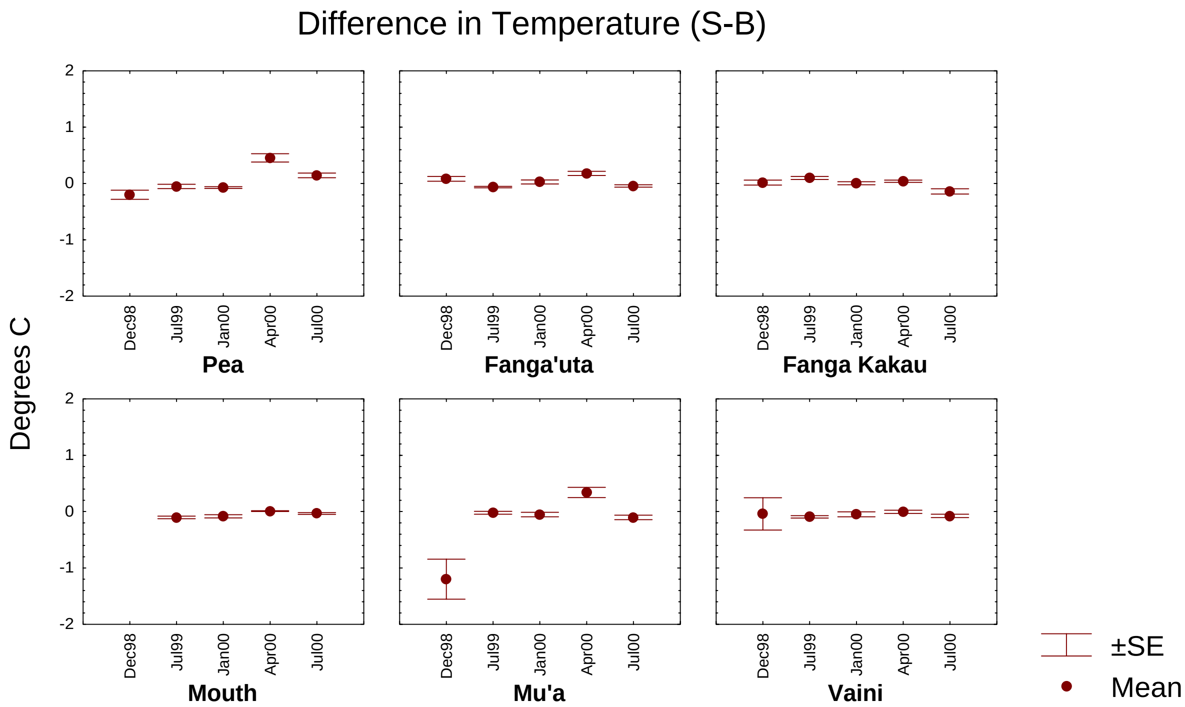




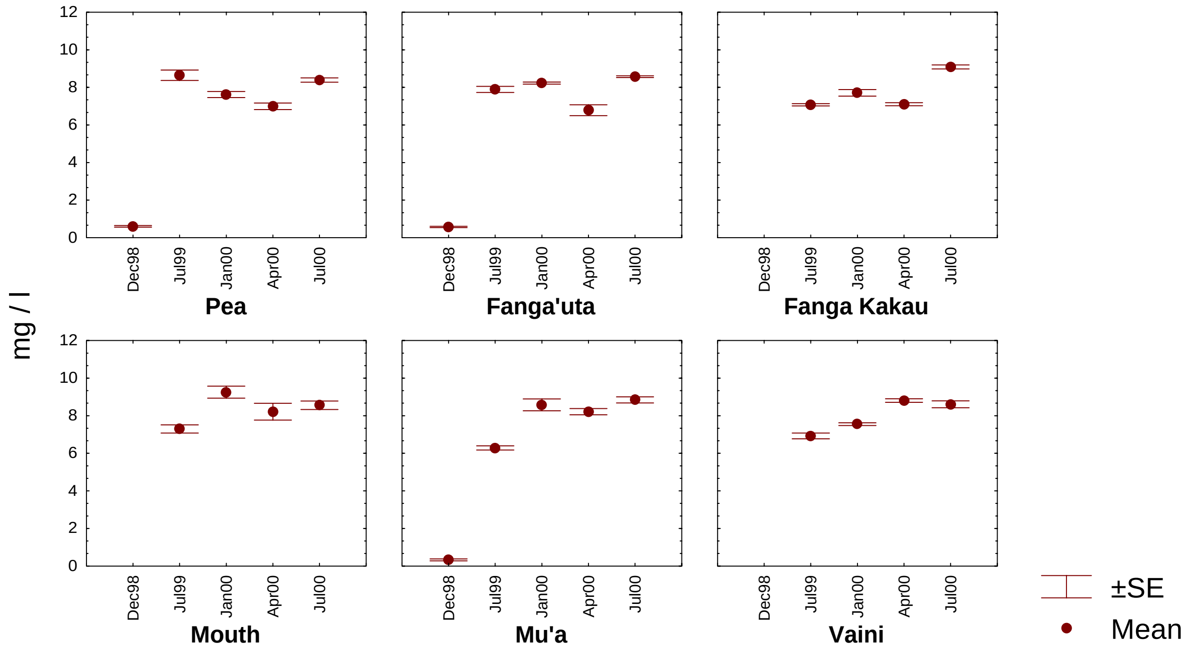

Difference in Salinity (B-S)
ppth
2
1
0
-1
-2
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean


Surface Temperature
Degrees C
40
36
32
28
24
20
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

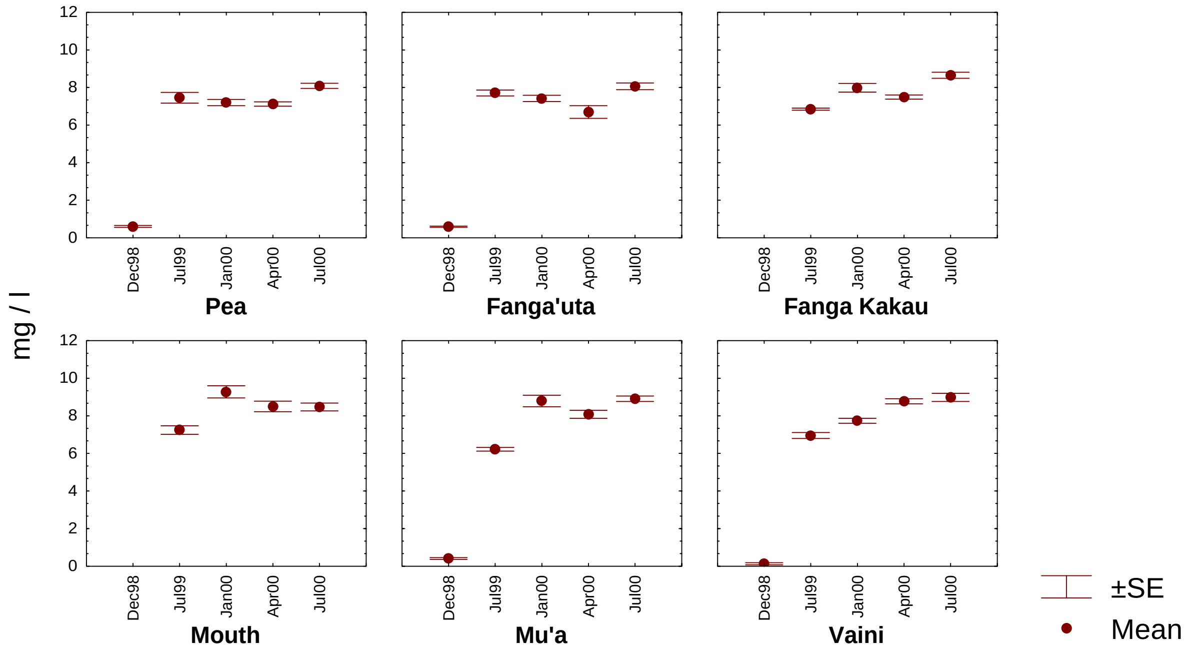

Bottom Temperature
Degrees C
40
36
32
28
24
20
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

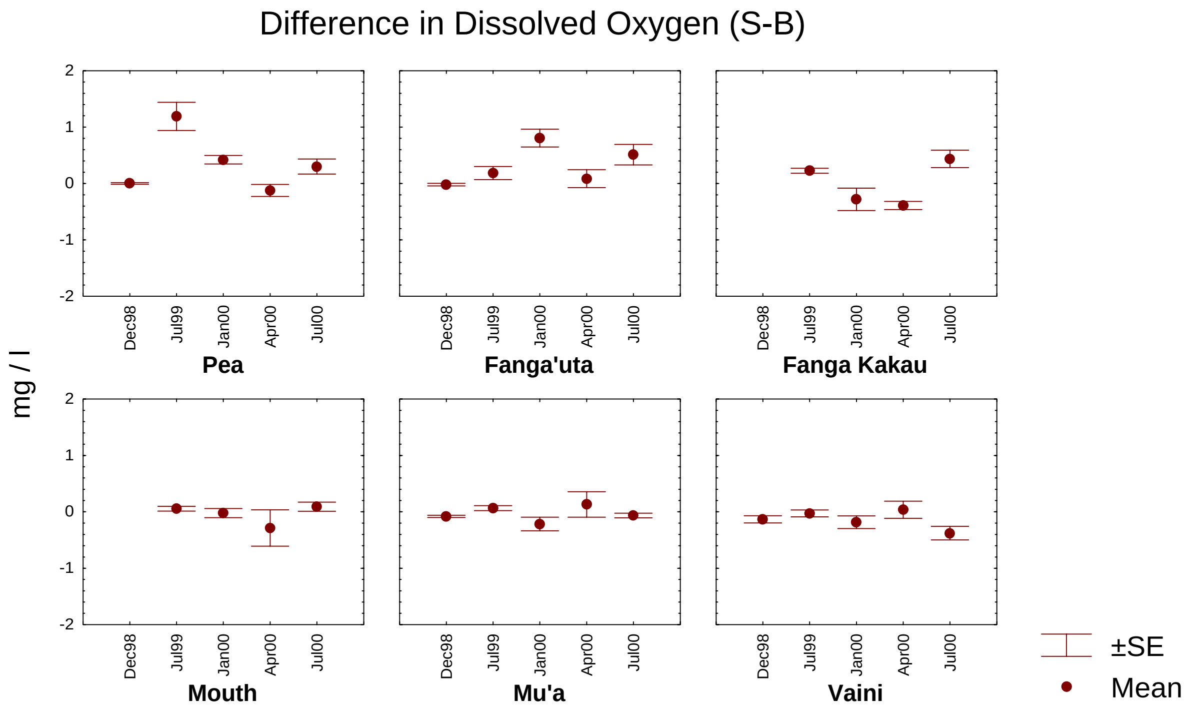

Difference in Temperature (S-B)
Degrees C
2
1
0
-1
-2
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

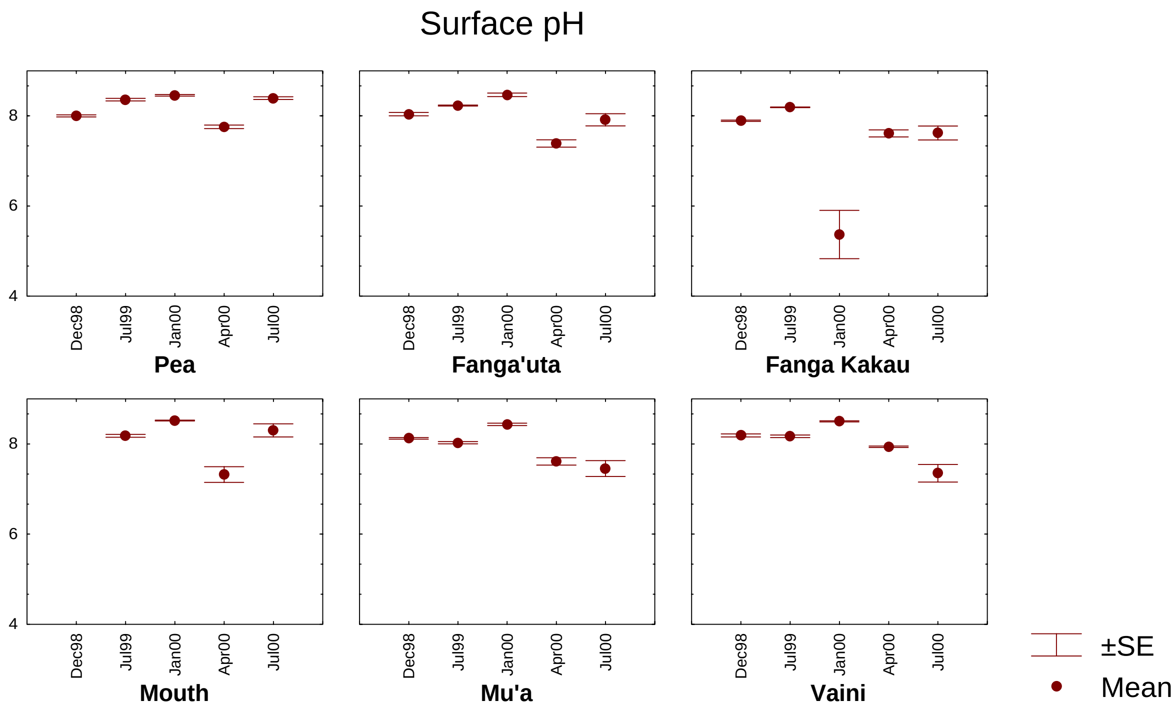
Surface Dissolved Oxygen (DO)

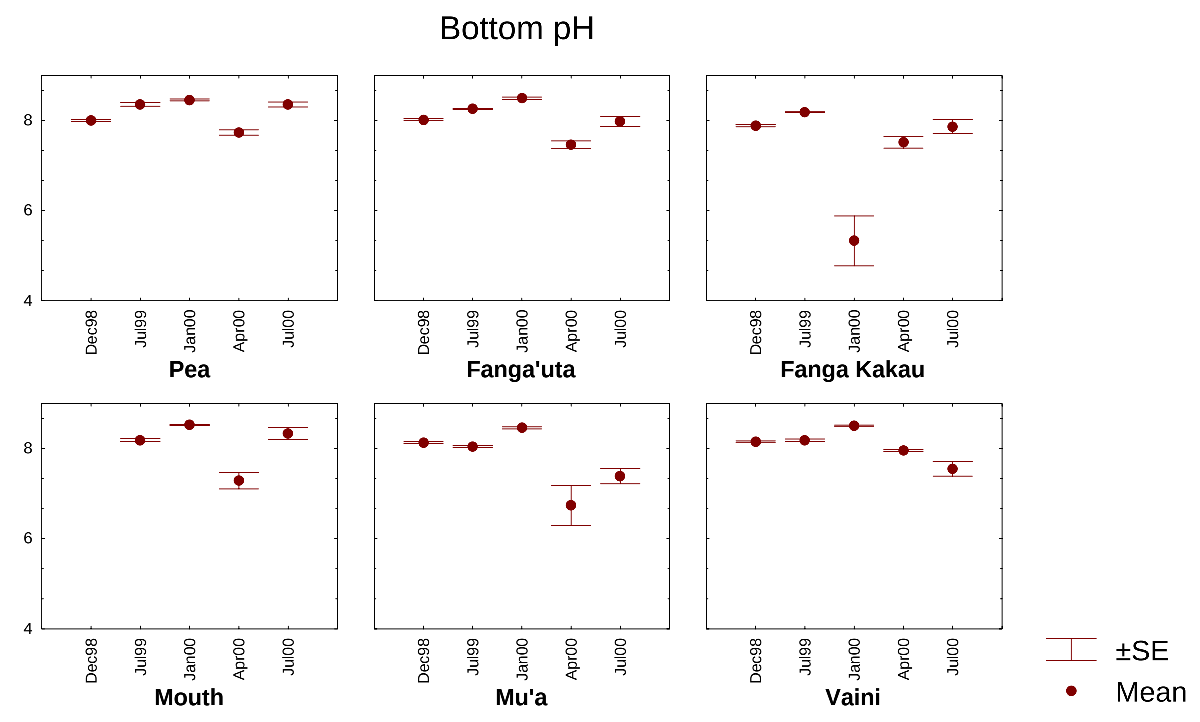


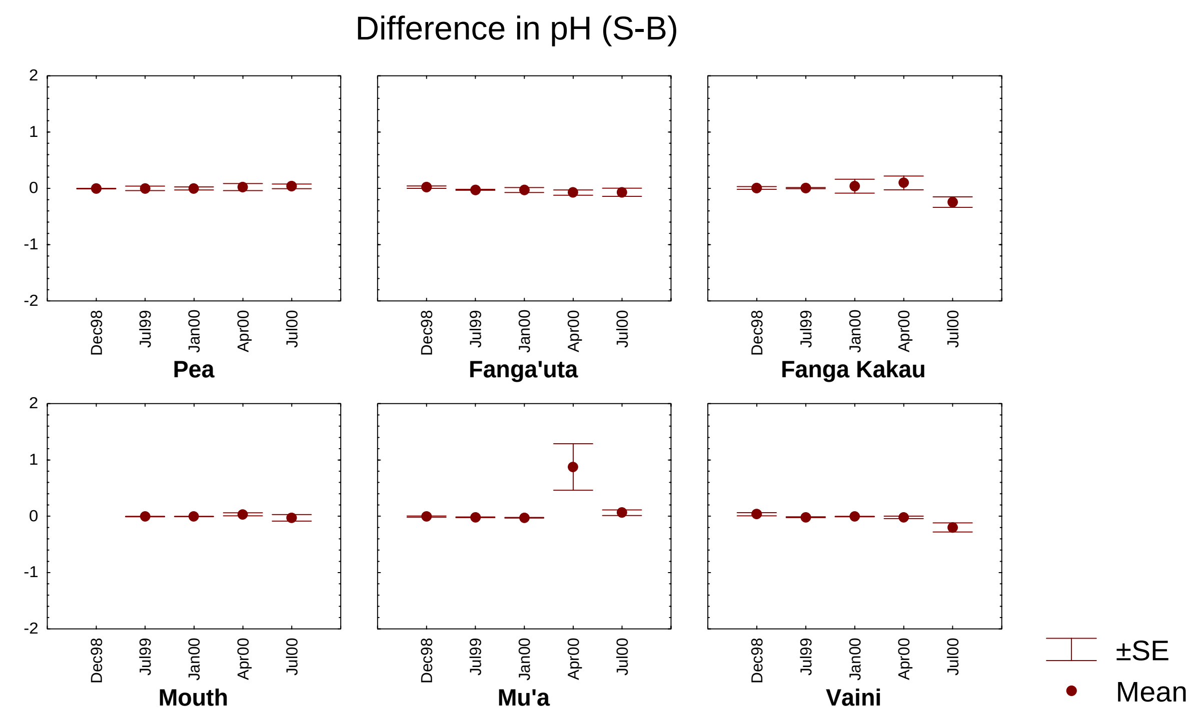
Bottom Dissolved Oxygen (DO)

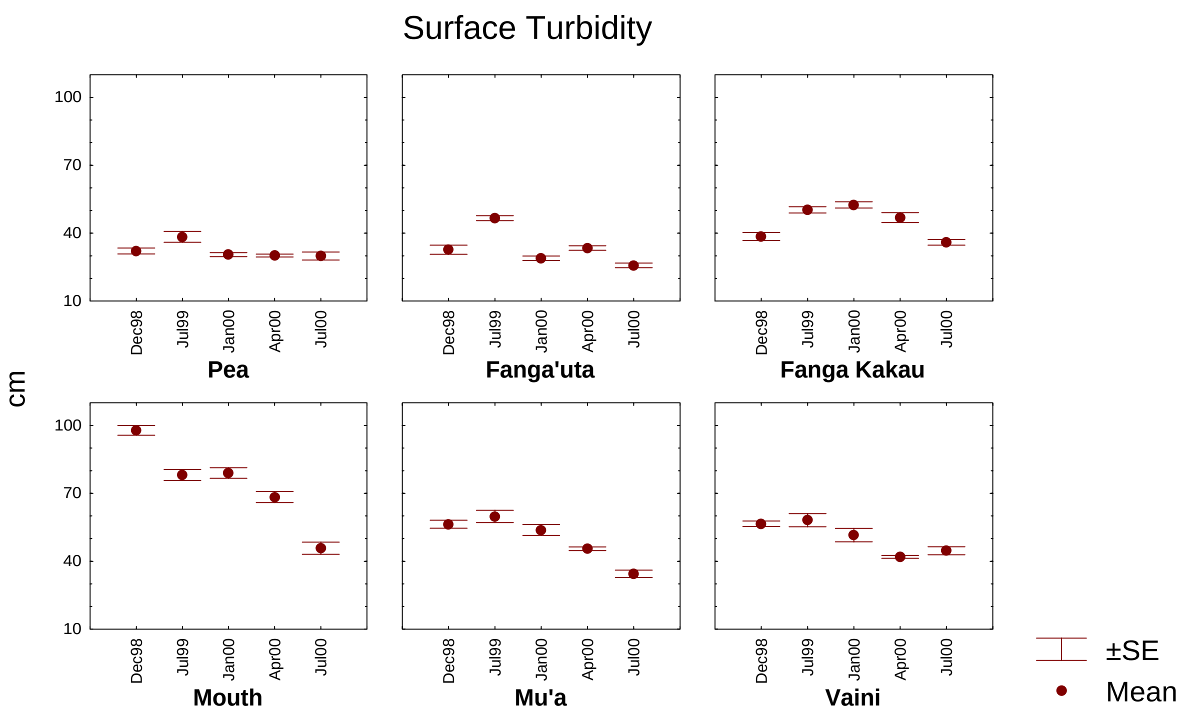


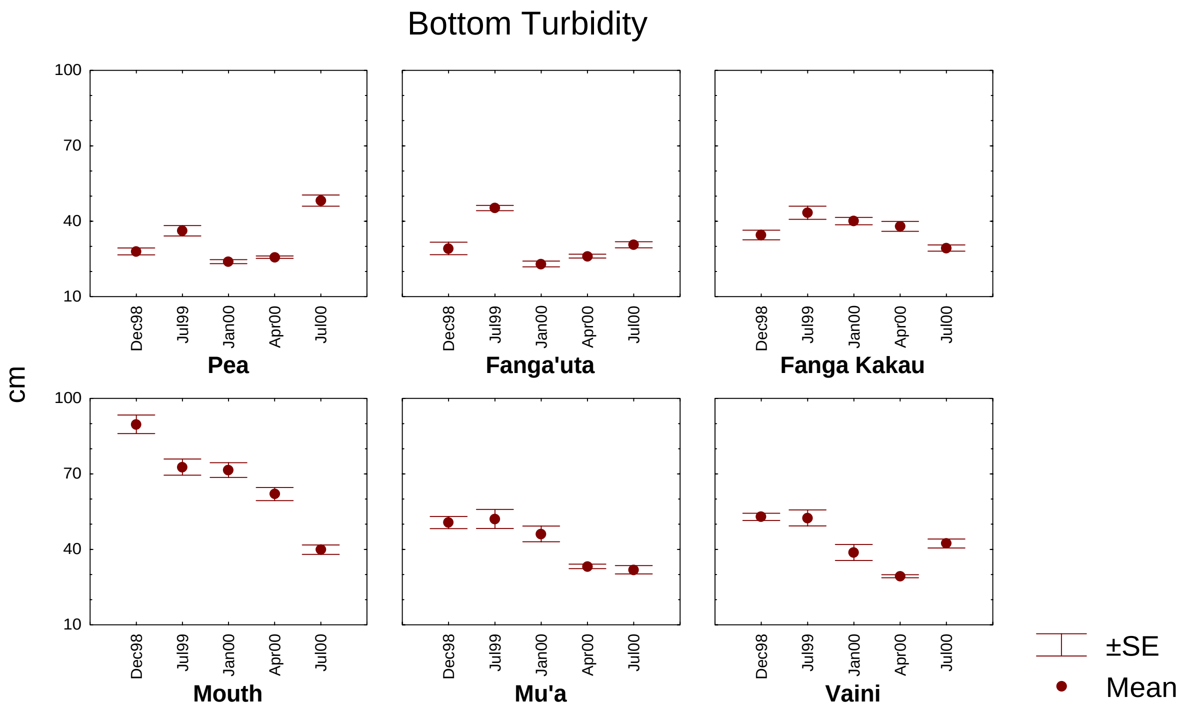

Difference in Dissolved Oxygen (S-B)
mg / l
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
Dec98
Jul99
Jan00
Apr00
Jul00
±SE
Mean

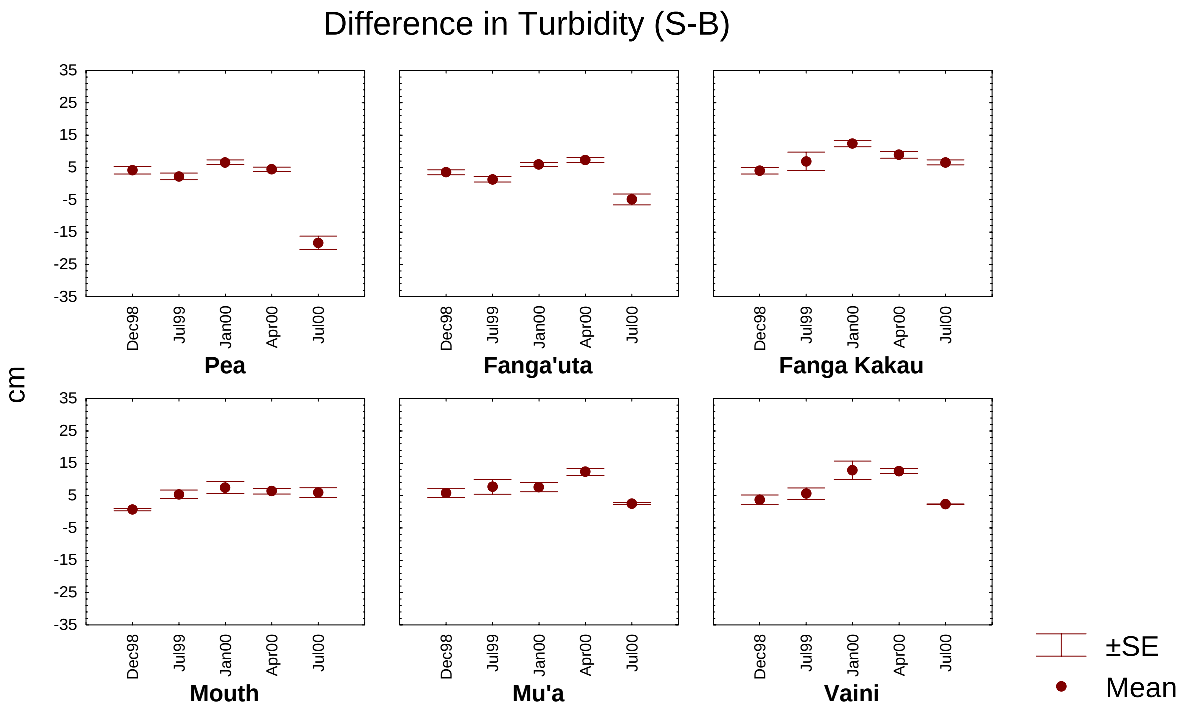

Surface pH
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
Dec98
Jul99
Jan00
Apr00
Jul00
±SE
Mean

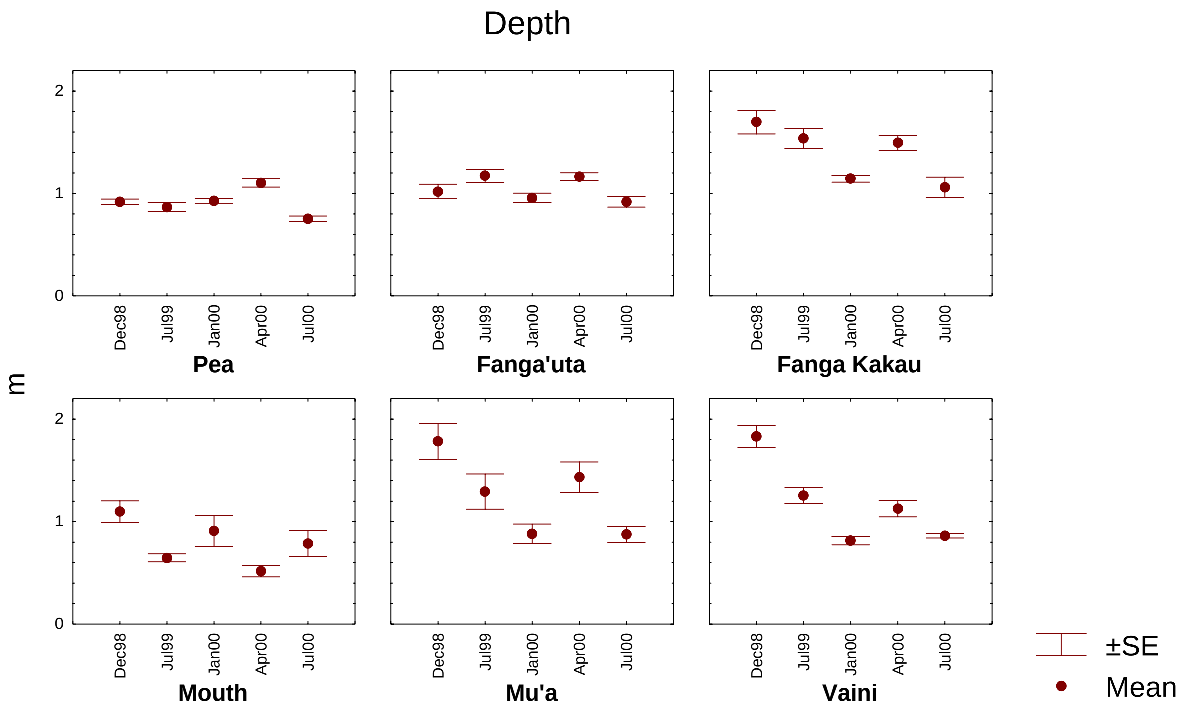

Bottom pH
8
6
4
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

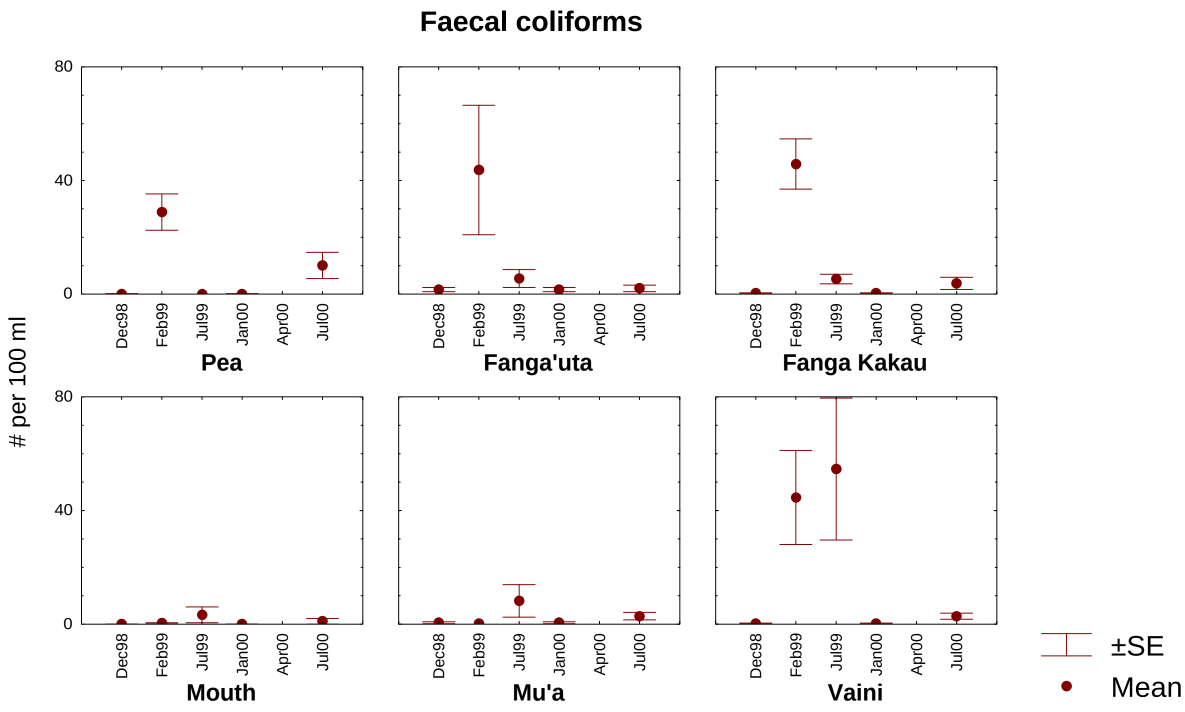

Difference in pH (S-B)
2
1
0
-1
-2
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean


Surface Turbidity
cm
100
70
40
10
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

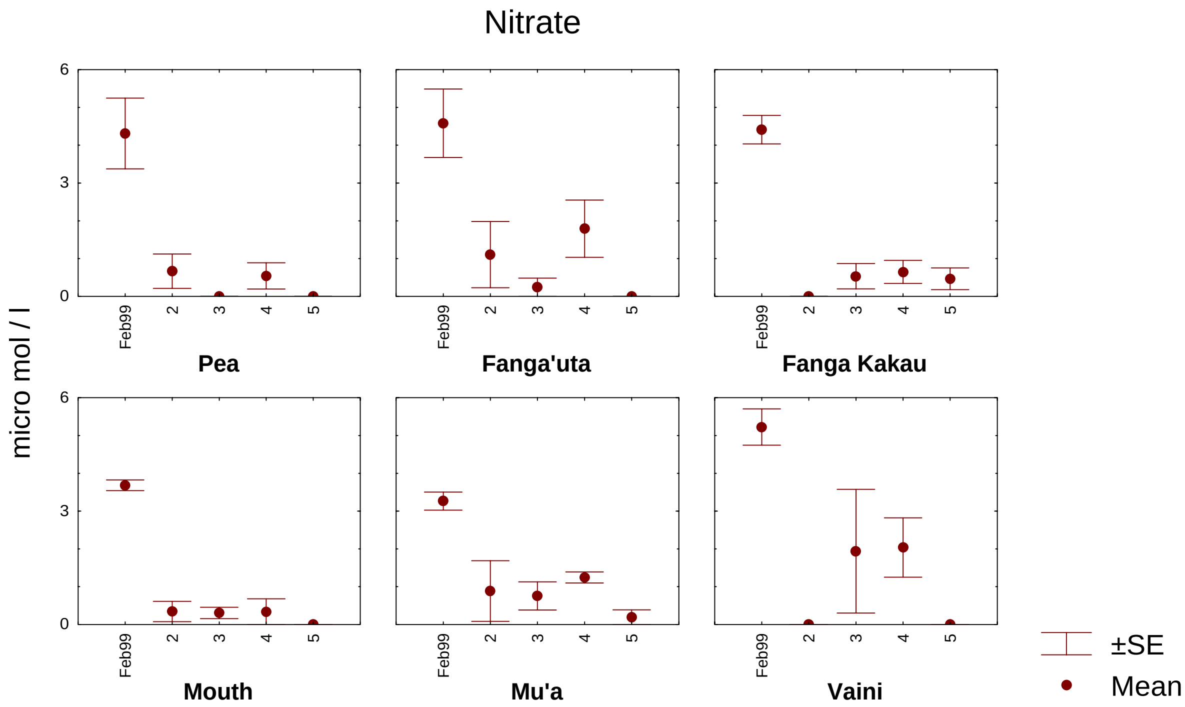

Bottom Turbidity
cm
100
70
40
10
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

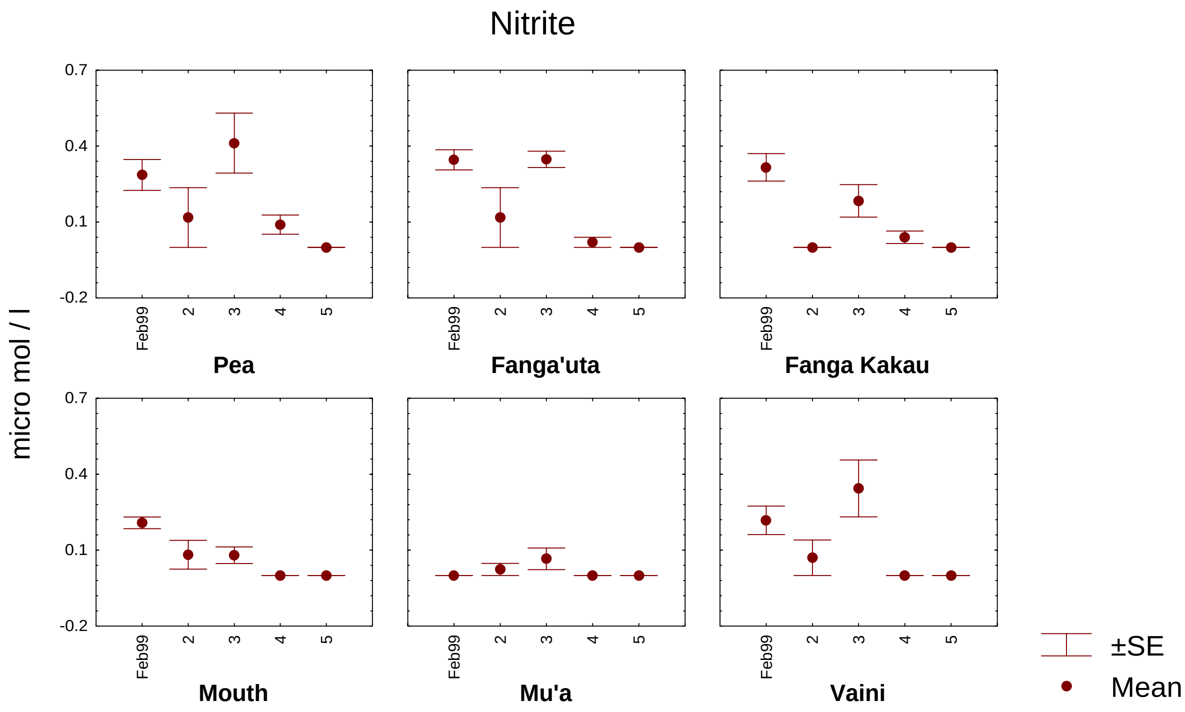

Difference in Turbidity (S-B)
cm
35
25
15
5
-5
-15
-25
-35
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

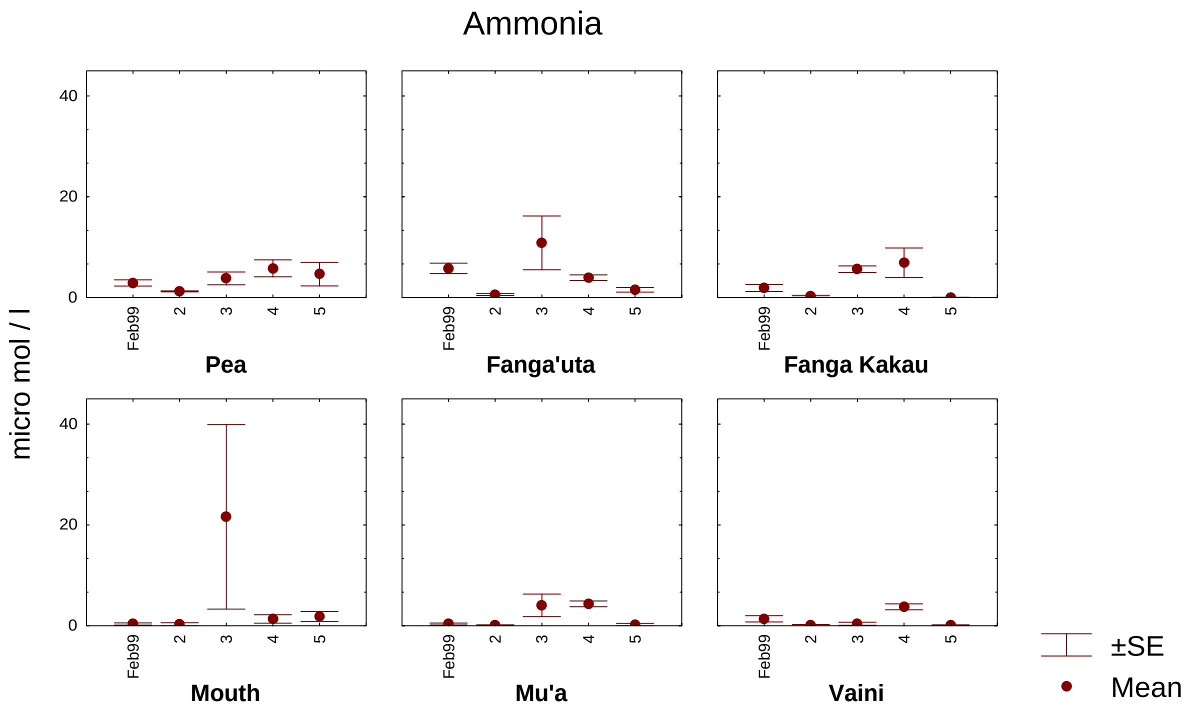

Depth
m
2
1
0
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

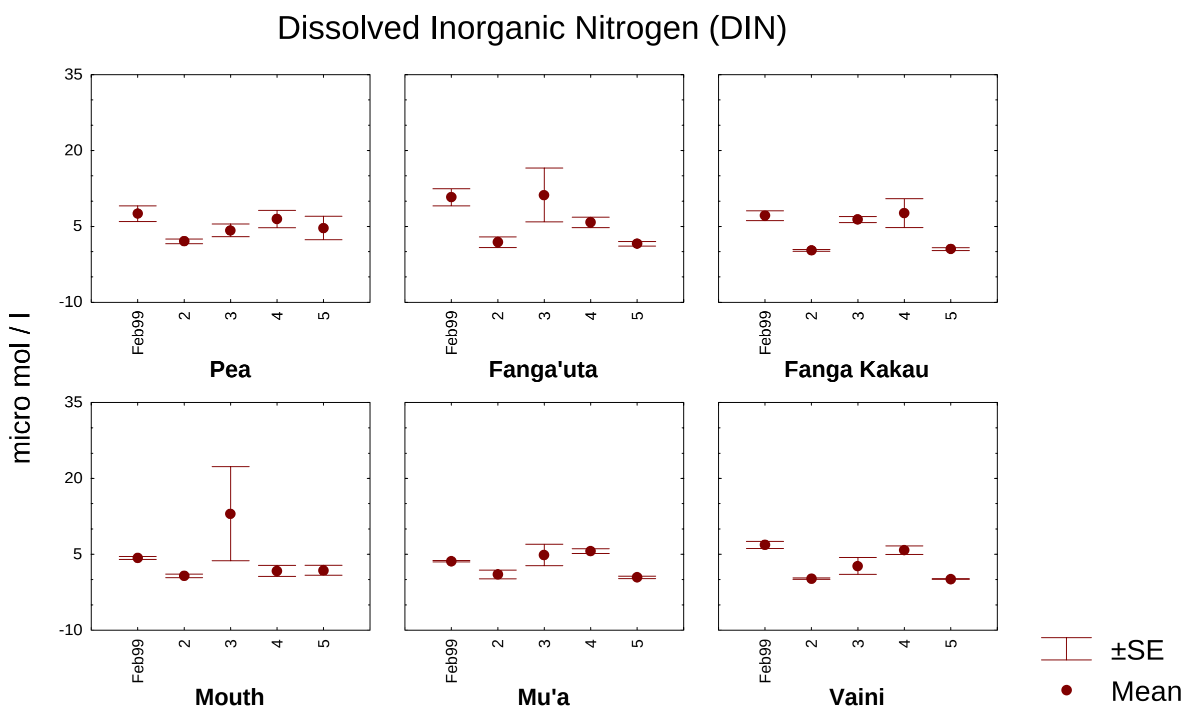


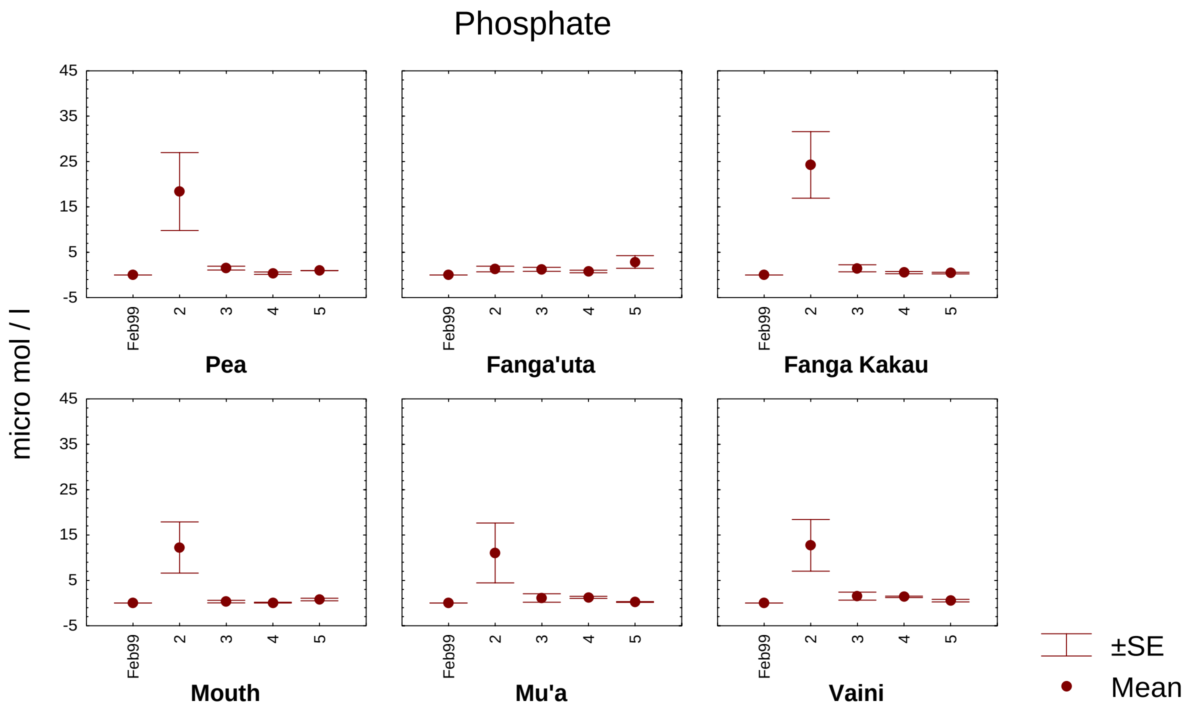
7.2.2 Water Chemistry variables



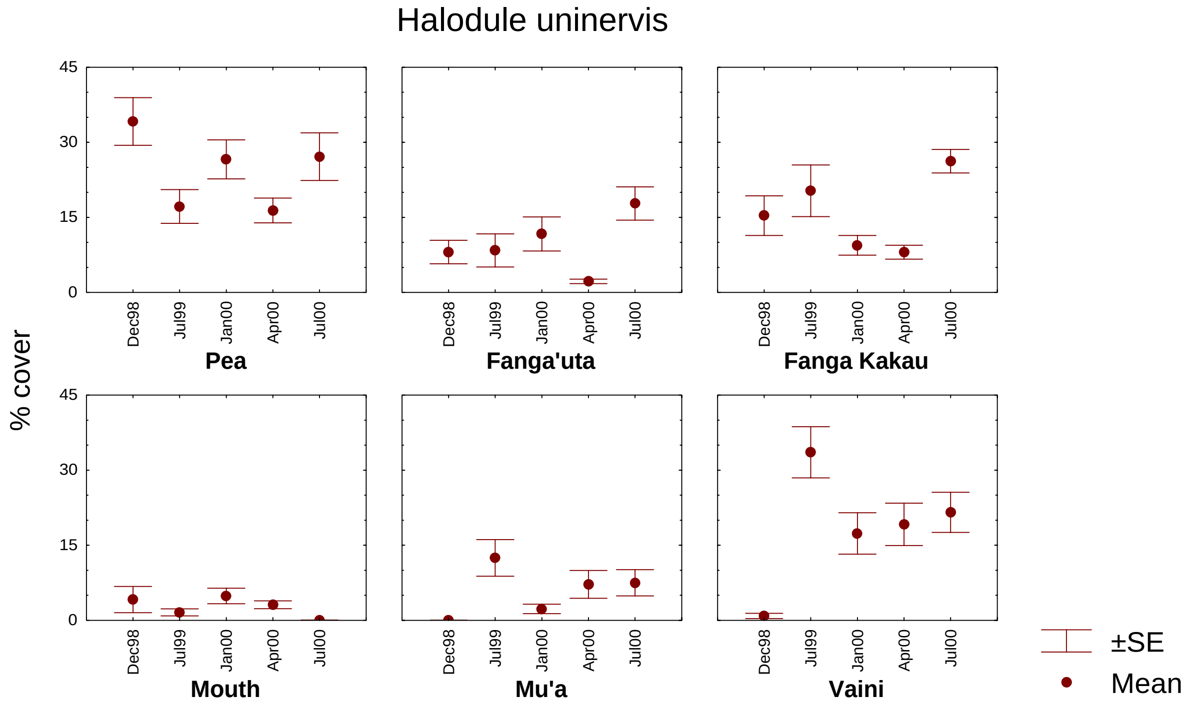

Nitrite
micro mol / l
0.7
0.4
0.1
-0.2
Feb99
2
3
4
5
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

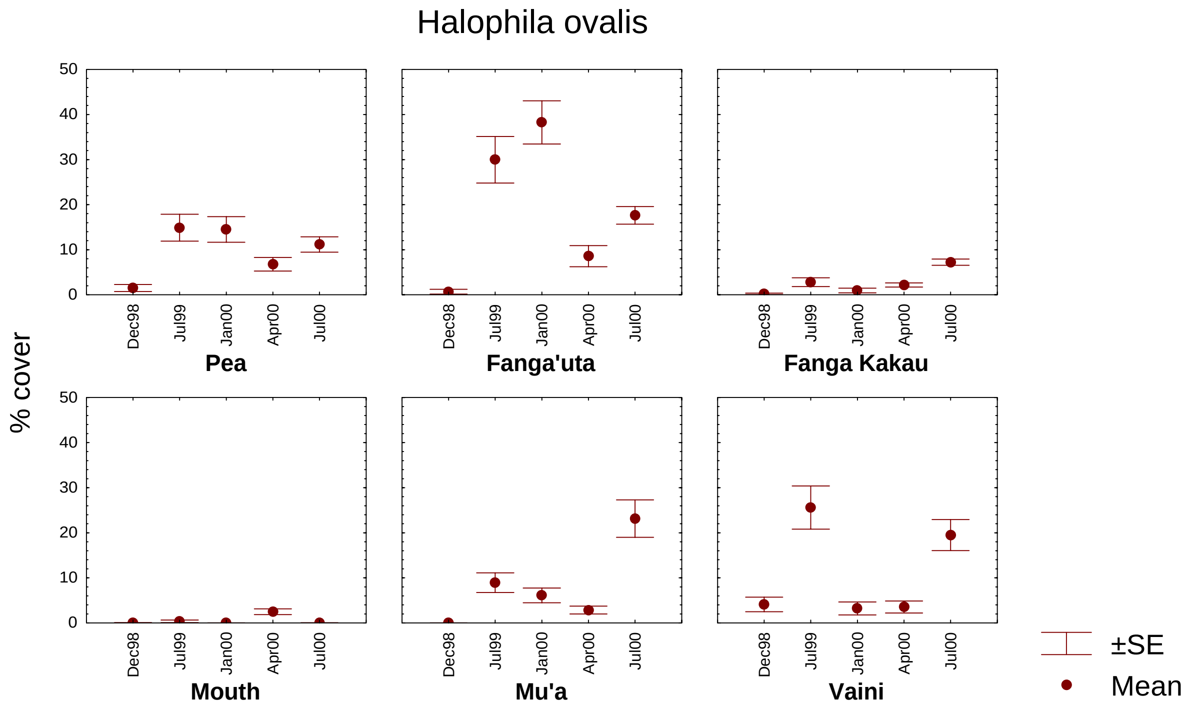

Ammonia
micro mol / l
40
20
0
Feb99
2
3
4
5
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

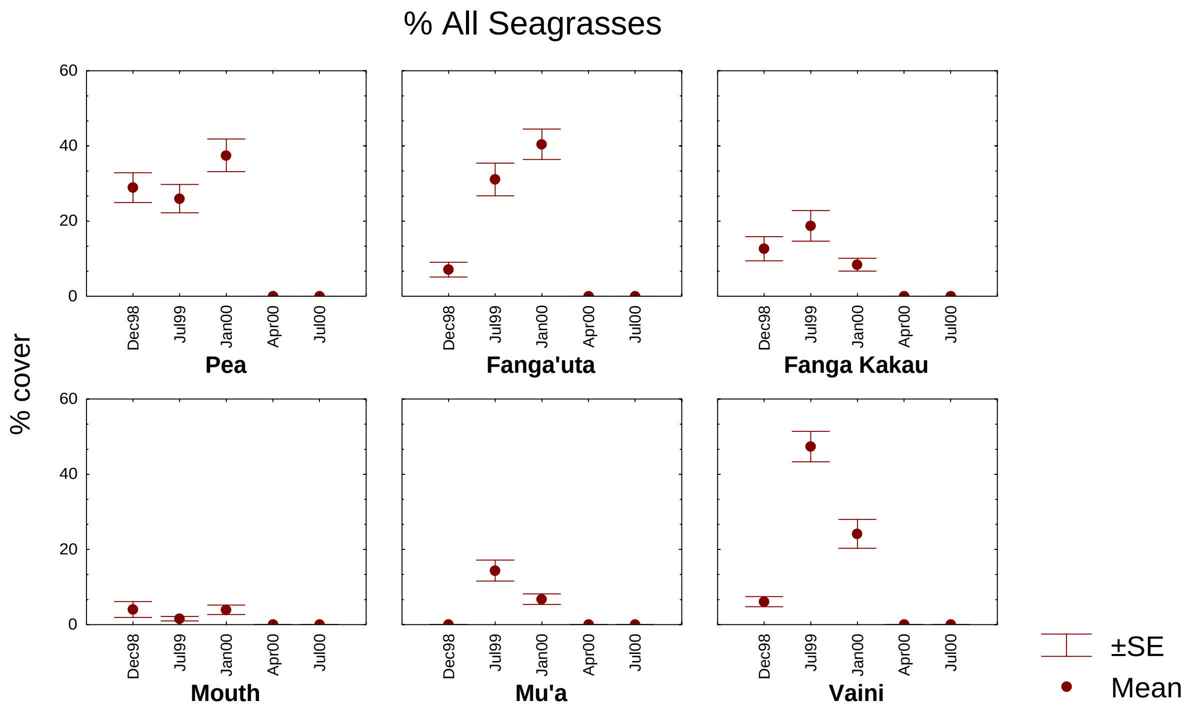

Dissolved Inorganic Nitrogen (DIN)
micro mol / l
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
Feb99
2
3
4
5
±SE
Mean

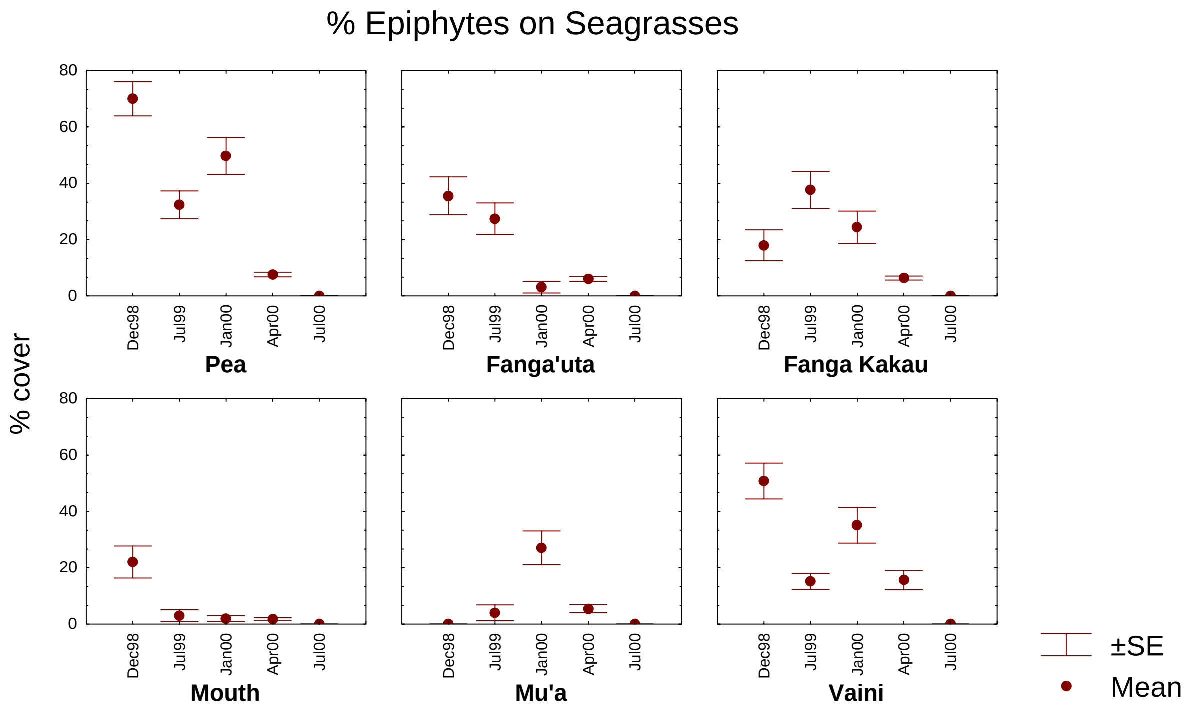

Phosphate
micro mol / l
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
Feb99
2
3
4
5
±SE
Mean

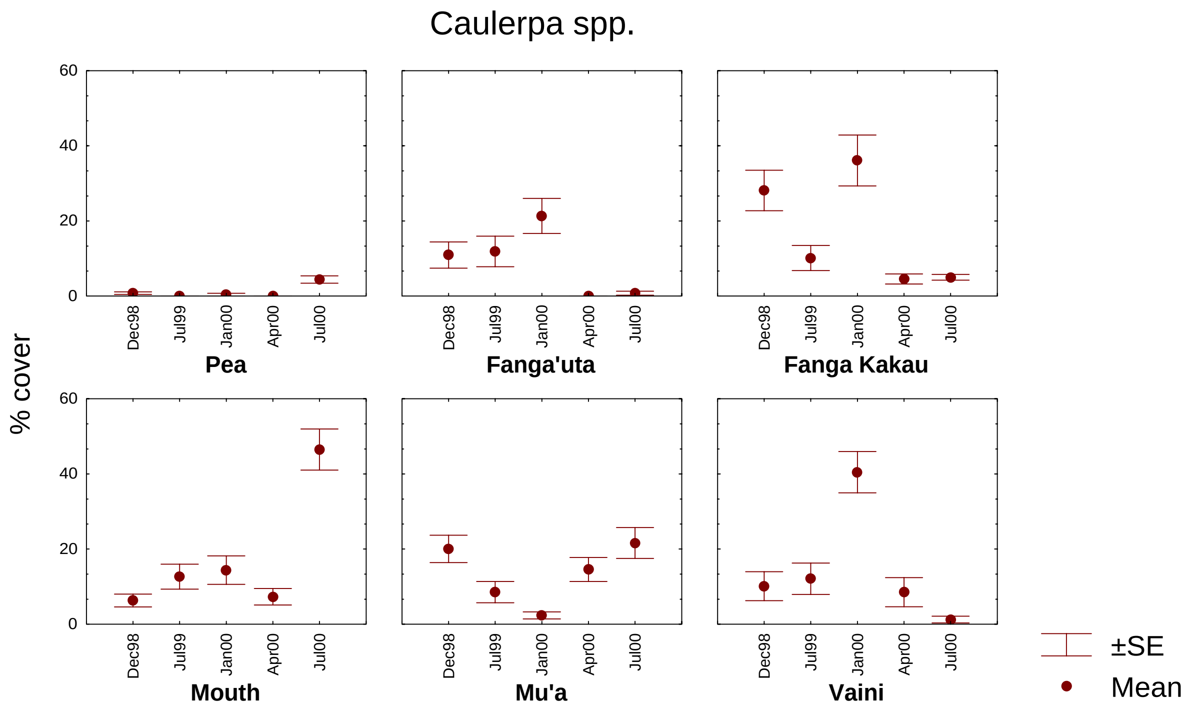
7.2.3 Seagrass community variables

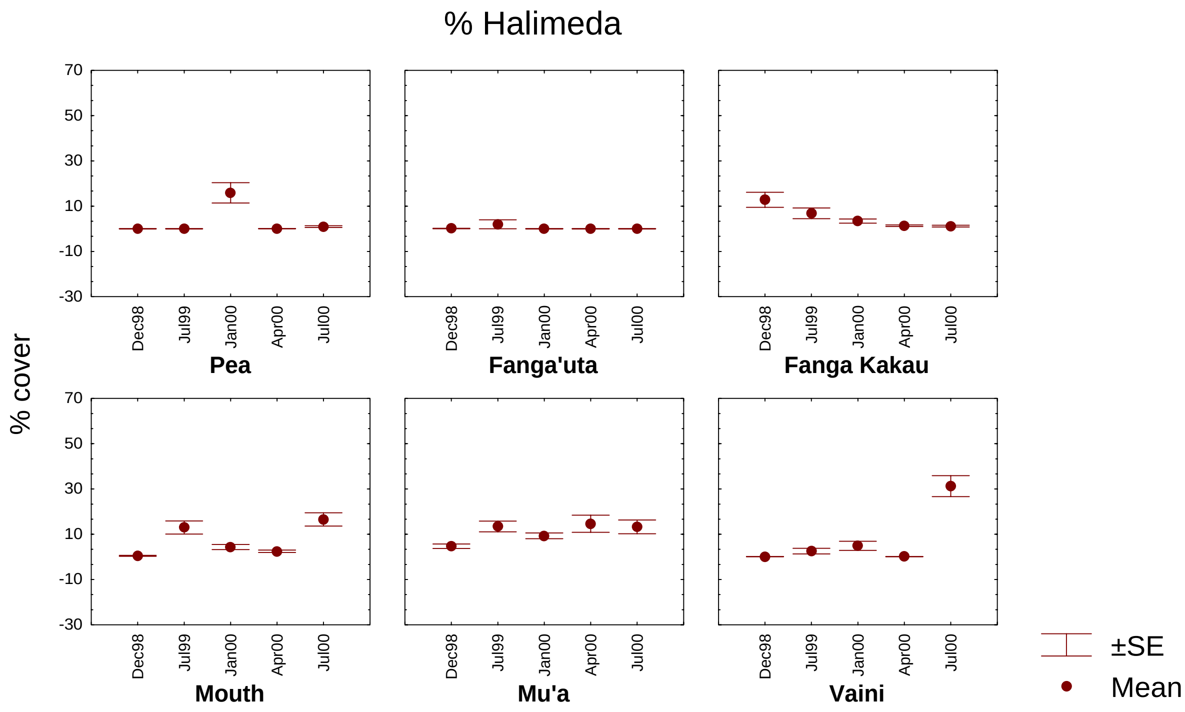





% All Seagrasses
% cover
60
40
20
0
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

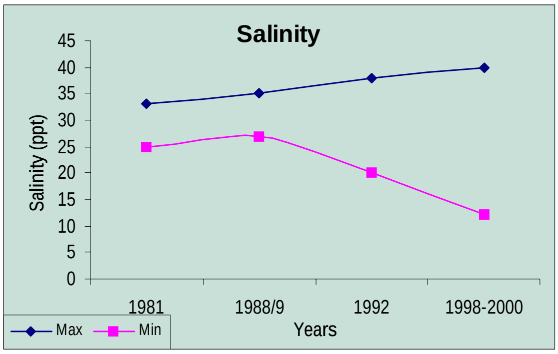

% Epiphytes on Seagrasses
% cover
80
60
40
20
0
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

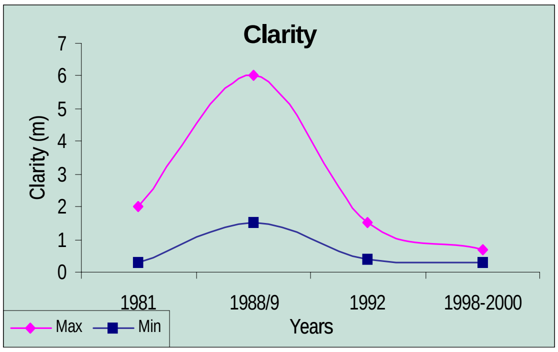

Caulerpa spp.
% cover
60
40
20
0
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

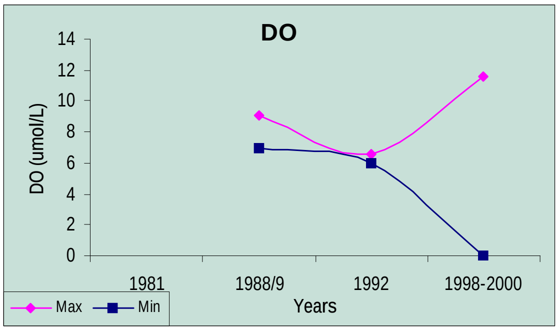

% Halimeda
% cover
70
50
30
10
-10
-30
Dec98
Jul99
Jan00
Apr00
Jul00
Pea
Fanga'uta
Fanga Kakau
Mouth
Mu'a
Vaini
±SE
Mean

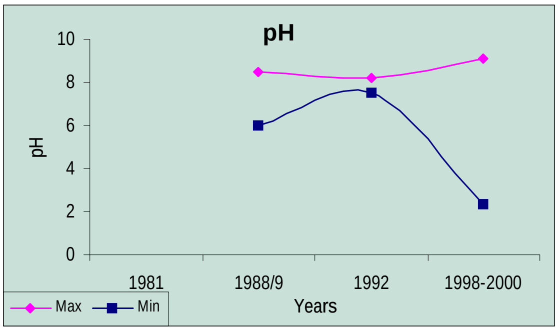
7.3 Graphs of ANZECC standards and maximum and miniumum values obtained for variables measured in previous studies for comparison in this study.

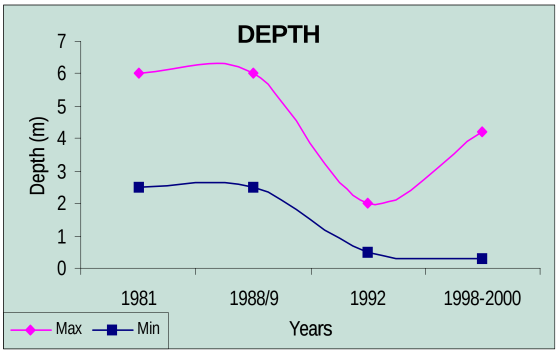
Australian Standards for either Seafood, Recreational use or the risk of blooms is indicated for each variable where available.

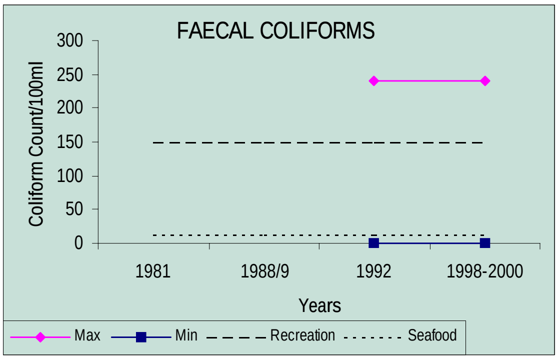


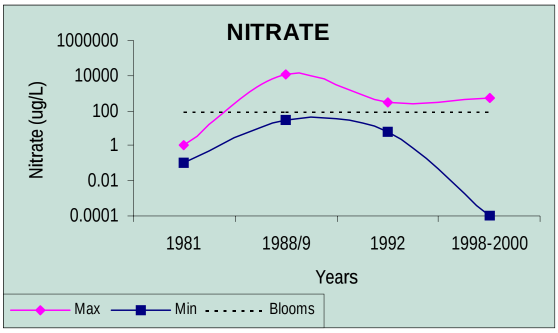


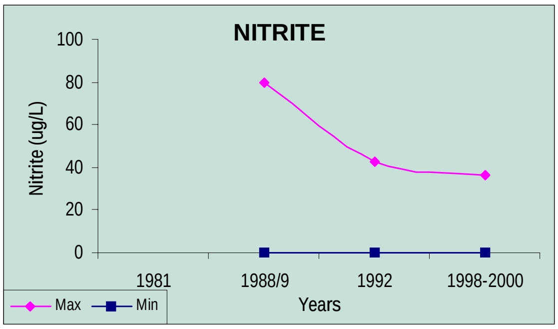


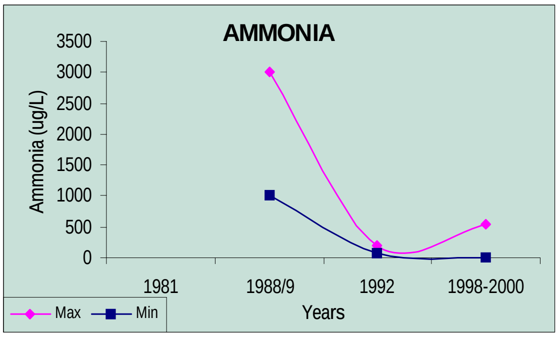


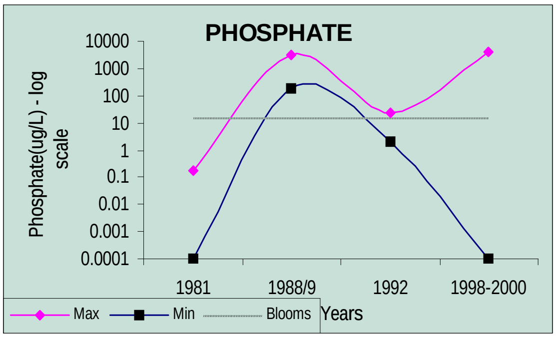





NITRATE
1000000
10000
100
1
0.01
0.0001
Nitrate (ug/L)
1981
1988/9
1992
1998-2000
Years
Max
Min
Blooms


NITRITE
100
80
60
40
20
0
Nitrite (ug/L)
1981
1988/9
1992
1998-2000
Years
Max
Min


AMMONIA
3500
3000
2500
2000
1500
1000
500
0
Ammonia (ug/L)
1981
1988/9
1992
1998-2000
Years
Max
Min


PHOSPHATE
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
Phosphate(ug/L) - log scale
1981
1988/9
1992
1998-2000
Years
Max
Min
Blooms