RESEARCH PUBLICATION No. 14

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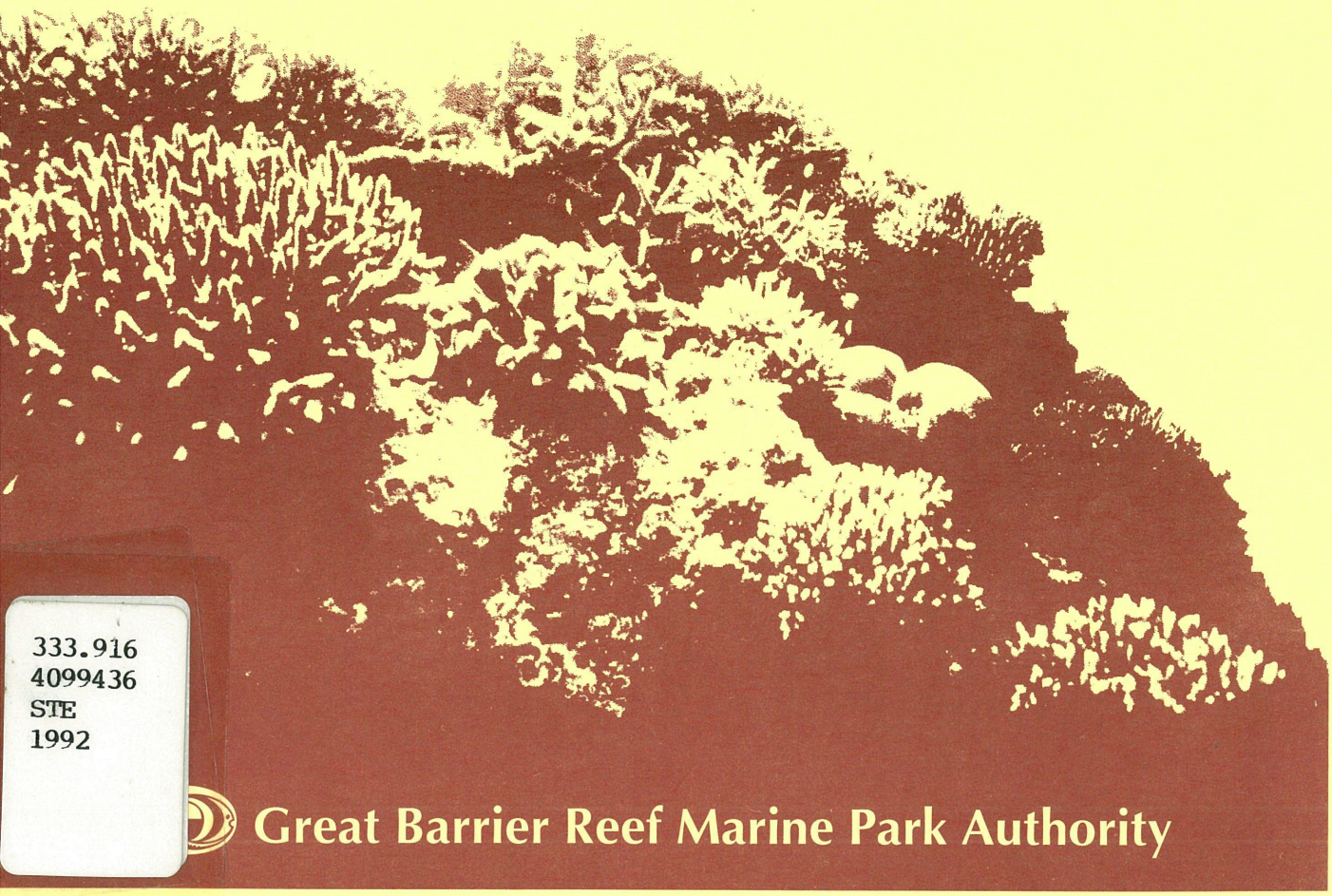

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Great Barrier Reef Marine Park Authority

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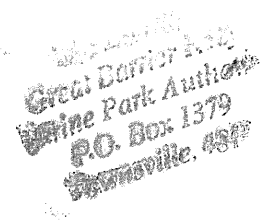

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A REPORT TO THE GREAT BARRIER REEF MARINE PARK AUTHORITY

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Bibliography.
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1. Water quality - Queensland - Green Island. 2. Environmental monitoring - Queensland - Green Island. I. Steven, A. D. L. (Andrew David Leslie), 1962- . II. Great Barrier Reef Marine Park Authority (Australia). (Series : Reserach publication (Great Barrier Reef Marine Park Authority (Australia)) ; no. 14).

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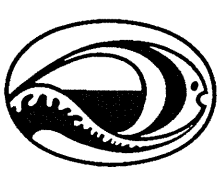

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EXECUTIVE SUMMARY

A pilot study was undertaken at Green Island in June 1989 to assess the spatial and temporal variation of a range of water quality parameters. It was a precursor to the implementation of a proposed baseline study of water quality around Green Island to ensure the optimum allocation of sampling in a cost effective manner.

Water quality parameters were measured over a range of nested spatial and temporal scales within the framework of three separate studies. Spatial variability was assessed with respect to **depth** and **habitat** (reef flat and slope) and over a range of nested horizontal scales; **Locations** (ca. 500 m); **Sites**, nested within locations (ca. 50 m), and **replicates** nested within all of the above factors (ca. 1-5m). Significant differences in concentration between **locations** (i.e. > 500 m) around Green Island were found for most inorganic nutrients (NO_2 + NO_3, NH_4, DIN, PO_4). Differences between **habitats** (reef flat and slope) were important for DIN and for PO_4. **Depth** and **site** were not important sources of variation for any of the parameters examined.

Higher values of DIN were recorded at locations (D & F) on the windward side of Green Island, whilst the mean DIN concentration at location E on the north-eastern side of the reef was significantly lower than other locations. Differences due to habitat were considered potentially significant. It was considered that the potential for nutrients to be modified as the water mass is advected across the reef should be addressed in the design of the baseline study.

Short term temporal variation was assessed over a 24 hour period sampling every 3 hours at two location on the reef **flat** and **slope**. Diel comparisons were made at the same time over 3 days at the same locations. The temporal study demonstrated that apart from DIN, **time of day** was not an important source of variation for most parameters of water quality. Multivariate analysis suggested there were changes in dissolved nutrient change consistent with tidal and diurnal cycles. Time periods sampled around low tides had higher concentrations of DIN than those around high tides. Sampling on different **days** was a significant source of variability for nitrogen species.

Differences in nutrient flux between days and over larger time frames (i.e. seasons) should be accounted for in the proposed sampling programme. Although diurnal variation is not a potential source of variability, sampling should be conducted at a

similar time on every sampling occasion. Sampling is preferable around the high tide for logistical reasons (i.e. boat handling).

Cost benefit analysis indicated that the most efficient allocation of sampling was to dispense with sampling sites or depth and to concentrate on replicates well dispersed within locations thus effectively integrating spatial variation at scales of 5-10 m and 50-70 meters.

It is proposed that the baseline water programme should sample surface waters at a number of sites (defined by habitat type) along transacts running across the reef from offshore. To account for temporal variability sampling would be carried out on two field trips during the Winter and Summer with sampling on two alternate days on each field trip. Sampling would be conducted around the diurnal high tide of every occasion.

No significant change in ambient water quality could be attributed to sewage discharge, although phosphate levels were higher in the vicinity. Explicit studies are needed to address this problem.

Values of the parameters measured were in the range of values reported from other studies on the GBR.

The results of the pilot study cannot be interpolated to studies on high island fringing reefs. For instance, factors such as bottom sediment type, resuspension, sediment nutrient pool are likely to be different for a turbid fringing reef.

It was considered analytical problems and prohibitive costs made particulate nitrogen and BOD_5 unsuitable parameters to measure in the baseline study.

Standardisation of sampling methods between workers is recommended if results are to be usefully compared. For example the use of filtration and filter type can have a substantial effect on nutrient concentrations.

Techniques of multivariate analysis provide a useful way for examining patterns which may not be apparent using univariate techniques.

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LIST OF ABBREVIATIONS

General

AIMS	Australian Institute of Marine Science
ANOVA	Analysis of variance
ca.	approximately
FIA	Flow injection analyser
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
MDS	Multi-dimensional scaling
NFR	Non Filtrable Residue
S.D	standard deviation
S.E.	standard error
%	percent

Chemical Abbreviations

BOD_5	Biological Oxygen Demand over 5 days.
Chl*a*	Chorophyll *a*
DIN	Dissolved Inorganic Nitrogen
NH_4	Ammonium
NO_2	Nitrite
NO_3	Nitrate
PO_4	Orthophosphate
PN	Particulate Nitrogen
TN	Total Nitrogen
TP	Total Phosphorous

Units of Measure

°C	degrees Celsius
cm	centimetres
ha.	hectares
m	metres
l/s	lites per second
mg/l	milligrams per litre
m^3/d	cubic metres per day
g at//l	gram atom per litre
μM	Micromolar
ppt	parts per thousand
blank	no data recorded
-	Missing value

nb. Totals may not represent the sum of individual values due to rounding.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the laboratory staff who performed the analytical work associated with this study - John Faithful, Paula Bachiella and Jane Orr, and Bruce Brady who assisted with sampling and on-site analysis. Cathy Robinson is thanked for her invaluable typographical assistance. We would also like to thank Claudia Baldwin who assisted with the planning of the study and obtaining funds to carry it out.

CHAPTER 1: GENERAL INTRODUCTION

1.1 INTRODUCTION

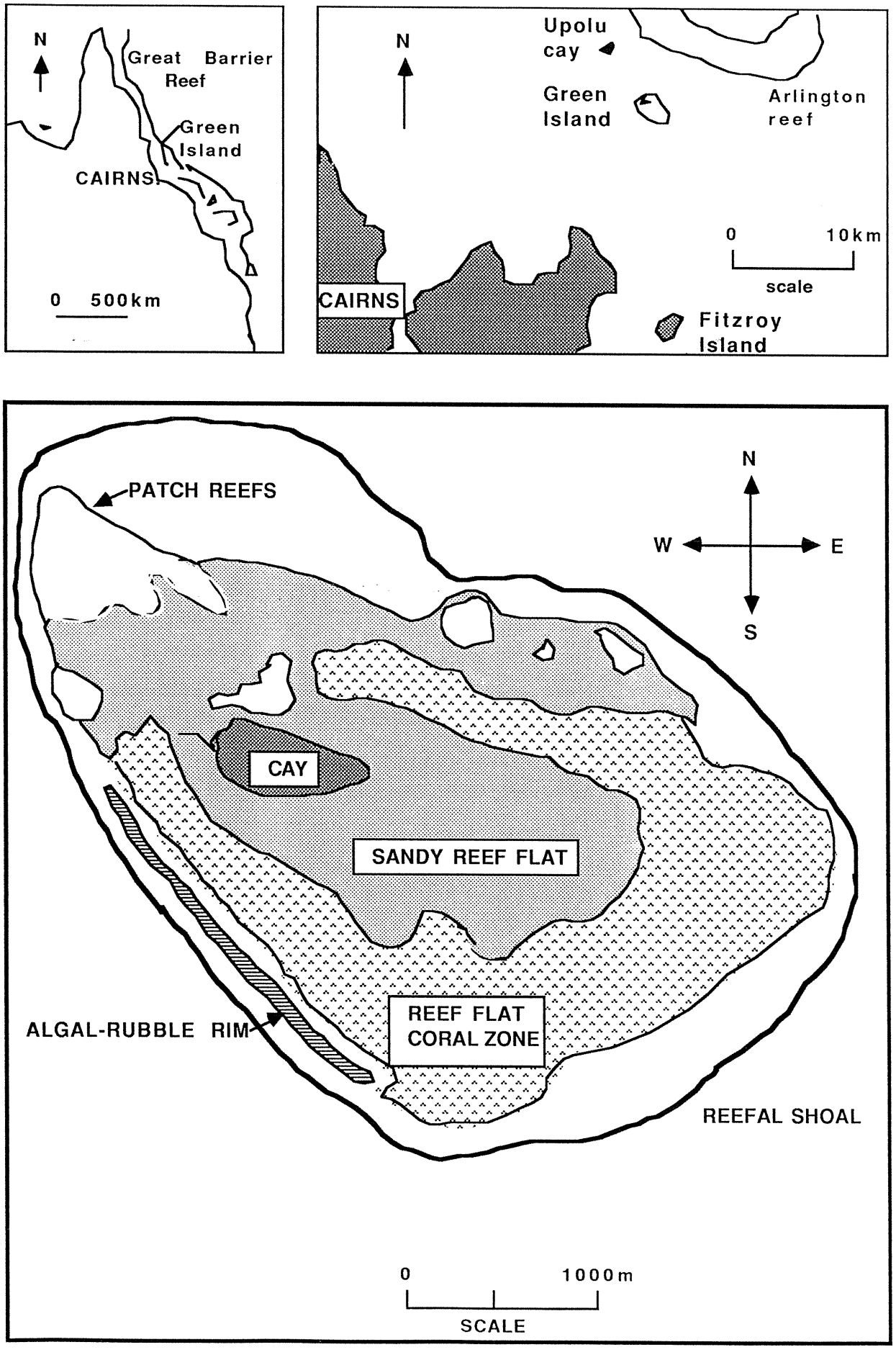
Concern has been expressed that anthropogenic influences ranging from riverine input carrying enhanced nutrient and sediment loads and agricultural fertilisers, to the more localised activities of tourist facilities (sewage discharge, dredging) has resulted in the degradation of inshore reefs in the Great Barrier Reef Marine Park (GBRMP). However, there is a lack of background information on the quantitative effect of waste water on Australian coral reef ecosystems. Case studies at Kaneohe Bay, Hawaii (Smith *et al.*, 1981) and Barbados (Tomascik and Sander, 1985) have demonstrated the deleterious effects of pollution and emphasized the importance of early detection and management to preserve the coral reefs. The most effective means of achieving some form of water quality control is through the setting of ambient water standards. If anthropogenic influences on ambient water quality are to be detected, accurate baseline levels of water quality parameters need to be determined. However, nutrients and a variety of related processes on reefs vary much more than is widely appreciated (Smith and Jokiel, 1975; Kinsey and Davies, 1979; Smith *et al.*, 1981; D'Elia, 1989) over a range of spatial and temporal scales. Recognising the complexity of coral reef systems, consideration of a range of large and local scale phenomena are required to adequately determine changes in water quality which are due to natural processeses and those that are anthopogenically induced. At a regional scale an understanding of the history of the water mass before it impinges upon the reef is necessary (river discharges, planktonic blooms and oceanic upwellings). At a reefal scale, a detailed understanding of the hydrological characteristics of the particular reef as well as the water residency and velocity is necessary. Other factors requiring consideration include nutrient flux between the benthos, sediments and sea water; nutrient input due to groundwater (Marsh, 1977) or terrestrial runoff; and water circulation patterns due to embayments. With regard to the input of anthropogenic material into receiving waters, or the effects of a development, it is difficult to generalise and predict the effects that changes in waste loadings may have on specific areas, or the cumulative effect over time.

Consequently, comprehensive, site specific baseline studies which determine the range of natural changes which occur over space and time are needed if realistic accceptable limits of change to the environment are to be defined.

The Great Barrier Reef Marine Park Authority (GBRMPA) recognises the need for an integrated research and monitoring programme on the effects of nutrients and siltation on the Great Barrier Reef (GBR). Such a programme has been discussed but its implementation is dependent on funding approval. A soundly based pilot study which facilitates the projection of optimal sampling designs is a necesssary pre-cursor to the implementation of such a large, costly, baseline or monitoring programme. A pilot study ensures the most powerful and cost effective design of a monitoring programme and minimises within sensible logistical constraints, the chances of making erroneous decisions about the presence or absence of environmental impacts (Mapstone *et al.*, 1989).

This pilot study was undertaken to examine the spatial and temporal variation in ambient levels of a range of water quality parameters around Green Island and to assess which ones best meet the requirements for assessing a change in the environment in a logistical and cost effective manner. The longer term objectives of studying Green Island was to collect baseline nutrient data so that comparisons can be made with the regional geographic studies and with data collected during re-development activities. Implicit is consideration of the consequences of changes in water quality on the patterns and processes on the surrounding coral reef.

Figure 1.1. Locality map of Green Island.



1.2 BACKGROUND INFORMATION

1.2.1 Study Area

Green Island (16°59'S 145°59'E) lies ca. 27 kilometres north east of Cairns (Figure 1.1). It is a vegetated sand cay surrounded by a lagoonal platform reef (Baxter, 1987). The cay lies towards the the north-west corner of the extensive reef flat and is composed mostly of sand and coralline rubble. It occupies an area of ca. 12 ha., the eastern 60 % of which is National Park. Six private leases are held on the western side of the cay. The largest of these is the site of the Coral Cay Hotel owned and operated by Great Adventures Pty. Previously it had been owned by Hayles Pty.

The reef itself occupies an area of 1200 ha. A shallow indistinct lagoon extends to the north of the cay (Green Island Management Committee,1980). The reef flat is generally at or near tidal datum, except to the north-west where there is a downslope dip. The windward flat is clearly divisible into coral and sand zones, with the latter more extensive on the leeward flat (Figure 1.1). Sea grass beds occur on the inshore flat to the north and north west of the cay. They are also widespread over the the reef flat to the east of the cay.

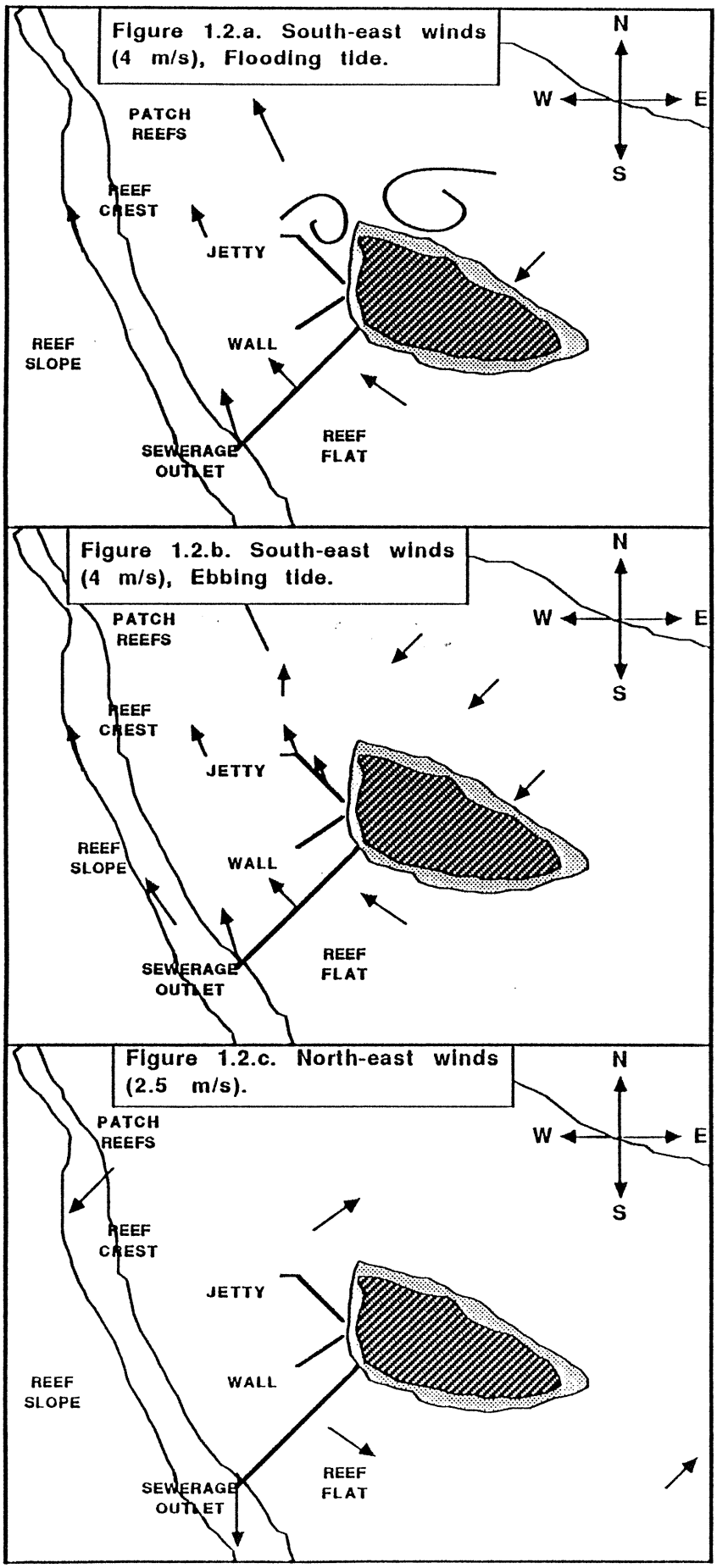
Green Island is zoned Marine National Park B within the Cairns Section of the Great Barrier Reef Marine Park. It has a Marine National Park Buffer Zone extending 500 metres out from the reef edge.

1.2.2 Hydrography and Hydrodynamics

The maximum tidal range is 3.1 metres with a spring tidal range of 1.7 metres. The lowest tides occur during the daylight in winter and at night during summer (Green Island Management Committee, 1980). Wolanski and Pickard (1985) and Black and Gay (1988) demonstrated seasonal and interannual fluctuations in currents were due to a local onshelf balance between winds and current in conjunction with fluctuations in Coral Sea circulation (Baxter, 1987).

On a local scale, van Woesik (1989) using Eulerian and Langrangian dye tracer studies, around the lee of the reef found that during north-east winds and a flooding tide the predominant residual current flow was spiralling around the island in an anticlockwise direction (Figure 1.2.c). During south-east winds and ebbing tide, currents flow towards the north-west, with a retention area in the lee of the reef (Figure 1.2.b.). A similar north-west flow occurs on the flooding tide with double spiralled eddies evident in the lee of the cay (Figure 1.2.a).

Figure 1.2. Local hydrodynamic patterns around Green Island over different weather and tide conditions (from van Woesik, 1989).



1.2.3 Anthropogenic Influences

Green Island has had a long history of human occupation and has clearly been subjected to increasing disturbance from human activity. Tourism has been heavy and has increased 5 fold since 1956 to ca. 150,000 visitors in 1978 (Baxter, 1987). In addition the reef has been subject to two major outbreaks of the crown of thorns starfish, *Acanthaster planci* in the last 25 years (1962-67, 1979-81). A combination of these events has modified the reefal environment, resulting in a greatly reduced hard coral cover. However, recovery in the form of diverse assemblages of *Acropora spp.* coral colonies has been observed along the south-west and north-east slopes (van Woesik and Fisk, *pers. obs.*, September 1989). The lee of the Island supports a high biomass of seagrass, whose presence has been attributed to anthropogenic factors (Kuchler 1978, van Woesik 1989).

1.2.4 Sewage Disposal

The Coral Cay Hotel and the public toilets are connected to a sewerage system (Green Island Management Report, 1986). Effluent is discharged from a detention tank through an outfall pipe made of perspex, located at the low water spring mark on the reef edge to the south west of the cay (Figure 2.1). Times of discharge are irregular as the system operates on a floating point discharge. The sewage is untreated apart from chlorination, with an average retention time of 2 hours (van Woesik, 1989) and an estimated mean discharge rate of 100 m^3/day (Bell, 1987). Water inlet and outlet pipes for the Marineland Melanesia aquarium system lie on the reef flat to the north of the cay (Fig. 1.1).

1.2.5 Re-development

With the recent change of ownership of the resort and the underwater observatory, a $25 million re-development has been proposed. This includes the upgrade of all facilties within the current lease boundaries, re-development of the cay beach and re-dredging of the harbour. To comply with GBRMPA requirements changes in the treatment of waste water are proposed with provision for the implementation of a secondary treatment plant.

1.3 GENERAL EXPERIMENTAL DESIGN

1.3.1 Rationale

Few water quality studies have been undertaken around Green Island, although at present a study of water quality on a transect from the Barron River mouth out to Green Island is in progress (Brady, *pers. comm.*). Water samples have been collected around Green Island as part of an ongoing project examining the effects of stress on corals (Rasmussen, *pers. comm.*). The preliminary results of the water movement studies undertaken as part of a multi-disciplinary study funded by GBRMPA suggested there is the potential for sewage effluent to be retained by eddies, which are in proximity to the areas of enhanced seagrass growth (van Woesik, 1989). In view of these results, the commonly held belief that sewage discharge has contributed to reef degradation, and the impending re-development of the resort, it was suggested that a detailed baseline study of the levels of nutrients around Green Island be undertaken. A necessary pre-cursor to such a study was a pilot study to determine the optimum allocation of sampling in a cost effective manner. The proposed baseline study is detailed in Appendix 1. As a number of other large water quality programmes are currently being proposed, such a pilot study is especially timely. The objectives for both the pilot and baseline studies are outlined below.

1.3.2 Objectives of Pilot Study

(1) To assess the variability of a range of water quality parameters at local spatial and small temporal scales around Green Island.

(2) To evaluate which parameters are of most use in assessing water quality.

(3) To design a sampling programme for the proposed baseline study, based on the results of this pilot study.

1.3.3 Overall objectives for the proposed baseline water quality study around Green Island.

(1) To collect baseline nutrient data around Green Island so that comparisons can be made with regional geographic studies and with data collected during marine re-development activities.

(2) To establish the spatial extent of nutrient enrichment resulting from the sewage discharge.

(3) To develop techniques which relate nutrient concentrations to biotic responses. i.e. the magnitude and spatial extent of benthic community change and primary productivity. (This will be carried out in conjunction with the proposed benthic monitoring programme (Fisk and van Woesik, 1989).

1.3.4 Sources of Variation

Due to a gamut of causes, water quality parameters are often spatially and temporally variable. To be able to detect differences which are due to anthropogenic activities, accurate baseline levels are firstly required which quantify natural ambient variation. The following potential sources of variability around Green Island were identified.

1. Depth variation.
2. Large scale variation between sampling sites.
3. Small scale variation between replicates.
4. Large temporal variation between seasons.
5. Diel variation.
6. Short term diurnal variation.
7. Tidal variation.
8. Large and small scale hydrodynamic processes (i.e. currents).
9. Prevailing wind and atmospheric conditions.
10. Topography of island and reef.
11. Mainland river runnoff.
12. Discharge from sewage outfall.
13. Biological blooms and other biological processes.
13. Sample handling error.
14. Sample analysis errors.

1.3.5 Constraints

While the study aims to measure 'baseline' levels, it should be noted that Green Island is already an 'impacted area' both from anthropogenic influences (i.e. sewage discharge and runoff) and other sources (*Acanthaster planci*). These effects have been compounded over time. The sampling undertaken during the pilot study was over a short duration with logistical and cost constraints limiting the number of sampling stations, replication levels and numbers of parameters that could be measured.

1.3.6 General Sampling Design

This pilot study was designed to measure the type and magnitude of spatial and temporal variation of a number of water quality parameters (mostly inorganic nutrients) around Green Island, over a range of scales. To such an end, 2 sub-programmes were undertaken:

(1) A study of temporal variation over one 24 hour period at two locations to assess the relative contribution of time, tidal phase and possibly sewage discharge to changes in water quality parameters. A study of between day (diel) variation was made on 3 consecutive days, sampling on the high tide.

(2) A study of spatial variation over a range of nested spatial scales.

These two studies are considered separately in the following two chapters.

1.4 GENERAL METHODS

1.4.1 Variables Measured

Nutrients:

- Nitrite (NO_2) + Nitrate (NO_3)
- Ammonium (NH_4)
- Orthophosphate (PO_4) (i.e Reactive Phosphorous)
- Total Nitrogen (**TN**)
- Total Phosphorous (**TP**)
- Particulate Nitrogen (**PN**)

Biological Parameters:

- Chlorophyll *a* (**Chl *a***)
- Biological Oxygen Demand (5 days) (BOD_5)

Physico-Chemical Parameters:

- Suspended solids (**SS**)
- Clarity
- Dissolved oxygen (**DO**)
- Temperature

Physical conditions:

- Wind direction and speed
- Wave direction and height

1.4.2 Sample Collection

On each sampling occasion measurements of the following parameters were made in the following manner:

Weather Conditions:

Windspeed: Anemometer

Wind & wave direction: vane and compass

Wave height: visual estimation trough to peak.

Physical parameters:

Dissolved oxygen and temperature were measured at each site using a TDS Oxygen analyser (Model LC 182A). Water clarity was measured using a secchi disk.

Water Samples:

All samples were stored in sterile 'Whirlpacs' of various sizes. Samples for inorganic nutrients were collected in small (ca. 140 ml) whirlpacs, whilst samples for particulate nitrogen, and total nitrogen and phosphorous were stored in large (ca. 400ml) whirlpacs.

Surface samples were collected ca. 0.2m below the surface so as to ensure minimum collection of the surface film. Samples taken at depth were collected in a PVC van

Dorn sampler. Nutrient samples were then transferred to the whirlpacs and immediately stored on ice in 'eskys'. Upon return to the island samples were stored in a -20 °C freezer. Samples for Chlorophyll *a* and suspended sediment analysis were collected in containers and filtered at the *in situ* laboratory. The filters were frozen until completion of the analysis at the Australian Centre for Tropical Freshwater Research. BOD_5 samples were stored in the dark at ca. 20 °C for the 5 day period.

1.4.3 Site Selection

The existing knowledge of water movements around the island were used to guide site selection. Sampling sites were selected to quantify both the ambient levels of nutrients in waters around the island in areas not affected by the sewage discharge, and also the levels of nutrients in the area around the sewerage pipe.

1.4.4 Timing

The field work for this study was undertaken from the 2nd to the 4th of June 1989.

1.4.5 Weather Conditions

Conditions were typical for this time of the year, winds were south south- east and less than 10 knots. Sea conditions were calm, wave heights being under 0.3 metres. Swell was predominantly from the south (Table 1.1). Tidal attenuation was greatest on the 4th of June, with the onset of the new moon.

Table 1.1. Summary table of weather and tide conditions during the sampling period, 2nd to 4th of June 1989.

DATE	TIDAL PREDICTIONS		WIND CONDITIONS		SEA CONDITIONS	
	Time hours	Height metres	Direction degrees	Speed knts	Direction degrees	Height metres
2/6/89	0121	0.74	-	-	-	-
	0706	2.07	160	7	160	0.2
	1330	0.05	180	8	190	0.2
	2018	2.67	100	5	150	0.1
3/6/89	0211	0.74	170	6	170	0.1
	0753	1.96	170	7	190	0.1
	1412	0.00	180	9	180	0.3
	2103	2.72	-	-	-	-
4/6/89	0301	0.78	-	-	-	-
	0837	1.87	-	-	-	-

1.5 STATISTICAL ANALYSIS

1.5.1 Analysis of Variance

Multi-factorial analysis of variance (ANOVA) was used to test the significance of spatial and temporal factors of variability. Due to the number of sources of variation several models were applied. These are considered in detail in chapters 2 and 3. A factor was considered a significant source of variation if the probability of the assertion being wrong (Type I) was less than 5 % and was considered potentially significant for error probabilities of 5-10%. Assumptions of independence and homogeneity of variance were assessed using residual analysis. Where appropriate a Log (X) transformation was applied (Zar, 1984). Where significant results were found, *a posteriori* comparisons among means were made using Tukey's studentized range test.

1.5.2 Multi-variate Analysis

Techniques of clustering and ordination were used to examine patterns of nutrient composition between locations and over time periods in the 24 hour study. These techniques are not based the underlying normality assumptions and as a consequence lack a framework for hypothesis testing (Clarke and Green, 1988). They do however, allow a description of the data, and may reveal patterns not apparent using univariate statistics. Untransformed mean values of nitrite + nitrate, ammonium, and phosphate for locations and and time periods were used in the analysis. A Bray-Curtis similarity coefficient was used in quantify their relative similarity. For the cluster analysis an 'unweighted group mean' sorting strategy was used to classify the similarity matrix. Non metric multi-dimensional scaling (MDS), an ordination technique, constructs a similarity map based on rank order, where the distance between data points reflects their relative dissimilarity. A measure of 'confidence' in the results is given by a stress statistic.

1.5.3 Power Analysis

Where a factor was found not to be a significant source of variation, analyses of statistical power was used to estimate *a posteriori* the probability that the sampling design would detect a difference in nutrient concentration of a specified magnitude, if indeed it existed (Mapstone *et al.*, 1988). Procedures followed those of Cohen (1977). When analyses indicated that a factor did not constitute a significant source of variation, that factor and residual sources of variation were pooled. These were used as an estimate of variation for calculation of the power of other terms in the analyses. Secondly, estimates of spatial and temporal variation obtained from this study were used to estimate the power and sample size characteristics of the suggested monitoring programme based on the power/sample size tables in Cohen (1977).

CHAPTER 2: TEMPORAL STUDY OF VARIATION

2.1 MATERIAL AND METHODS

2.1.1 Objectives

(1) To examine temporal variation in water quality over one 24 hour period at two locations assessing the relative contributions of time, tidal phase and possibly sewage discharge to changes in water quality parameters.

(2) To assess between day (diel) variation at the two locations on 3 consecutive days, sampling on the high tide during daylight hours.

2.1.2 Variables

- Dissolved Inorganic Nutrients, NO_2 + NO_3, NH_4, PO_4
- Total Phosphorous and Total Nitrogen
- Particulate Nitrogen
- Dissolved oxygen
- Temperature
- Chlorophyll *a*
- BOD_5
- Suspended solids
- Clarity

Section 1.4.2 details the sampling procedures, whilst Appendix 2 explains the analytical procedures used for the determination of these parameters.

2.1.3 Experimental Design

Temporal variation of surface waters, both between days (3), and within a 24 hour period were assessed at 2 locations (Figure 2.1) from high water on the 2nd of May 1989 at 0706 hours.

(i) 24 Hour study

The following factors were assessed as potential sources of variability.

Location: Variation between two locations. Location A was located ca. 250m to the north of the sewerage pipe. Location B was situated 250 metres to the south of the sewerage pipe.

Habitat: Variation between the **reef flat** and **reef slope** within each location.

Time Period: Variation due to tidal and temporal influences. Samples were collected around high and low water and 3 hours after each of these events.

Replication: Replicate samples were taken 2-3 minutes apart. This factor necessarily contained components of small scale spatial and short term temporal variability.

(ii) Daily Study

The following factors were assessed.

Location: Variation between two locations. Location A was located ca. 250m to the north of the sewerage pipe. Location B was situated 250 metres to the south of the sewerage pipe.

Day: Variation between 3 consecutive days. Sampling occurred on the high tide of every day.

Habitats: Variation between the **reef flat** and **reef slope** within each location.

Replication: Replicate samples were taken 2-3 minutes apart.

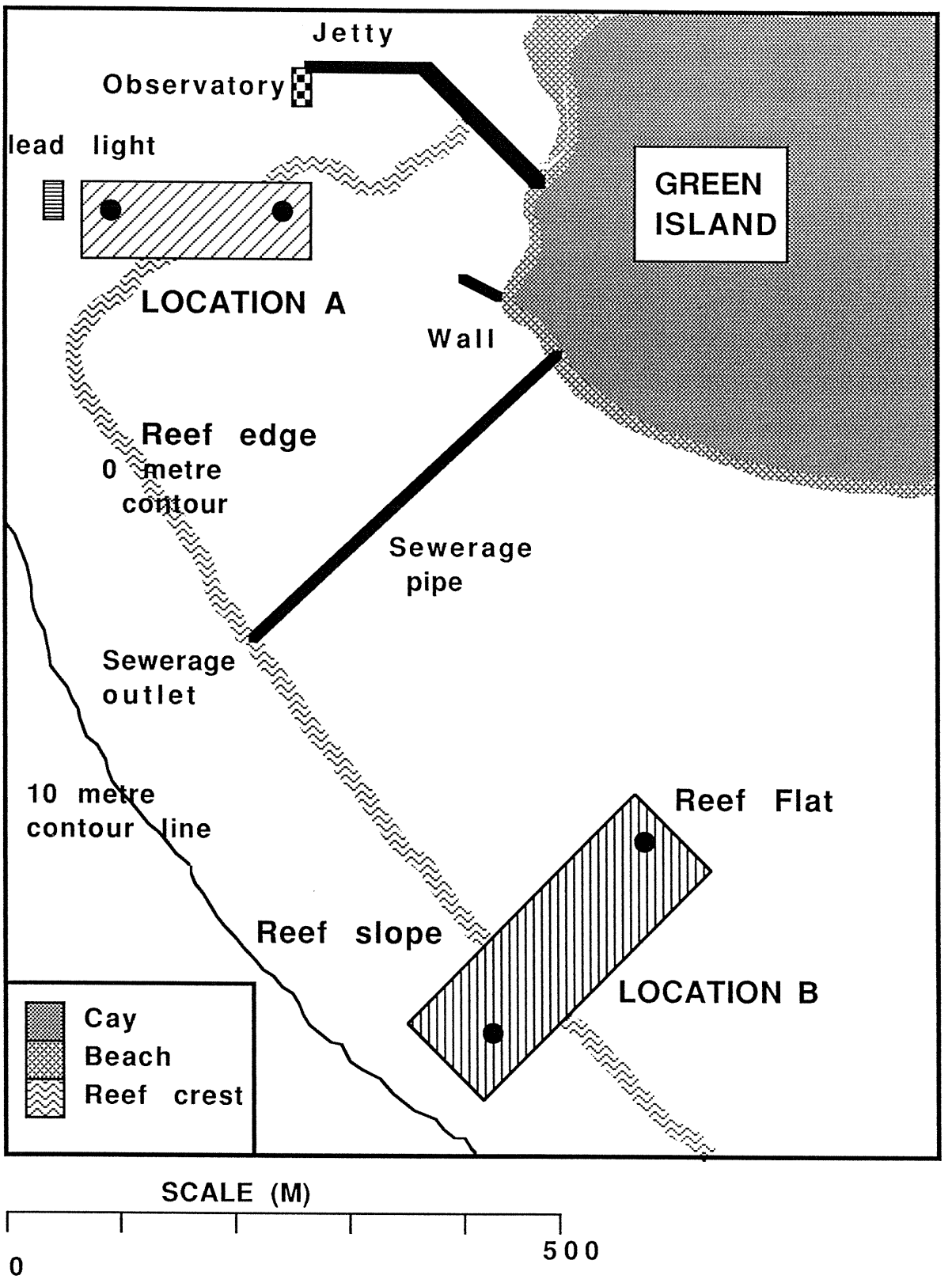
2.1.4 Site Selection

Two sampling locations were selected, ca. 250 metres either side of the sewerage discharge pipe (Fig. 2.1.). This placement allowed a preliminary assessment of the potential effects of sewage discharge on the ambient water by measuring upstream and downstream effects. Times of sewage discharge were noted in order to separate natural variation from potential sewage effects.

2.1.5 Timing

The 24 hour sampling study was undertaken from 700 hours on the 2nd of June, 1989 through until 1000 hrs on the 3rd June, 1989. Samples were collected approximately every 3 hours throughout this period. Samples for the diel study were collected on the daylight high tide from the 2nd to the 4th of June 1989.

Figure 2.1. Map of sampling locations for the Temporal pilot study.



2.1.6 Sampling Strategy

Surface water measurements were collected at 3 hourly intervals at each habitat within each location. Wind and sea conditions were noted. Dissolved oxygen, temperature and secchi disk measurements were made. Water samples were collected and immediately stored in an 'esky'.

2.1.7 Analysis

Temporal variability was analysed in a 3 factor design comprising Habitats (fixed) x Locations (fixed) and either time of day (fixed), or day (fixed).

2.2 RESULTS

2.2.1 24 HOUR STUDY

(i) Components of Variation

Time of Day Effects

Dissolved inorganic nitrogen was the only dissolved nutrient to vary significantly ($F = 3.24$; 7,11 df; $P = 0.040$) in concentration with time of day (Table 2.3.a). Significant temporal differences were found for temperature ($F = 20.46$; 7,9 df; $P < 0.0001$) oxygen ($F = 6.81$; 7,11 df; $P = 0.002$) and suspended solids ($F = 7.80$; 7,12 df; $P = 0.001$), consistent with changes in solar irradiation and tidal effects (Table 2.2.b.).

Habitat Effects

No significant differences between reef flat and slope habitats were found for any of the nutrient parameters measured (Table 2.1.a). Mean sea temperature ($F = 3.97$; 1,9 df; $P = 0.077$) and oxygen ($F = 6.44$; 1,11 df; $P = 0.028$) were higher on the reef slope (25.4 ± 0.2 °C, 7.8 ± 0.2 mg/l) than on the reef flat (22.5 ± 2.5 °C, 7.5 ± 0.5 mg/l).

Location Effects

No significant locations effects were recorded.

Interaction Effects

Within each habitat, dissolved inorganic nitrogen ($F = 4.01$; df 6,11; $P = 0.023$) and dissolved oxygen ($F = 4.55$; 5,11 df; $P = 0.017$) varied significantly with respect to time of day (Tables 2.1.a., 2.1.b.)

(ii) Analysis of Power

The small scale temporal patterns identified in the 24 hour study are unlikely to be due to deficencies in the sampling design. The power of the design to detect differences of small (< 25 %) and moderate (50 %) changes in ambient levels of the measured parameters was $P > 0.56$ and $P > 0.95$ repectively.

(iii) Multi-variate Analysis

Clustering and ordination techniques suggested that there were consistent patterns of temporal variation on nutrient concentrations due to tidal and diurnal effects.

Sampling periods roughly divided into high water sampling and low water sampling times. DIN levels influenced mostly by increases in ammonium and were found around low water sampling times. This is consistent with tidal resuspension.

2.2.2 DIEL STUDY

(i) Components of Variation

Diel Variation

Ammonium ($F = 5.22$; df 2,8; $P = 0.035$) and dissolved inorganic nitrogen ($F = 7.18$; df 2,8; $P = 0.02$) concentrations varied significantly between days. Both were both significantly lower in mean concentration on the 2/6/89 (0.30 ± 0.11 μM, 0.57 ± 0.13 μM) than on the 3/6/89 (0.79 ± 0.11 μM, 1.19 ± 0.13 μM) or the 4/6/89 (0.89 ± 0.16 μM, 1.23 ± 0.17 μM). Diel variation for total phosphorous was potentially significant ($F = 3.83$; df 2,8; $P < 0.075$). Mean sea temperature differed significantly between days ($F = 166.4$; df 1,7; $P < 0.0001$) but problems with equipment calibration may have caused this result.

Habitat Effects

Dissolved inorganic nitrogen concentrations differed marginally ($F = 9.12$; df 1,7; $P < 0.095$) between reef flat (0.93 ± 0.13 μM) and slope (2.21 ± 0.23 μM) environments (Table 2.4). Mean sea surface temperature differed significantly ($F = 5.78$; df 1,7 ; $P < 0.047$) between habitats (Table 4.2.), but the analytical error associated with the equipment makes this result dubious.

Location Effects

Ammonium ($F = 15.61$; df 1,8; $P < 0.019$) and dissolved inorganic nitrogen ($F = 9.12$; df 1,8; $P < 0.019$) concentrations were significantly greater on all days at location B. Mean values pooled over days were 0.89 ± 0.16 μM and 1.24 ± 0.16 μM respectively for location B, and 0.38 ± 0.10 μM and 0.70 ± 0.12 μM for location A.

(ii) Analysis of Power

The experimental design for the diel study had low power to detect small (< 25%) effects but reasonable power ($P > 0.53$) to detect moderate (> 50%) changes in ambient conditions.

2.2.3 SUMMARY OF TEMPORAL VARIATION

Ammonium and DIN were the only nutrient parameters to vary significantly with respect to either time of day or between days. Both were both significantly lower in mean concentration on the 2/6/89 (0.30±0.11 μM, 0.57±0.13 μM) than on the 3/6/89 (0.79±0.11 μM, 1.19±0.13 μM) or the 4/6/89 (0.89±0.16 μM, 1.23±0.17 μM). Weather conditions on this day were not different in any obvious way (Table 1.1). Over 24 hours DIN levels were higher around the turn of the tide than at mid tide sampling periods (Table 2.2.a.). Dissolved inorganic nitrogen concentrations differed between reef flat (0.93 ± 0.13 μM) and slope (2.21 ± 0.23 μM) environments. Ammonium and dissolved inorganic nitrogen concentrations were significantly greater on all days at location B. Mean values pooled over days were 0.89±0.16 μM and 1.24±0.16 μM respectively for location B, and 0.38±0.10 μM and 0.70±0.12 μM for location A. This location variation was not significant over 24 hours though.

Surface values for dissolved oxygen and temperature varied significantly with respect to time of day within each habitat. Mean values were greater over sampling times 2 to 4 (1105 ebbing, - 1645 rising), consistent with increased light attenuation, weather conditions and tidal mixing. Suspended solids were also greater during this time consistent with tidal resuspension during low tide. Chlorophyll *a* and BOD_5 did not vary with respect to any of the temporal components of variation (Table 2.1.b).

Table 2.1.a. Summary table of analysis of variance results for nutrients in the **24 hour** temporal study. All data was log transformed after residual analysis for heteroscedascity. * = sign. at 0.1; ** sign. at 0.05; *** = sign. at 0.01 level.

SOURCE VARIATION	DF	NO_{2+} NO_3	NH_4	PO_4	DIN	TN	TP
(A) TIME PERIOD	7	NS	NS	NS	**	NS	NS
(B) LOCATION	1	NS	NS	NS	NS	NS	NS
(C) HABITAT	1	NS	NS	NS	NS	NS	NS
A*B	7	NS	NS	NS	NS	NS	NS
A*C	7	*	NS	NS	**	NS	NS
B*C	1	NS	NS	NS	NS	NS	NS
A*B*C	7	NS	NS	NS	NS	NS	NS

Table 2.1.b. Summary table of analysis of variance results for physical and biological parameters in the **24 hour** temporal study. All data was log transformed after residual analysis for heteroscedascity. * = sign. at 0.1; ** sign. at 0.05; *** = sign. at 0.01 level.

SOURCE OF VARIATION	DF	Temper-ature	O_2	Suspended solids	Chl *a*	Phaeo phytin
(A) TIME PERIOD	7	***	**	***	NS	NS
(B) HABITAT	1	*	**	NS	NS	NS
A*B	6	NS	**	NS	NS	NS

Table 2.2.a. Summary table of analysis of variance results for nutrients in the **Diel** temporal study. All data was log transformed after residual analysis for heteroscedascity. * = sign. at 0.1; ** sign. at 0.05; *** = sign. at 0.001 level.

SOURCE VARIATION	DF	NO_{2+} NO_3	NH_4	PO_4	DIN	TN	TP
(A) DAY	2	NS	**	NS	**	NS	*
(B) LOCATION	1	NS	***	NS	**	NS	NS
(C) HABITAT	1	NS	NS	NS	*	NS	NS
A*B	2	NS	NS	NS	NS	NS	NS
A*C	2	NS	NS	NS	**	NS	NS
B*C	1	NS	NS	NS	NS	NS	NS
A*B*C	3	NS	NS	NS	***	NS	NS

Table 2.2.b. Summary table of analysis of variance results for physical and biological parameters in the **Diel** study. All data was log transformed after residual analysis for heteroscedascity. * = sign. at 0.1; ** sign. at 0.05; *** = sign. at 0.001 level.

SOURCE OF VARIATION	DF	Temper-ature	O_2	Suspended solids	Chl*a*	Phaeo phytin
(A) TIME PERIOD	7	***	**	***	NS	NS
(B) HABITAT	1	**	**	NS	NS	NS
A*B	6	*	**	NS	NS	NS

Table 2.3. Summary Table of Nutrient Water Quality parameters by time period.

Collection	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Time	710	1105	1420	1645	2110	2405	2700	3000
Tide	High Water		Low Water		High Water		Low Water	
Nitrite + Nitrate (μM)								
Mean ± SE	0.29±0.03	0.29±0.03	0.34±0.04	0.25±0.03	0.30±0.02	0.28±0.02	0.32±0.03	0.29±0.01
Range	0.23-0.35	0.20-0.46	0.21-0.32	0.13-0.34	0.23-0.39	0.19-0.34	0.14-0.41	0.24-0.34
N	8	8	8	7	8	8	8	8
Ammonium (μM)								
Mean ± SE	0.30±0.11	1.24±0.52	0.91±0.41	0.59±0.15	0.80±0.80	0.53±0.11	1.15±0.30	0.34±0.17
Range	0.00-0.55	0.40-3.71	0.19-1.60	0.06-1.15	0.00-1.60	0.11-0.75	0.42-1.63	0.11-0.57
N	5	6	3	6	2	5	4	3
DIN (μM)								
Mean ± SE	0.57±0.13	1.52±0.49	1.24±0.50	0.85±0.15	1.13±0.86	0.80±0.11	1.48±0.29	0.63±0.17
Range	0.24-0.91	0.71-3.90	0.41-2.15	0.33-1.36	0.27-1.99	0.39-1.06	0.67-2.04	0.28-0.85
N	5	6	3	6	2	5	4	3
Phosphate (μM)								
Mean ± SE	0.14±0.02	0.11±0.02	0.19±0.03	0.17±0.03	0.28±0.08	0.19±0.04	0.21±0.04	0.17±0.04
Range	0.11-0.22	0.06-0.16	0.14-0.22	0.07-0.81	0.17-0.54	0.11-0.36	0.14-0.30	0.08-0.22
N	5	6	3	6	4	5	4	3
Total Nitrogen (μM)								
Mean ± SE	5.97±0.70	7.74±1.19	2.58±1.56	5.37±0.26	6.83±0.76	6.67±0.73	6.12±0.39	9.63±3.97
Range	4.6-10.6	4.9-15.8	3.9-14.8	4.0-6.3	3.6-10.3	5.3-10.7	5.1-8.3	4.4-37.4
N	8	8	8	7	8	7	7	8
Total Phosphorous (μM)								
Mean ± SE	0.2±0.0.0	0.25±0.03	0.35±0.05	0.20±0.00	0.33±0.09	-	0.25±0.05	-
Range	0.2-0.2.0	0.2-0.3	0.3-0.4	0.2-0.2	0.2-0.5	-	0.2-0.3	0.3-0.6
N	2	4	2	1	3	0	2	0
Dissolved Oxygen (mg/l)								
Mean ± SE	7.38±0.20	9.53±0.99	8.35±0.75	8.20±0.30	7.28±0.22	7.20±0.40	7.70±0.15	6.45±1.84
Range	6.8-7.7	7.6-10.9	7.6-9.1	7.9-8.5	6.8-7.8	6.4-7.7	4.8-7.9	6.1-6.9
N	4	3	2	2	4	3	3	4
Temperature (° C)								
Mean ± SE	24.7±0.0	25.2±0.2	27.2±0.5	25.6±0.2	25.1±0.0	24.9±0.1	24.4±0.2	24.7±0.4
Range	24.6-24.8	24.8-25.4	26.7-27.6	25.4-25.8	25.1-25.2	24.7-25.0	24.0-24.7	24.3-25.1
N	4	3	2	2	4	3	3	2
Suspended solids (mg/l)								
Mean ± SE	2.1±0.1	-	2.3±0.5	2.6±0.4	1.6±0.1	1.9±0.1	1.8±0.1	1.8±0.0
Range	2.0-2.2	-	2.3-2.4	2.3-3.4	1.4-1.7	1.7-2.3	1.6-2.0	1.8.-1.8
N	2	0	2	4	4	4	4	4
Chlorophyll a (μg/l)								
Mean ± SE	-	6.41±2.24	0.68±0.00	2.35±1.86	-	3.06±1.86	-	-
Range	-	4.17-8.66	-	0.49-4.22	-	1.20-4.92	-	-
N	-	3	1	2	1	2	-	-

Table 2.4. Summary of **Habitat** differences of water quality parameters in Temporal Study. F = Flat; S = Slope.

		24 Hour Study				Diel Study			
Parameter	**Habitat**	**N**	**Mean**	**S.E.**	**Range**	**N**	**Mean**	**S.E.**	**Range**
Nitrite + Nitrate	F	31	0.31	0.05	0.13-0.55	12	0.35	0.02	0.23-0.49
(μM)	S	32	0.28	0.01	0.19-0.39	12	0.31	0.02	0.17-0.51
Ammonium	F	19	0.61	0.11	0.00-1.63	11	0.67	0.12	0.08-1.35
(μM)	S	15	0.89	0.23	0.00-3.71	18	0.72	0.14	0.01-1.25
DIN	F	19	0.93	0.13	0.27-2.15	10	1.04	0.15	0.31-1.73
(μM)	S	15	2.21	0.23	0.24-3.90	8	1.03	0.16	0.24-1.61
Phosphate	F	20	0.18	0.02	0.06-0.54	10	0.22	0.04	0.01-0.38
(μM)	S	16	0.17	0.01	0.08-0.26	9	0.22	0.03	0.12-0.36
Total Nitrogen	F	31	7.5	1.1	3.4-37.4	12	6.3	0.5	4.1-9.8
(μM)	S	30	5.9	0.5	3.6-15.8	12	7.7	0.7	4.6-12.3
Total Phosphorus	F	11	0.3	0.04	0.2-0.6	9	0.3	0.01	0.2-0.3
(μM)	S	5	0.2	0.02	0.2-0.3	8	0.3	0.03	0.2-0.4
Particulate N	F	-	-	-	-	6	1.45	0.12	1.2-1.8
(μM)	S	-	-	-	-	6	1.62	0.06	1.4-1.8
Dissolved Oxygen	F	9	7.01	0.56	4.8-10.9	3	7.67	0.52	6.8-8.6
(mg/l)	S	16	7.79	0.26	6.6-10.1	3	7.60	0.10	7.4-7.7
Temperature	F	8	24.7	0.2	24.0-25.4	5	25.1	0.4	24.5-26.8
(°C)	S	15	25.3	0.2	24.6-27.6	6	25.1	0.3	24.3-26.2
Chlorophyll *a*	F	8	3.94	1.44	0.68-8.66	2	0.43	0.04	0.40-0.53
(μg/l)	S	6	2.33	1.84	0.49-4.17	4	1.66	1.14	0.40-5.10
BOD_5	F	-	-	-	-	2	0.8	0.4	0.4-1.2
(mg/l)	S	-	-	-	-	4	0.3	0.1	0.1-0.5
Suspended solids	F	10	1.9	0.2	1.6-3.4	-	-	-	-
(mg/l)	S	14	2.0	0.1	1.4-2.4	-	-	-	-

Figure 2.2.a. Non-metric Multidimensional scaling (MDS) plot in 2 dimensions of pooled mean nutrient concentrations at 8 sampling times (1-8) from the temporal pilot study. Between sample similarities were calculated using the Bray-Curtis coefficient. Stress for the MDS is low at 0.03.

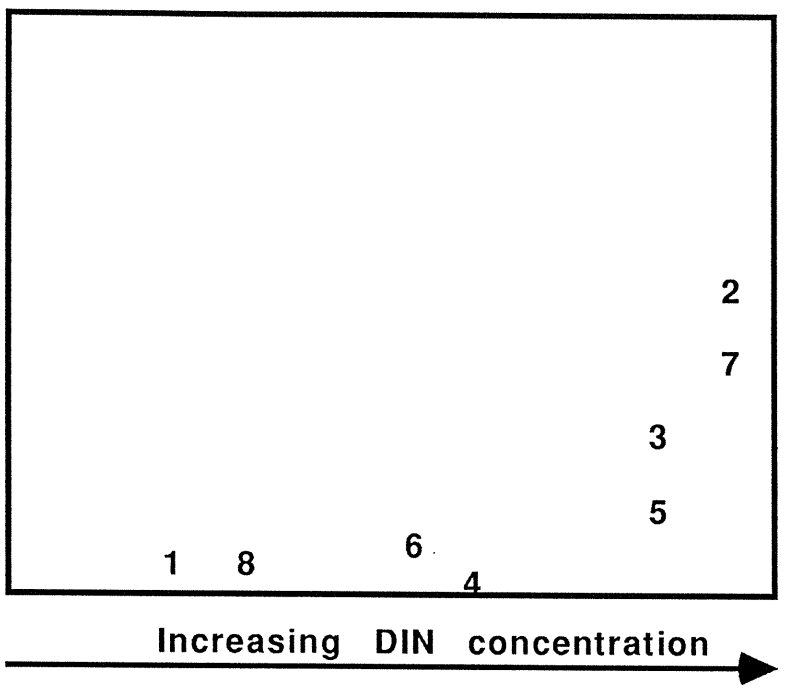


Figure 2.2.b. Dendrogram of classification of time periods in the 24 hour study by mean concentration of inorganic nutrients. Between sample similarities were calculated using the Bray-curtis coefficient, and an unweighted group mean sorting strategy was applied.

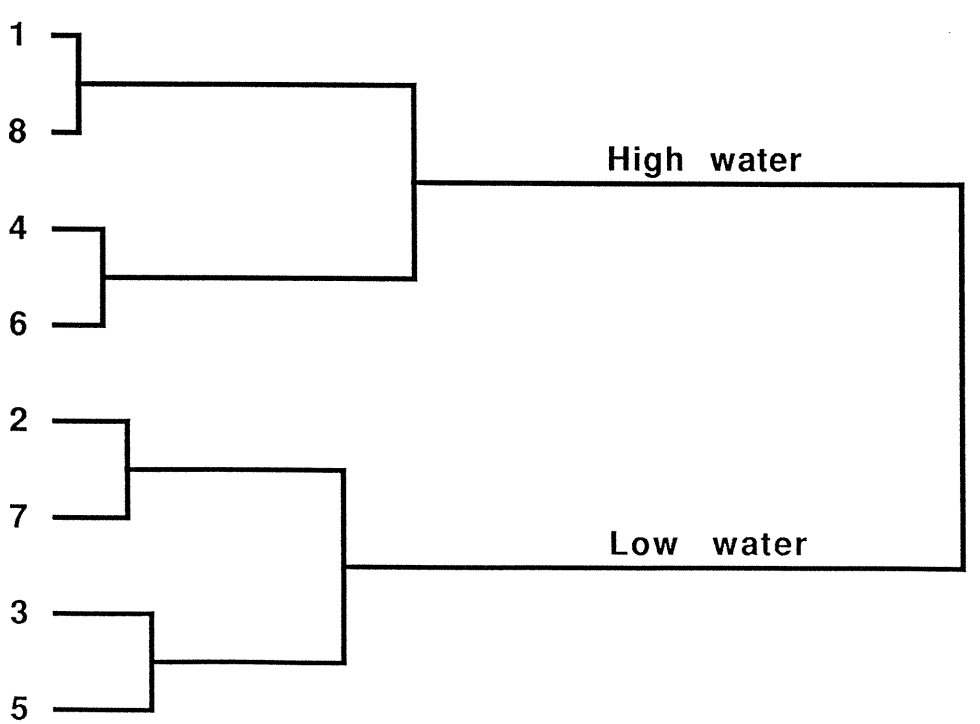


Figure 2.4. Pooled Mean concentration (uM) of Phosphate, Total Nitrogen anf Total Phosphorous over the eight sampling periods in the 24 hour temporal study around Green Island.

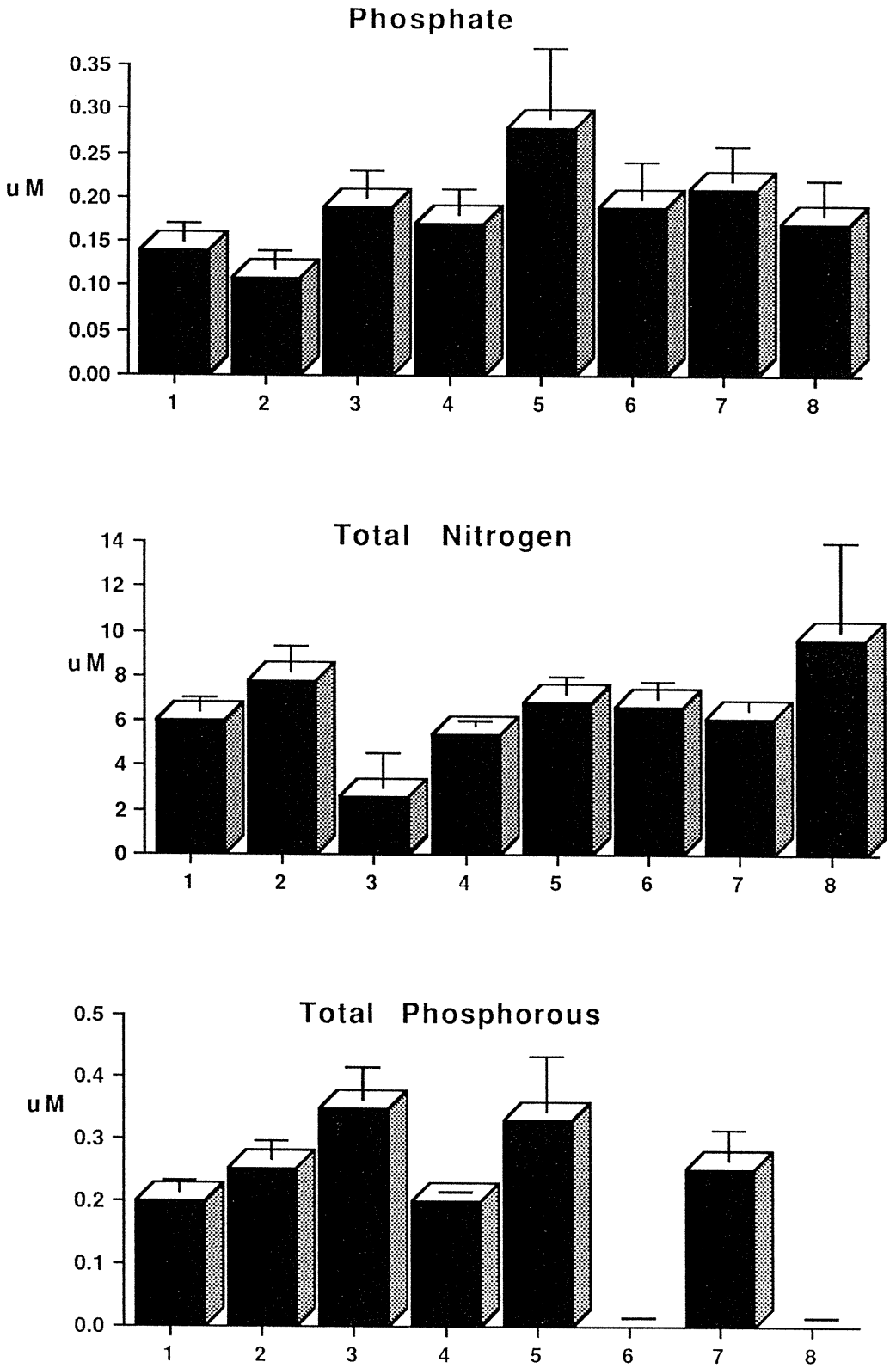
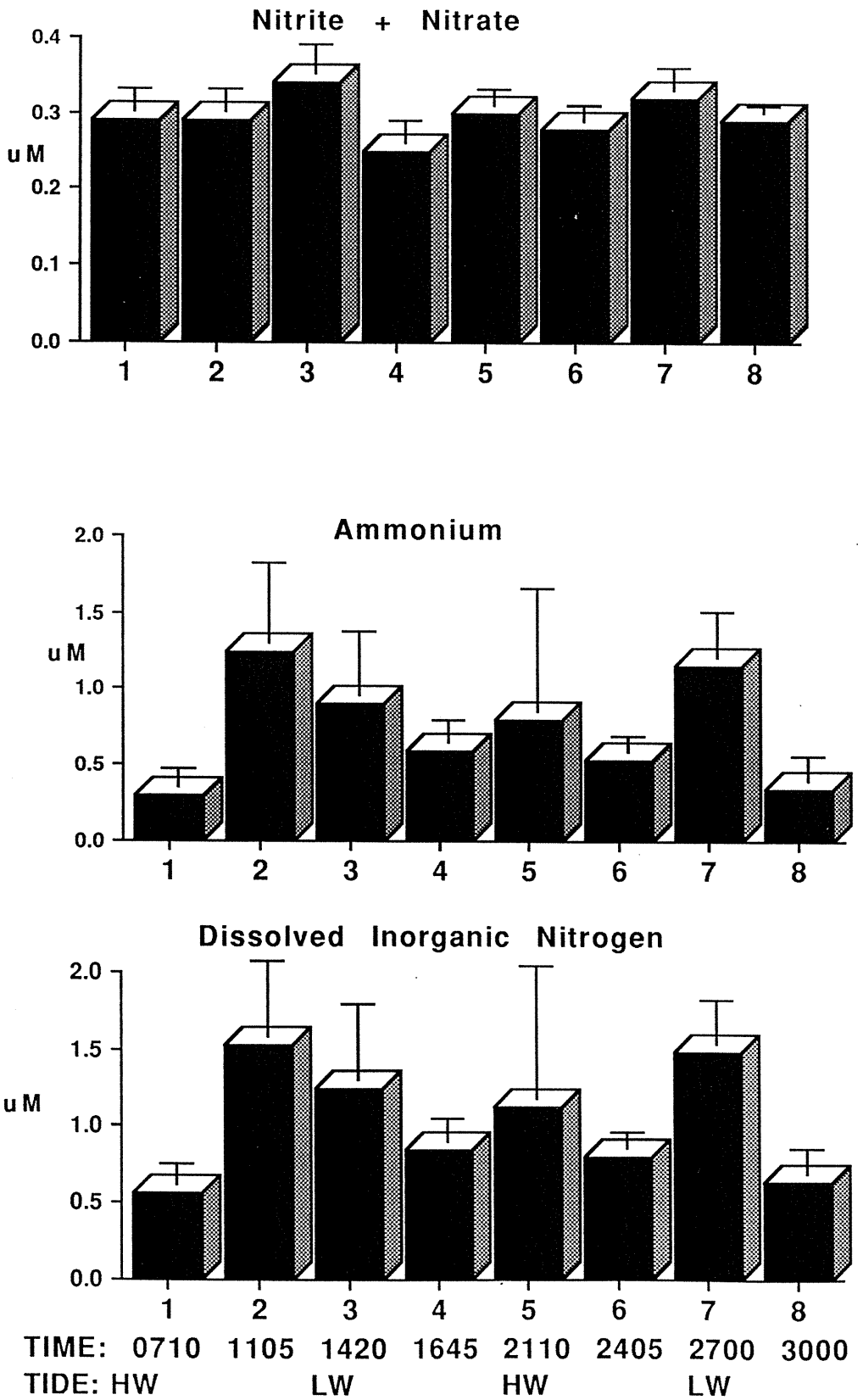


Figure 2.3. Pooled mean concentration (uM) of Nitrite + Nitrate, Ammonium and Dissolved Inorganic Nitrogen over the eight sampling periods in the 24 hour temporal study around Green Island.



CHAPTER 3: SPATIAL STUDY OF VARIATION

3.1 MATERIAL AND METHODS

3.1.1 Objectives

To assess spatial variation in water quality around Green island with respect to depth and over a range of nested horizontal scales.

3.12 Variables

- Dissolved Inorganic Nutrients, NO_2 + NO_3, NH_4, PO_4
- Total Phosphorous and Total Nitrogen
- Dissolved oxygen
- Clarity
- Chlorophyll *a*
- BOD_5
- Suspended solids

Section 1.4.2 details the sampling procedures, whilst Appendix 2 gives the analytical procedures used for the determination of these parameters.

3.1.3 Experimental Design

Sampling was undertaken to assess the contribution of the following factors to variabilty in water quality around at Green Island. Sampling was undertaken only in the reef slope environment. Figure 3.1.b. represents the sampling of these factors schematically.

Depth: Variation between 2 depths. Surface samples were taken at 0.2 m below the surface, and depth samples were taken 1 metre above the bottom (ca. 7-10 metres).
Location: Variation between 6 locations (Figure 3.1), each location a minimum of 500 metres apart. Locations were selected to cover the range of environmental conditions around Green Island.
Site: Variation between 2 sites within each location, ca. 75-100 metres apart.
Replication: Variation between 2 replicate samples, ca. 5-10 metres apart, taken at each combination of site and depth.

3.1.4 Site Selection

Sampling locations were selected to quantify the range of ambient conditions around the island. On the western side of the island, locations A and B from the temporal study were utilised. Locations C and D were located at the southern end of the island, location C being in an embayment. Locations E and F were located on the eastern side of the island (Figure 3.1).

Table 3.1. Description of sampling locations

Location	Description
A	250 metres north of the sewerage pipe and some 100m south of the jetty in line with the outer lead light.
B	250 metres to the south of the sewerage pipe. Both flats and slopes sampled.
C	On the western side of the reef away from the influence of the cay. In an embayment along the consolidated reef edge at ca. 7 metres.
D	At the southern end of the reef in a bommie field at ca. 7 metres depth.
E	Located at the north-eastern end of the reef amongst patch reefs at ca. 8 metres depth.
F	Located at the south eastern end of the reef amongst patch reefs at ca. 8 metres depth.

3.1.5 Timing

The spatial sub-programme was undertaken on the the 3rd of June 1989 from 1010 to 1710 hours.

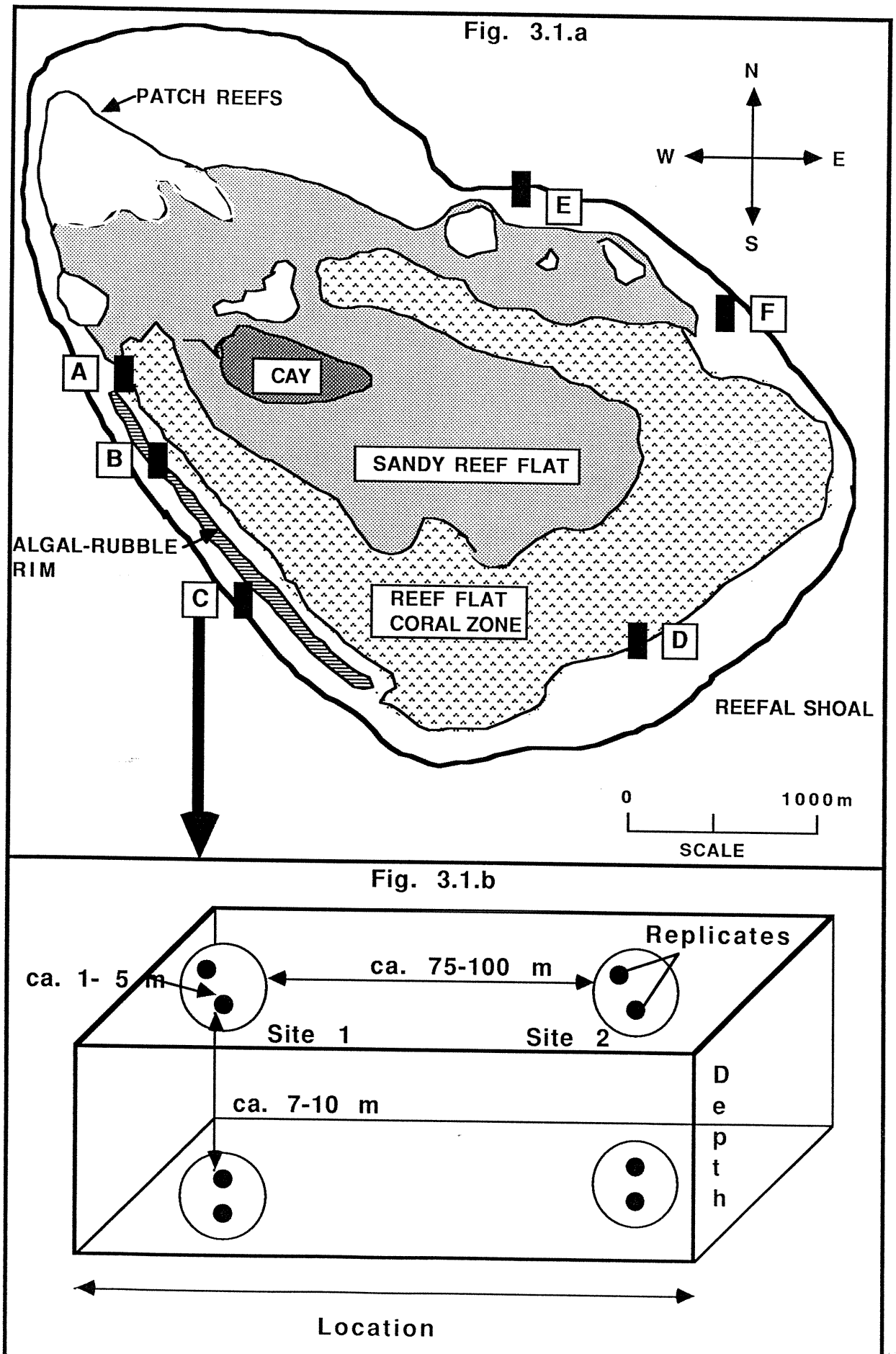
3.1.6 Constraints

As this study was not repeated on any other days due to cost constraints it must be assumed that conditions on June 3, 1989 were typical. The extent to which temporal variabilty may have confounded the apparent spatial patterns was qualitatively examined using the temporal study results.

3.1.7 Analysis

The analysis of spatial variation constituted a three factor design, (location x depth x site). Location and depth were treated as fixed orthogonal factors, whilst sites was considered a random variable and was nested within location.

Figure 3.1. Map of Spatial study sampling locations around Green Island (3.1.a.) and a schematic representation of the sampling design (3.1.b).



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P.O. Box 1379

3.2 RESULTS

3.2.1 Components of Variation

Depth Effects

Ammonium was the only parameter to potentially vary, albeit marginally (F = 14.02; 1,22 df; P = 0.056) between samples taken on the surface (0.90 ± 0.15 μM) and at depth (0.76 ± 0.06 μM). Data for depths were subsequently pooled to analysis of other factors. Table 3.3 summarises mean values of water quality parameters by depth.

Location Effects

Location was a significant source of variation for all inorganic nutrients, but not for total phosphorous, total nitrogen or particulate nitrogen (Table 3.2.a.). Pooled mean values are summarised in Table 3.4.a. Nitrite + nitrate mean concentrations at locations A (0.27±0.01 μM) and C (0.23±0.02 μM) were both significantly less (F = 5.37; 5,6 df; P = 0.032) in mean concentration from locations D (0.38±0.03 μM) and E (0.37±0.02 μM). Location F (0.35±0.03 μM) was also significantly different from location C. Differences in ammonium concentrations between locations were only marginally significant (F = 5.49; 5,6 df; P = 0.079) and consequently were not detectable using Tukey's test. Dissolved inorganic nitrogen concentration were significantly (F = 5.61; 5,6 df; P = 0.021) higher at location D (1.69±0.27 μM) than at locations A (0.89±0.09 μM) and E (0.78±0.16 μM).The mean orthophosphate concentration at location B (0.21±0.02 μM) was significantly (F = 8.58; 5,6 df; P = 0.010) higher than location E (0.13±0.04 μM). Differences in location were not a significant source of variation for dissolved oxygen, temperature and BOD_5.

Site Effects

Sites, nested within locations, were not a significant source of variation in any cases (Table 3.2).

3.2.2 Analysis of Power

Power was less than 0.4 to detect differences in the spatial study for small changes (<25%) in ambient water quality parameters. However, the ability to detect moderate changes (> 50%) was good (P = 0.93). There may have been some temporal confounding but the results of the temporal study indicated this was unlikely.

3.2.3 Multi-variate analysis

Classification analysis (Figure 3.2.a.) showed that locations split broadly into windward (D and F) and leeward (A,B, and C). However, location E, on the north-eastern edge of the reef was highly dis-similar. The MDS analysis (Figure 3.2.b.) suggested that sites grouped according to DIN concentration. Locations on the windward side of Green Island had a greater concentration of DIN whilst location E had the least.

Table 3.2.A. Summary table of results of analysis of variance results for nutrients in the spatial study. All data was log transformed after residual analysis for heteroscedascity. * = sign. at 0.1; ** sign. at 0.05; *** = sign. at 0.01 level.

SOURCE OF VARIATION	DF	NO_2+ NO_3	NUTRIENT SPECIES NH_4	DIN	PO_4	TN	TP
(A) DEPTH	1	NS	NS	*	NS	NS	NS
(B) LOCATION	5	**	***	***	**	NS	NS
(C) SITE(LOCATION)	6	NS	NS	NS	NS	NS	NS
A*B	5	NS	NS	NS	NS	NS	NS
A*C	6	NS	NS	NS	**	**	NS

Table 3.2.b. Summary table of results of analysis of variance results for nutrients in the spatial study. All data was log transformed after residual analysis for heteroscedascity. * = sig at 0.1; ** sig at 0.05; *** = sig at 0.01 level.

SOURCE OF VARIATION	DF	Tempera-ture	O_2	BOD5	PN
(A) DEPTH	1	NS	NS	NS	NS
(B) LOCATION	5	NS	NS	NS	NS
A*B	6	NS	NS	NS	NS

Table 3.3. Summary statistics of Depth Differences in the Spatial Study. S= surface; D = depth.

Parameter	Habitat	N	Mean	S.E.	Range
Nitrite + Nitrate	S	23	0.33	0.02	0.17-0.46
(μM)	D	23	0.31	0.02	0.20-0.51
Ammonium	S	21	0.90	0.15	0.03-2.29
(μM)	D	19	0.76	0.06	0.33-1.45
DIN	S	20	0.49	0.04	0.28-0.84
(μM)	D	17	0.45	0.02	0.35-0.63
Phosphate	S	22	0.17	0.02	0.01-0.41
(μM)	D	23	0.17	0.08	0.04-0.41
Total P	S	9	0.4	0.02	0.3-0.5
(μM)	D	12	0.4	0.05	0.2-0.9
Total N	S	23	6.6	0.5	3.2-12.3
(μM)	D	23	7.5	0.7	2.8-15.0
Dissolved Oxygen	S	11	8.44	0.24	7.7-10.5
(mg/l)	D	12	8.42	0.13	7.8-9.2
Temperature	S	12	26.4	0.06	26.1-26.7
(°C)	D	12	26.3	0.04	26.1-26.5

Table 3.4. Summary Table of Water Quality parameters by location.

Parameter	Location A	B	C	D	E	F
Nitrite + Nitrate (μM)						
Mean	0.27±0.01	0.31±0.03	0.23±0.02	0.38±0.03	0.37±0.02	0.35±0.03
Range	0.24-0.33	0.17-0.42	0.17-0.34	0.27-0.51	0.26-0.44	0.20-0.46
N	7	7	7	8	8	8
Ammonium (μM)						
Mean	0.62±0.01	0.74±0.06	0.82±0.22	1.33±0.27	0.39±0.18	1.02±0.31
Range	0.46-1.13	0.56-1.03	0.51-2.15	0.50-2.20	0.03-0.96	0.08-2.28
N	8	8	7	6	5	6
DIN (μM)						
Mean	0.89±0.09	1.08±0.08	1.08±0.29	1.69±0.27	0.78±0.16	1.33±0.31
Range	0.72-1.38	0.88-1.45	0.70-2.48	0.85-2.49	0.46-1.29	0.48-2.61
N	7	7	6	6	5	6
Phosphate (μM)						
Mean	0.19±0.02	0.21±0.02	0.14±0.02	0.20±0.03	0.13±0.04	0.16±0.02
Range	0.13-0.27	0.12-0.27	0.09-0.25	0.07-0.30	0.01-0.41	0.07-0.27
N	8	7	7	7	8	8
Total N (μM)						
Mean ± SE	7.4±1.4	6.3±0.8	5.8±0.6	5.7±0.6	7.9±1.1	9.0±1.1
Range	3.9-14.7	2.8-9.0	4.4-8.3	3.2-9.1	4.6-15.0	4.6-14.7
N	8	7	7	8	8	8
Total P (μM)						
Mean ± SE	0.4±0.03	0.4±0.03	0.4±0.07	0.3±0.0	0.5±0.1	0.3±0.03
Range	0.3-0.4	0.3-0.4	0.3-0.4	0.3-0.3	0.3-0.9	0.2-0.4
N	4	4	2	1	5	5
Particulate N (μM)						
Mean ± SE	1.5±0.1	1.1±0.1	1.4±0.2	3.9±2.7	1.4±0.2	1.4±0.1
Range	1.4-1.6	1.0-1.2	1.2-1.6	1.2-6.6	1.2-1.6	1.3-1.5
N	2	2	2	2	2	2
BOD_5 (mg/l)						
Mean ± SE	0.3±0.2	1.4±1.1	0.5±0.2	0.9±0.2	1.1±0.1	0.5±0.1
Range	0.1-0.5	0.2-2.5	0.3-0.7	0.1-1.1	1.0-1.2	0.4-0.6
N	2	2	2	2	2	2
Dissolved Oxygen (mg/l)						
Mean ± SE	7.78±0.05	9.03±0.55	8.33±0.16	8.40±0.13	8.40±0.14	8.53±0.28
Range	7.7-7.9	8.0-10.5	8.1-8.8	8.2-9.7	8.1-8.6	8.0-9.1
N	4	4	4	4	4	4
Temperature (°C)						
Mean ± SE	26.3±0.03	26.4±0.14	26.3±0.12	26.3±0.11	26.4±0.0	26.5±0.0
Range	26.2-26.3	26.1-26.7	26.1-26.6	26.1-26.6	26.4-26.4	26.5-26.5
N	4	4	4	4	4	4

Figure 3.2.a. Non-metric Multidimensional scaling (MDS) plot in 2 dimensions of mean nutrient concentrations at 6 locations (A-F) from the spatial pilot study. Between sample similarities were calculated using the Bray-Curtis coefficient. Stress for the MDS is low at 0.03.

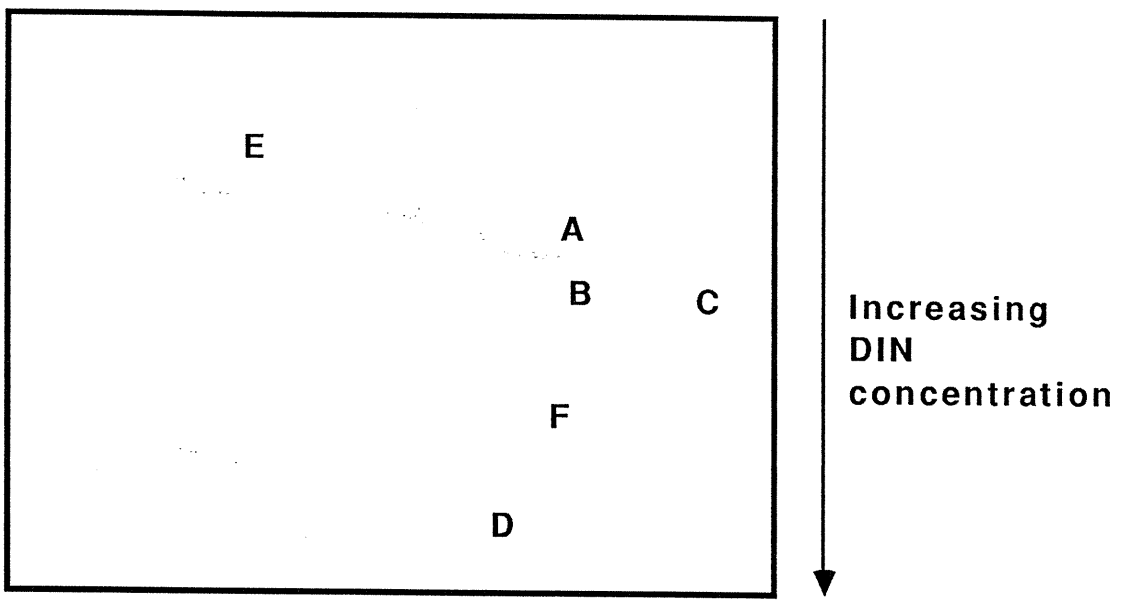


Figure 3.2.b. Dendrogram of classification of locations in the spatial study by mean concentration of inorganic nutrients. Between sample similarities were calculated using the Bray-curtis coefficient, and an unweighted group mean sorting strategy was applied.

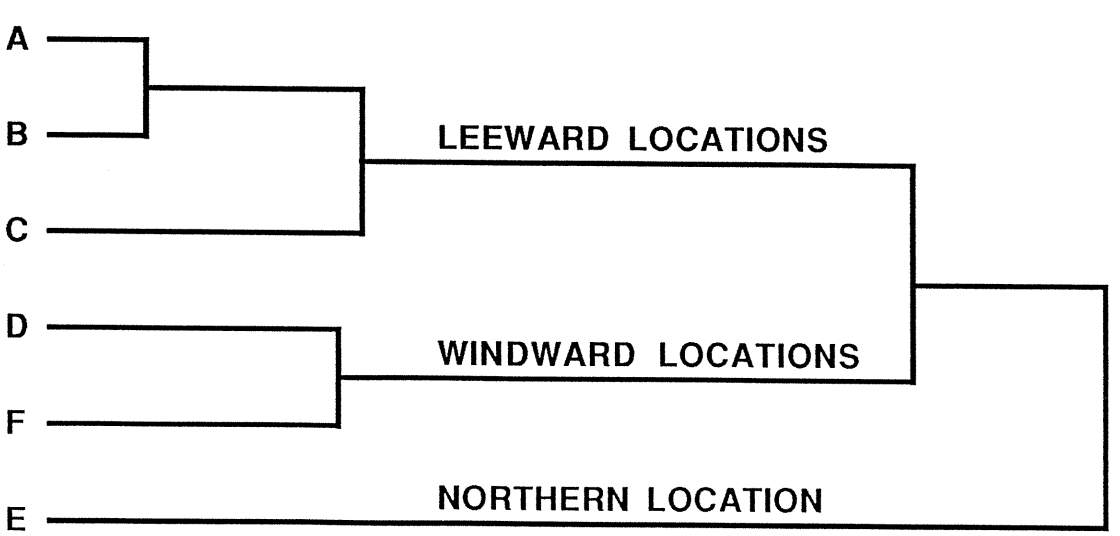


Figure 3.3. Pooled mean concentration (uM) of Nitrite+Nitrate, Ammonium and Dissolved Inorganic Nitrogen between locations in the Spatial study of variation around Green Island.

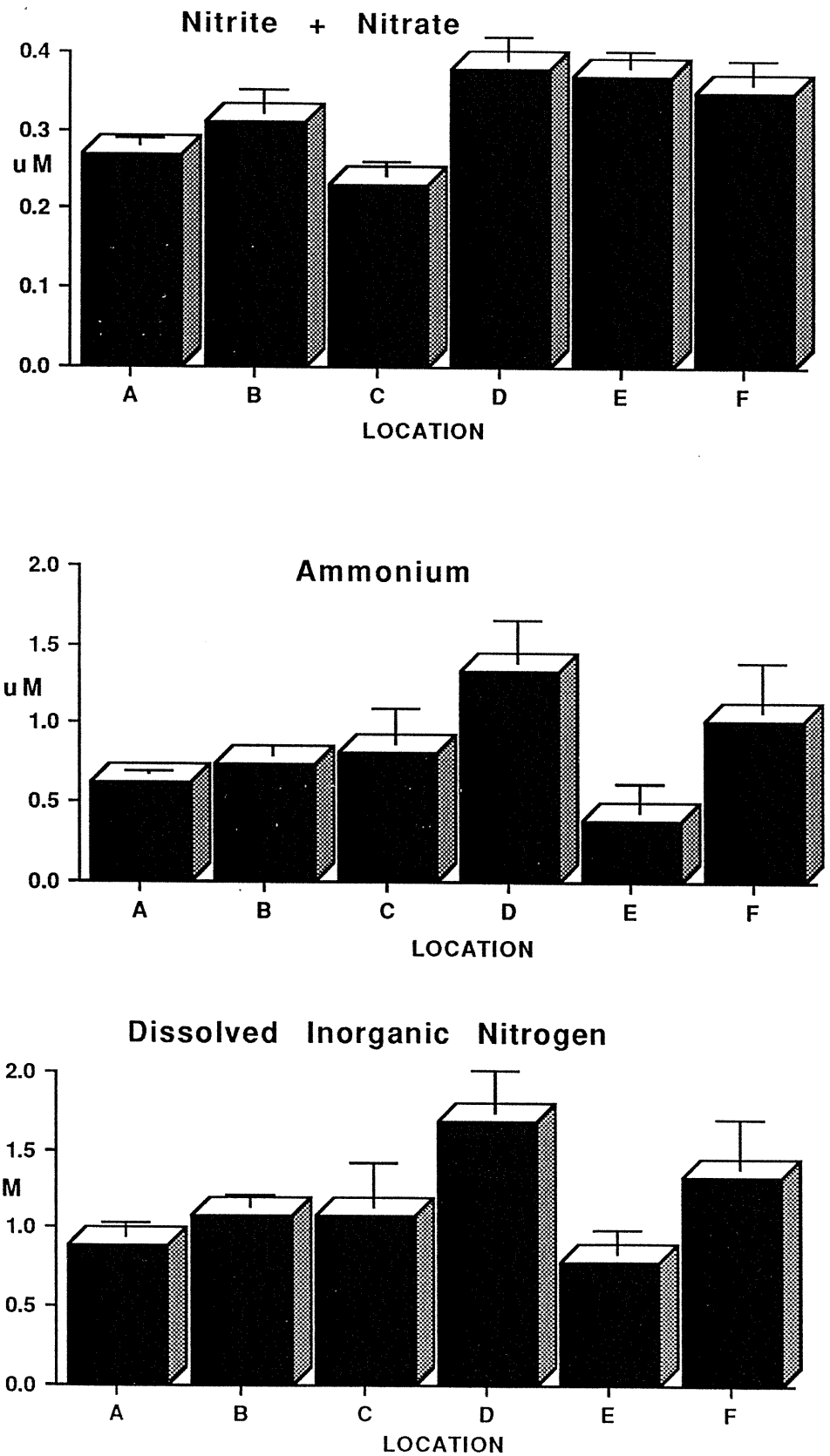
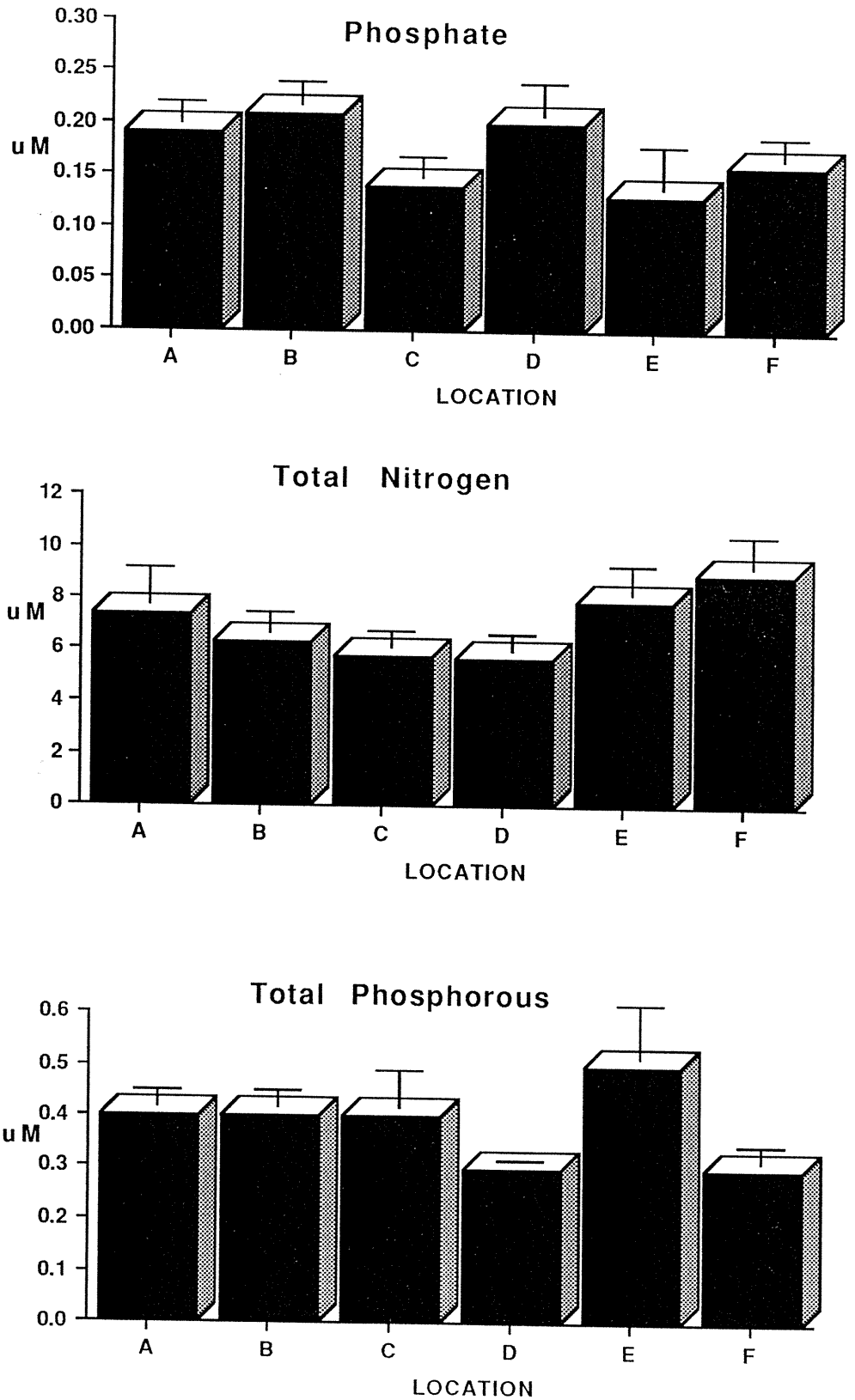


Figure 3.4. Pooled mean concentration (uM) of Phosphate, Total Nitrogen and Total Phosphorous and between locations in the Spatial study of variation around Green Island.



CHAPTER 4: DISCUSSION

3.1 WATER QUALITY PARAMETERS

The spatial and temporal variability of individual water quality parameters and comparison to data from other studies is discussed below. The usefulness and sampling constraints of each parameter is assessed.

4.1.1 Nitrite + Nitrate

Large scale location differences were the only significant source of variation. Values ranged between 0.13 and 0.54 μM with an overall mean of 0.32 $\pm$0.01 μM. Between locations mean values ranged from 0.23$\pm$0.02 μM (location C, hereafter C) to 0.38$\pm$0.03 μM (D). Locations D,E and F were significantly higher in mean concentration, than the other 3 locations. Over 24 hours mean values ranged between 0.25$\pm$0.03 μM (T4) and 0.34$\pm$0.04 μM (Time 3, hereafter T3) with an overall pooled mean of 0.30$\pm$0.01 μM. A pooled mean from the diel study of 0.33 $\pm$ 0.02 μM was obtained.

The range of values found in this study are similar to those found by Brady (1989) in a transect from the Barron River (0.33-0.51 μM), and to other studies in the GBRL, at Magnetic Island (0.28 μM, Brodie *et al.* 1989), Hayman Island (0.27 μM, Steven and van Woesik 1989), and shelf waters in the Whitsundays (0.38 μM, Furnas, *et al.* 1988). At John Brewer reef Jones *et al.* (1989) found that sampling in the presence of *Trichodesmium* blooms gave significant differences in nitrite + nitrate concentrations (0.26 μM) compared to sampling in the absence of such phenomena (0.45μM). This clearly indicates that sampling studies need to consider a range of biological and physical phenomena.

4.1.2 Ammonium

Ammonium was the most labile nutrient species with values ranging from 0.01 to 3.71 μM, indicating high small scale patchiness. Spatial variation between locations and temporal differences between days were significant sources of variation. However, the high variability between replicates may have masked the significance of other factors. Mean values between locations in the spatial study varied between 0.39$\pm$0.18 (E) and 1.33$\pm$0.28 μM (E) with an overall mean of 1.14$\pm$0.09 μM. Temporal variation over 24 hours was similar ranging from 0.30$\pm$0.11 μM (T1) to 1.24$\pm$0.52 μM (T2). Pooled mean values for the 3 studies were similar (Table 4.1).

In comparison Brady (1989) found relatively low levels (0.04-0.14 μM) of ammonium in a transect out from the Barron river. However, most studies on the GBR have noted a great range of ammonium concentrations; Magnetic Island (0.07-2.8 μM, Brodie *et al.*, 1989), Hayman island (1.0-15.0 μM, Steven & van Woesik, 1989) and Hamilton Island (0.2-1.6 μM, Blake and Johnson, 1988). Jones (1989) noted high levels of ammonium during a 24 hour survey at John Brewer reef (ca. 0.74 μM). He attributed these high ammonia concentrations to a combination of increased tidal mixing, rough weather and also releases from sediments. Increased turbulence resulting from zero tides during the present study most probably released ammonia from sediment pore waters resulting in occasional high ammonia and nitrite + nitrate concentrations. The extremely patchy distribution of ammonium can pose problems in statistical analysis as the often high within sample (between replicate) variance can result in non significant results despite the apparently wide range of concentrations (Boto and Wellington, 1988). Care is needed in interpreting arithmetic means for ammonium and factors such as *Trichodesmium* blooms and other sources of ammonification should be considered.

4.1.3 Dissolved inorganic nitrogen (DIN)

DIN concentrations varied temporally with respect to day and time of day, and spatially between locations and between habitats. Between locations DIN values ranged from 0.78 ± 0.16 μM (E), and 1.68 ± 0.27 μM (D), with a pooled mean concentratation of 1.14 ± 0.09 μM. DIN levels on day 1 were significantly less (0.57 ± 0.13 μM) than on days 2 and 3 (1.19 ± 0.13 μM, 1.24 ± 0.17 μM). Over 24 hours mean values ranged from 0.57 ± 0.02 μM (T1) to 1.48 ± 0.30 μM (T7). Overall mean values for the 24 hour and the Diel study were similar (1.02 ± 0.12 μM and 1.03 ± 0.11 μM respectively).

Brady (1989) noted concentrations of 0.63 μM around Green Island. The range of DIN values recorded at Green Island (0.24-3.91 μM) are also similar to values recorded in other studies on the GBR (Steven & van Woesik, 1989; Blake & Johnson, 1988; Brodie *et al.*, 1989).

4.1.4 Orthophosphate

Orthophosphate concentration did not vary significantly ($P < 0.05$) with respect to any of the temporal or spatial factors measured. Values ranged from 0.01 to 0.41 μM with an overall mean of 0.17 ± 0.01 μM. Over 24 hours means ranged from 0.11 ± 0.02 μM (T2) to 0.28 ± 0.08 μM (T5), with an overall mean of 0.18 ± 0.01 μM. A pooled mean of 0.22 ± 0.02 μM was calculated in the diel study. Between locations mean orthophosphate concentration was greatest at B (0.21 ± 0.02 μM) and least at E (0.13 ± 0.04), with an overall mean of 0.17 ± 0.01 μM.

Brady (1989), found orthophosphate concentrations decreased in a transect from the mouth of the Barron river (0.22 μM) to Green Island (0.11 μM) with an overall mean concentration of 0.17±0.05 μM. Other studies at Magnetic Island (0.20 ±0.02 μM, Brodie *et al.*, 1989) and the Whitsundays (0.23 uM, Furnas et al., 1988) have found similar concentrations. Jones *et al.*, 1989 noted during Trichodesmium bloomsthere was a 23% increase in dissolved inorganic phosphate.

4.1.5 Total Phosphorous

TP concentrations differed marginally between days (F = 3.83; 2,16 df; P = 0.075), but the loss of a number of samples due to contamination, makes these results speculative. Mean TP values ranged from 0.3 μM (D, 1 sample) and 0.5±0.1 (E) between locations with an overall mean of 0.38±0.03 μM. Over 24 hours values ranged from 0.2±0.0 (T1) to 0.45±0.15 (T8) with a pooled mean of 0.29±0.03 μM. A similar mean of 0.3±0.02 μM was found for the diel study.

Levels of TP were approximately twice that of orthophosphate. This is similar to results found elsewhere (Brodie *et al.*, 1989 and Furnas *et al.*, 1988). Brady (1989) found a range of TP concentrations from 0.94 to 1.12 μM in a transect from the Barron river to Green Island, but also noted blooms of the blue green algae *Trichodesmium*. Few other estimates of TP exist for the GBR.

Jones *et al.*, (1989) found a range of 3.42 to 4.27 μM at John Brewer reef

4.1.6 Total Nitrogen

Apart from a marginally significant depth by location interaction effect (P = 0.042) there were no other detectable differences in TN over any spatial or temporal scales. Mean concentrations over 24 hours ranged from 4.7±0.7 μM (T4) to 9.6±0.2 μM (T8) with a pooled mean of 7.05±0.59. Similarly in the spatial study values ranged from 5.1±0.9 μM (C) to 9.0±1.1 μM (F) with an overall mean from the spatial study of 7.06±0.43 μM. A mean of 7.01±0.43 was calculated from the diel study.

Few measurements of total nitrogen have been made on the GBR. Jones *et al.*, (1989) found a range of 3.6 to 8.2 μM at John Brewer reef.

4.1.7 Particulate Nitrogen

No significant differences were found at any spatial or temporal scales. Pooled mean values were 1.78±0.41 μM for the spatial study and 1.53±0.6 μM for the diel study. However, there was low power for detecting differences between depths ($P < 0.66$) and locations ($P < 0.3$) for moderate changes (50%) in ambient conditions. The values obtained are however similar to values found by Furnas *et al.* (1988) in the Whitsundays (2.0 ± 0.5 μM) and in the Central and Southern GBR (1.6 ± 0.4 μM), and by Crossland and Barnes (1983) at Lizard Island (1.2 ± 0.4 μM).

Differences in the measurement technique used in different studies makes comparisons difficult.

4.1.8 Dissolved Oxygen and Temperature

Short term temporal differences were the major source of variation for oxygen and temperature. Mean dissolved oxygen and temperature were greater over sampling times T2 to T4 (Table 2.3.b.) consistent with increases in solar irradiation, and surface water mixing due to strengthening wind conditions (i.e sea breezes). No significant spatial difference either between depth or location were recorded. Marginal habitat differences ($P < 0.05$) are ambiguous (Table 2.3.b).

4.1.9 Suspended Solids

Suspended sediment concentration varied significantly between time periods, consistent with resuspension during low tide. Mean values ranged from 1.58 mg/l (T5) to 2.63 mg/l (T4) with an overall mean of 1.98±0.09 mg/l.

Brodie *et al.* (1988) found a mean suspended sediment level of 3.95±4.29 mg/l at Magnetic Island. Results from John Brewer reef lagoon (2.64 mg/l) are more comparable (Jones *et al.*, 1988) to Green Island.

4.1.10 Clarity

Water clarity data, measured with a secchi disk was greater than the total depth of water on the reef, and consequently provided no useable information. Further, suspended sediment measurements cannot be strongly correlated with clarity. Nephelometric turbidity instruments aren't sensitive enough to give reliable readings. The use of multi-level light sensors at different depths which give instantaneous extinction coefficient readings may help to overcome some of these problems in future sampling programmes.

4.1.11 Chlorophyll *a*

No significant spatial or temporal variation was identified in the study, as samples varied widely. Values of Chlorophyll *a* ranged from 0.4 μg/l to 8.4 μg/l with an overall value of 3.48$\pm$1.11 μg/l. The high range of values and suggest that high within sample variance and insufficient replication may have resulted in the non-significance of these results.

Brodie *et al.*, 1989 noted a large range (0.05-2.0 μg/l) of Chlorophyll *a* values at Magnetic Island with significant inter site variation. Furnas *et al.*, (1988) noted a difference in chlorophyll *a* between coastal waters in the Whitsundays (1.17$\pm$0.25 μg/l) and shelf waters (0.68$\pm$0.13 μg/l). Jones *et al.*, (1989) found a mean of 0.58 μg/l at John Brewer reef and noted a 56% decrease in Chlorophyll *a* in the presence of *Trichodesmium* blooms.

4.1.12 Biological Oxygen Demand

No significant spatial or temporal variation was identified in the study. Values ranged from 0.1- 2.5 mg/l with an overall value of 0.47$\pm$0.16 mg/l around the sewage pipe and 0.78$\pm$0.18 mg/l averaged over all locations. This is within the range of value reported by other workers on the GBR (1.1 mg/l, Brodie *et al.*, 1989 ;0.5 mg/l, Jones *et al.*, 1989). Bell *et al.* (1987) notes a value of 0.7 mg/l for unpolluted Carribean reefs. Measurement difficulties with BOD levels as low as this make comparisons, either within the present study or with other workers results, problematic.

Table 4.1. Summary of mean values from the Spatial and Temporal Study.

Parameter	Spatial Study N	Mean	S.E.	Range	24 Hour Study N	Mean	S.E.	Range	Diel Study N	Mean	S.E.	Range
Nitrite + Nitrate (μM)	45	0.32	0.01	0.17-0.51	63	0.29	0.01	0.13-0.54	23	0.33	0.02	0.17-0.51
Ammonium (μM)	39	0.82	0.09	0.03-2.28	34	0.73	0.12	0.00-3.71	19	0.69	0.09	0.00-1.35
DIN (μM)	37	1.14	0.09	0.46-2.61	34	1.02	0.12	0.24-3.91	18	1.03	0.11	0.24-1.73
Phosphate (μM)	45	0.17	0.01	0.01-0.41	36	0.17	0.01	0.06-0.54	19	0.22	0.02	0.01-0.38
Total Nitrogen (μM)	46	7.1	0.4	2.8-15.0	61	6.72	0.59	3.6-37.4	24	7.01	0.41	4.1-12.3
Total Phosphorous (μM)	21	0.38	0.03	0.2-0.9	16	0.29	0.03	0.2-0.6	17	1.14	0.02	0.2-0.4
Particulate N (μM)	12	1.8	0.4	1.0-6.6	-	-	-	-	12	1.5	0.1	12.0-18.0
Dissolved Oxygen (mg/l)	12	8.45	0.13	7.7-10.5	32	7.51	0.23	4.8-10.9	12	7.6	0.3	6.8-8.6
Temperature (^{o}C)	12	26.3	0.1	26.1-26.7	32	25.1	0.2	24.0-27.6	11	25.1	0.2	24.3-26.8
Chlorophyll *a* (μg/l)	-	-	-	-	10	3.48	1.11	0.49-8.66	7	1.14	0.66	0.4-5.1
BOD_5 (mg/l)	12	0.7	0.2	0.1-2.5	-	-	-	-	6	0.41	0.17	0.0-1.2
Suspended solids (mg/l)	-	-	-	-	24	2.0	0.1	1.4-3.4	-	-	-	-

4.2 GENERAL DISCUSSION

This study demonstrated that there were significant differences in concentrations of inorganic nutrients between locations around Green Island. Higher concentrations of DIN were recorded at locations on the windward side of the reef (D & F), and a significantly lower concentration of DIN at location E on the north-eastern side of the reef in an area of patch reefs. There was also some evidence of potential difference in DIN concentration by habitat in the temporal study. However, habitat differences were only tested on the leeward side of the reef. However, given the study was undertaken over a very small time frame it is impossible to draw any firm conclusions regarding the source of these enhanced levels of nitrogen. A detailed understanding of both large and local scale hydrodynamics is required to adequately test such hypothesees. These findings are however, consistent with observations by other workers (Webb *et al.* 1975; Andrews and Muller, 1983; Crossland, 1983; Entsch *et al.* 1983; Hatcher and Frith, 1985). In a recent review Hamner and Wolanski (1988) suggest that water flowing over the reef crest is qualitatively different from the water seaward of the reef because it is it is modified by biological processes (e.g. fish feeding and defaecating) and physically through wave energy (e.g. resuspension of sediments and detritus). Other workers (Webb *et al.* 1975; Andrews and Muller, 1983; Crossland, 1983; Entsch *et al.* 1983; Hatcher and Frith, 1985) found that DIN levels on portions of the reef complex were found to alter as water flows across the reef.

Differences were significant between days but not over smaller time frames. It is considered that seasonal differences would be substantial as a number of studies have noted seasonal differences (Andrews and Muller, 1983; Crossland, 1983; Hatcher and Frith 1985). Hatcher and Frith (1985) found the relative influence of advection across the the windward reef crest changed with season and differed for the two forms of DIN. The relative magnitudes of fluxes are more similar to each other in summer than in winter indicating the potential for shifts in the dominance hierarchy at small time and space scales. They further note this variability between nitrogen species has implications for sampling strategies. i.e. different time frames.

Differences in phosphate concentration were apparent between locations only.
Changes in the concentration of phosphorous across the reef are difficult to measure because rates of phosphorous uptake from the water column by reef communities is slow (ca. 1-2 %) relative to to the flux of water (Atkinson and Smith 1987). No significant diurnal changes of phosphate have been noted although changes with time of year were detected (Pilson and Betzer, 1973).

No effects attributable to the discharge of sewage were detected, though it should be emphasized this was not an objective of the pilot study. It was noted sewage was discharged on the the 2nd

June at ca. 1500 hours. A pulse of increased phosphate concentration was detected in a few samples at time 4 (1645, flooding tide, 0.81 μM) on the slope at location B, but it did not give a significant difference in concentration.

4.3 SAMPLING AND MEASUREMENT PROBLEMS

Care is needed in interpreting and comparing data from nutrient and energy flux studies. Sampling design often limited by cost and time constraints, differing sampling techniques, analytical uncertainties and statistical interpretation all are potential sources of error. Burton (1973) notes that our knowledge of the distribution of nutrients in tropical waters is limited by the number of data sets, the small number of samples taken and the effects due to analytical uncertainties regarding sample collection and storage, and the way in which different nutrient species in sea water respond to different analytical techniques. For example the use of filtering samples on site before freezing for nutrient analysis has been a common procedure (Ryle *et al.*, 1981), but problems with loss of analyte may occur depending on filter type (Jones et al. 1989). Filtration through filters of a pore size of ca. 0.45 μm is an arbitrary division of material into 'particulate'and 'dissolved'. For nitrogen the distinction between dissolved inorganic forms, dissolved organic forms (< 0.45 μm) and particulate forms (> 0.45 μm) is relatively clear, however, which of these forms is bio-available is not. For phosphorous the situation is more complex since some of the fine colloidal phosphorous reacts in the molybdate method used for the analytical determination of orthophosphate. Consequently the operational term 'reactive dissolved phosphorous' better describes what is being measured. What fraction of this phosphorous is bio-available is also not clear. Future work needs to research for which nutrients the use of filters is suitable and for which unfiltered samples are preferable (Jones *et al.*, 1989).

The results of a sampling study are often not readily interpretable without understanding the influence of processes, both natural and anthropogenic, which occur at a range of scales. These complicate our ability to measure ambient conditions in an areas and to make comparisons between areas. Andrews and Muller (1983) note the space and time scales on which a study is performed will determine the relative influence of the physical environment and chemical and biological interactions on the results; much of the variance is caused by the changing physical environment and can be resolved with adequate sampling. Ideally the influence of regional processes such as river runoff from the Barron River, planktonic blooms (i.e *Trichodesmium)*, coastal upwelling and oceanic intrusions, as well as local processes both natural and anthropogenic (hydrodynamic and biotic processes, dredging and sewage discharge) on nutrient levels need to be considered. Jones *et al.* (1989) have drawn attention to the fact that *Trichodesmium* blooms can substantially alter the relative concentrations of dissolved nutrients and chlorophyll.

Due to the potential sources of error mentioned above it is not necessarily correct to present the mean and variance of a set of chemical data as an adequately determined result (Andrews and Muller, 1983). Talbot and Simpson (1983) note for skewed data geometric means may be a better estimator than arithmetic treatment of the data. The use of univariate statistics which are suddenly regarded as being significant at a magical number (0.05) is incorrect. Further, Boto and Wellington (1988) note high within sample variance can lead to non significant results an apparent wide range of concentrations. Multivariate statistics can provide a good method of demonstrating processes that may not be apparent using a univariate approach.

LITERATURE CITED

Andrew, N.L. and Mapstone, B.D. (1987). Sampling and the description of spatial pattern in marine ecology. *Oceanogr.Mar. Biol. Ann. Rev.* 25:39-90.

Andrews, J.C. and Muller, H. (1983). Space time variability of nutrients in a lagoonal patch reef. *Limnol. Oceanogr.*, 28(2):215-227.

Andrews, J.C., Dunlap, W.C. and Bellamy (1984). Stratification in a small lagoon in the Great Barrier Reef. *Aust. J. Mar. Freshw. Res.* 35:273-84.

Atkinson, M.J., and Smith, S.V. (1987). Slow uptake of phosphorous over a Barrier reef flat. *Limnol. Oceanogr.* 32(2):2436-441.

Atkinson, M.J. (1988). Are coral reefs nutrient-limited? *Proc. 6th Int. Coral Reef Symp., Australia,* 1: 103-113.

Baxter, I. (1987). Green Island. Review of current knowledge. Unpub. report to GBRMPA.

Bell, P.R.F., Greenfield, P.F., Gough, G., Hawker, D. and Connell, D. (1987). Guidelines for the management of waste discharges into the Great Barrier Reef Marine Park. Unpub. report to GBRMPA.

Bernstein, B.B. and Zalinski, J. (1983). An optimum sampling design and Power tests for environmental biologists. *J. Env. Management 16:35-43.*

Black, K.P.and Gay, S.L. (1987). V.I.M.S. Tech. Report 8: 1-16.

Blake, S.G. and Johnson, D.P. (1988) Preliminary report on water quality, current patterns and sediment composition around Hamilton and Hayman Islands, the Whitsundays. Unpub. report to GBRMPA.

Boto, K.G. and Wellington, J.T. (1988). Seasonal variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical, tidally-dominated, mangrove waterway. *Mar. Ecol. Prog. Ser.* 50:151-160.

Brodie, J.E., Mapstone, B.D., Mitchell, R.L. (1989). Magnetic Quay water quality and sediment baseline study. Unpub. report to GBRMPA.

Burton, J.D. (1973). Problems in the analysis of phosphorous compounds. *Water Res.* 7: 291-307.

Clarke, K.R. and Green, R.H. (1988). Statistical design and analysis for a biological effects study. *Mar. Ecol. Prog. Ser.* 46:213-226.

Cohen, J. (1977). *Statistical Power analysis for the Behavioural Sciences.* Revised Edition. Academic Press, New York.

Crossland, C.J. (1983). Dissolved nutrients in coral reef waters. In: *Perspectives on Coral Reefs.* D.J. Barnes (ed.) pp. 56-65. B. Clouston, Hong Kong.

D'Elia, C.F. (1989) The cycling of Essential Elements in Coral Reefs. In: *Concepts of Ecosystem Ecology.* Pomeroy L.R. and Alberts J.T. (eds.). Springer Verlag Ecological studies 67.

Done, T.J. (1983). Coral zonation: Its nature and significance. In: *Perspectives on Coral Reefs*. D.J. Barnes (ed) pp. 56-65. B. Clouston, Hong Kong.

Entsch, B., Boto, K.G., Sim, R.G. and Wellington, J.T. (1983). Phosphorous and Nitrogen in coral reef sediments. *Limnol. Oceanogr.* 28:465-476.

Fisk, D.A. (1987). Dynamics of the *Acanthaster* / hard coral interaction. Progress report to GBRMPA.

Fisk, D.A., van Woesik, R. (1989). Green Island, impact assessment program. Proposal to GBRMPA.

Furnas M., Mitchell, A.W., Wellington, J., and Brady, B. (1988) Dissolved and particulate nutrients in waters of the Whitsunday island Group. Unpub. report to GBRMPA.

Green Island Management Committee (1980). Green Island Management Plan. Queensland National Parks and Wilfdlife Service Publication.

Green, R.H. (1984). *Sampling Design and statistical methods for environmental biologists*. John Wiley & Sons, New York.

Grasshoff, K. (1983). Grasshoff, K., Ehrhardt, M. and Kremling, K. (ed.) In: *Methods of Seawater analysis*. Publ. Verlag Chemie, Weinheim.

Hamner, W.M., and Wolanski E. (1988). Hydrodynamic forcing functions and biological processes on coral reefs: A status review. *Proc. 6th Int. Coral Reef Symp., Australia*, 1: 103-113.

Hatcher, A.I. and Frith, C.A. (1985). The control of nitrate and ammonium concentrations in a coral reef lagoon. *Coral Reefs* 4: 101-110

Hatcher, A.I. and Hatcher, B.G. (1981). Seasonal and spatial variation in dissolved organic nitrogen in One Tree Reef lagoon. *Proc. 4th Int. Coral Reef Symp., Manila 1:419-424.*

Hawker, D.W. and Connell, D.W. (1989). An evaluation of the tolerance of corals to nutrients and related water quality characteristics. *Intern. J. environmental Studies* 34:179-188.

Johannes, R.E. (1975). *Pollution and degradation of coral reef communities*. In: Ferguson Wood, E.J., Johannes, R.E. (ed.) Tropical marine pollution. Elsevier, Amsterdam, p.13-51.

Jones, G.B., Burdon-Jones, C. and Thomas, F.G. (1982). Influence of *Trichodesmium* red tides on trace metal cycling at a coastal station in the Great Barrier Reef lagoon. *Oceanol. Acta* 1982. No. SP, 319-26.

Jones, G.B., McConchie, D. and Saenger, P. (1989). Compliance assessment programme for the Barrier Reef Resort - John Brewer Reef. Unpub. report to GBRMPA.

Kinsey, D.W. and Davies, P.J. (1979). Effects of elevated nitrogen and phosphorous on coral reef growth. *Limnol. Oceanogr.* 24(5):935-940.

Kinsey, D.W. and Domm, A. (1974). Effects of fertilisation on a coral reef environment-primary production studies. In *Proc 2nd Int Coral Reef Symp* 1:49-66.

Kuchler, D.A. (1978). Green Island: The man-environment interface, a geomorphological perspective. Unpub. report to the Great Barrier Reef Committee, Canberra.

Loya, Y. (1976). Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. *Bull. Mar. Sci.* 26, 450-466.

Mapstone, B.D., Choat, J.H., Cumming, R.L and Oxley, W.G. (1989). The fringing reefs of Magnetic Island: Benthic Biota and Sedimentation. Unpub report to GBRMPA.

Marsh, J.A. (1977). Terrestrial inputs of nitrogen and phosphorous on fringing reefs of Guam. *In: Proc. 3rd Int. Coral Reef Symp. Miami, Florida* 1:331-336.

Millard, S.P. and Lettenmaier, L. (1986). Optimal design of biological sampling programs using the anlaysis of variance. *Estuarine Coastal and Shelf Science* 22:637-656.

Millard, S.P., Yearsly, J.R. and Lettenmaier, L. (1985). Space time correlation and its effects on methods for detecting aquatic ecological change. *Can. J. Fish. Aquat. Sci.* 42:1391-1400.

Murphy, J. and Riley, J.P. (1962). A modified single solution method for the determination of soluble phosphate in sea water. *J. Mar. Biol. Ass. UK.*, 37, 9-14.

Parnell, K.E. (1986). Water movement within a fringing reef flat, Orpheus Island, North Queensland, Australia. *Coral Reefs* 5: 1-6.

Parnell, K.E. (1987). The hydrodynamics of fringing reef bays in the Great Barrier Reef Marine Park, with emphasis on management. Department of Geography, James Cook University, Unpubl. PhD thesis.

Pastorok, R.A. and Bilyard, G.R. (1985). Effects of sewage pollution on coral ref communities. *Mar Ecol. Prog. Ser.* 21: 175-189.

Pilson, M.E.Q. and Betzer, S.B.(1973). Phosphorous flux across a coral reef. *Ecology* 54:581-8.

Relevante, N. and Gilmartin, M. (1982). Dynamics of phytoplankton in the Great Barrier Reef lagoon. *J. Plankton Res.* 4: 47-76.

Rogers, C.S. (1983). Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. *Mar. Poll. Bull.* 14: 378-382.

Ryle, V.D., Mueller, H.R. and Gentien, P. (1981). Automated analysis of nutrients in Tropical Sea Waters. Australian Institute of Marine Science Technical Bulletin, Oceanography Series No.3.

Smith, S.V. and Jokiel, P.L. (1975). Water composition and biogeochemical gradients in the Canton Atoll lagoon: 2. Budgets of phosphorous, nitrogen, carbon dioxide and particulate materials. *Mar. Sci. Communs.* 1: 165-207.

Smith, S.V., Kimmerer, W.J., Laws, E.A., Brock, R.C. and Walsh, T.W. (1981). Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. *Pac. Sci.* 35(4), 279-402.

Steven, A.D.L. and van Woesik, R. (1989). A multidisciplinary study of the effects of sewage outfall on Hayman Island. Unpub. interim report on water quality and waste water to GBRMPA.

Strickland, J.D.R. and Parsons, T.R. (1968). *A practical handbook of seawater analysis.* Fisheries Res. Bd. of Canada, Bulletin 167, 49-52

Sugimura, Y. and Suzuki, Y. (1988). A high temperature catalytic oxidation method for the determination of non-volatile DOC in sea water by direct injection of liquid samples. *Marine Chemistry* 24: 105-131.

Talbot, V. and Simpson, C. (1983). The validity of using arithmetic means to summarize environmental pollution data. Chemistry in Austrlia 50(5):156-158.

Tomascik, T. and Sander, F. (1985). Effects of eutrophication on reef building corals. 1. Growth rate of the reef building coral *Montastrea annularis. Marine Biology* 87, 143-155.

van Woesik, R. (1989). A preliminary examination on the sedimentology, reef growth and hydrography of Green Island. Unpub. report to GBRMPA.

Webb, K.L., DuPaul, W.D., Weibe, W.J., Sottile, W. and Johannes R.E. (1975). Enewetak (Eniwetok) Atoll: Aspects of nitrogen cycle on a coral reef. *Limnol Oceanogr* 20:198-210.

Weibe, W.J. (1976). Nitrogen cycles on a coral reef. *Micronesia* 12:23-26.

Wolanski, E. and Pickard G.L. (1985). Long term observations of currents on the Central Great Barrier Reef continental shelf. *Coral Reefs* 4: 47-87.

Zar, J.H. (1984). *Biostatistical Analysis.* Prentice-Hall Inc. Englewood Cliffs New Jersey pp 718.

APPENDIX 1: ANALYTICAL METHODS

Quality Assurance

Within the laboratory quality assurance is based on reference standard control charts, sample replication for batch methods and repetition of sample where replicates do not meet prescribed criteria. Precision of methods has been estimated from a preliminary error analysis based on repeated analysis of a single standard. While this gives an over optimistic long term precision estimate (due to batch to batch variabilty) the reference standard used for the control chart is used to verify long term (batch to batch) precision. Accuracy is followed using the control chart where the reference standard used in each batch has been prepared from a stock standard prepared from chemicals independent of the calibration stocks and standards. This system has been used for the following analysis; nitrite and nitrate, ammonia, orthophosphate, total nitrogen, total phosphorous and BOD_5.

In laboratory replicates were routinely run for these parameters, i.e. the single field sample was split and run as a pair through the method. Where replicates did not agree within 20% of the higher value, the sample was repeated in the next batch. Samples which were outside the standards range were also repeated after appropriate dilution. No replicates were run for Chlorophyll *a*, suspended sediments, or particulate nitrogen. BOD_5 samples were replicated in the sense that serial dilutions were made but in marine samples values were so low that only the first dilution was used in the result calculation.

The limits of detection and sensitivity shown with each method reflect the particular method and instrumentation used. While general precision values are also given, it should be realised that these have been estimated from a standard near the upper end of the expected range of values and that precision near the limit of detection will not be as good.

Nutrients

Samples were collected in individual sterile Whirl-pacs, and stored frozen until required for analysis.

Nitrate and Nitrite

Nitrate was reduced to nitrite on a copper coated cadmium reduction column using a Flow Injection Analysis (FIA) system. Nitrite was measured on this system using the sulphonilamide/N-l-Naphthylethylene diamine colour reaction at 520 nm. Nitrate was calculated from the nitrate plus nitrite value and the nitrite value by difference.

	Nitrite	**Nitrate**
Limit of detection: (μM)	0.07	0.07
Sensitivity: (μM)	0.03	0.03
Precision: (% at 2 μM)	5%	11%

Ammonium

Analysis was by indophenol blue colour development method and measurement at 630 nm (Grasshof, 1983).

Limit of detection: 0.07 μM
Sensitivity: 0.05 μM
Precision: 18% at 2 μM

Orthophosphate
Analysis was by molybdenum blue colour development method using ascorbic acid reductant and measurement at 885 nm (Grasshof, 1983).
Limit of detection: 0.05 μM
Sensitivity: 0.03 μM
Precision: 15% at 0.2 μM

Total Phosphorous
The sample was digested using alkaline persulphate and analysis of the resultant phosphate carried out using a molybdenum blue colour development on the FIA.
Limit of detection: 0.06 μM
Sensitivity: 0.04 μM
Precision: 20% at 0.5 μM

Particulate Nitrogen
400ml samples were filtered through GF-C filters and the residue analysed for nitrogen using a C,H,N analyser.

Supended Solids
One litre water samples were filtered, with vacuum assistance,through pre-weighed 4.7 cm GF-C glass fibre filters. Filters were then dried at 95°C and the residue weighed.
Limit of detection: 0.6 mg/l
Sensitivity: 0.4 mg/l.

Chlorophyll *a* and Phaeophytin analysis
One litre water samples were collected and stored frozen till analysis. Samples were filtered through GF-C filters, the residue and filter ground, soaked in acetone overnight in the dark, and extraction completed. The extract was centrifuged and the pigments were read on a spctrophotometer. Chlorophyll *a* was read at 750 nm and Phaeophytin at 665 nm (Strickland and Parsons, 1968).
Limit of Detection: 0.05 μg/l.
Sensitivity: 0.02 μg/l.

Biochemical Oxygen Demand (BOD_5)
Samples were collected in one litre containers and frozen till analysis. Analysis was by serial dilution (in general for the marine samples, addition of seed only and 1:1 dilurion with BOD dilution water and addition of seed) and measurement after 5 days at 20°C (± 1°C). Initial and final dissolved oxygen readings were made using a YSI 57 D.O. meter calibrated against moist air.
Limit of Detection: 0.08 mg/l
Sensitivity: 0.05 mg/l.
Precision: 50% at 1 mg/l.

APPENDIX 2.1.: ANALYSIS OF VARIANCE RESULTS

TEMPORAL STUDY

24 Hr Study

SOURCE OF VARIATION	NITRITE+NITRATE df	F	P	AMMONIUM df	FP
(A) TIME OF DAY	7	0.76	0.624	7	0.74	0.644
(B) LOCATION	1	2.04	0.164	1	0.06	0.811
(C) HABITAT	1	2.17	0.151	1	0.17	0.690
A*B	7	1.54	0.192	5	0.25	0.933
A*C	7	2.18	0.064	4	1.28	0.342
B*C	1	1.66	0.207	1	1.09	0.321
A*B*C	7	0.83	0.569	0		
RESIDUAL	31			10		

SOURCE OF VARIATION	DIN df	F	P	PHOSPHATE df	F	P
(A) TIME OF DAY	7	3.24	0.040	7	1.73	0.193
(B) LOCATION	1	0.04	0.841	1	0.58	0.461
(C) HABITAT	1	0.47	0.509	1	0.06	0.813
A*B	5	0.56	0.727	6	0.21	0.966
A*C	6	4.01	0.023	6	1.56	0.240
B*C	1	1.91	0.194	1	0.04	0.844
A*B*C	0			0		
RESIDUAL	11			12		

SOURCE OF VARIATION	TOTAL NITROGEN df	F	P	TOTAL PHOSPHATE df	F	P
(A) TIME OF DAY	7	0.54	0.799	6	3.46	0.389
(B) LOCATION	1	0.01	0.942	1	4.50	0.280
(C) HABITAT	1	1.61	0.215	1	0.22	0.720
A*B	7	0.79	0.599	2	1.56	0.493
A*C	7	1.47	0.218	1	3.97	0.296
B*C	1	0.07	0.799	1	0.00	1.000
A*B*C	7	0.73	0.646	0		
RESIDUAL	29			7		

SOURCE OF VARIATION	TEMPERATURE df	F	P	DISSOLVED OXYGEN df	F	P
(A) TIME OF DAY	7	20.42	0.0001	7	7.88	0.002
(B) HABITAT	1	3.97	0.077	1	6.44	0.028
A*B	5	1.78	0.212	5	4.55	0.017
RESIDUAL	9			11		

SOURCE OF VARIATION	CHLOROPHYLL *A* df	F	P	SUSPENDED SOLIDS df	F	P
(A) TIME OF DAY	5	2.73	0.218	6	7.80	0.001
(B) HABITAT	1	0.64	0.483	1	0.38	0.550
A*B	3	2.25	0.262	4	1.04	0.428
RESIDUAL	3			3		

APPENDIX 2.2. ANALYSIS OF VARIANCE RESULTS

TEMPORAL STUDY

Daily Study

SOURCE OF VARIATION	NITRITE+NITRATE df	F	P	AMMONIUM df	F	P
(A) DAY	2	1.48	0.269	2	5.22	0.035
(B) LOCATION	1	0.43	0.526	1	15.61	0.004
(C) HABITAT	1	2.28	0.159	1	0.01	0.924
A*B	2	0.49	0.628	2	0.32	0.732
A*C	2	1.95	0.188	2	0.31	0.590
B*C	1	0.27	0.611	1	0.02	0.901
A*B*C	2	2.42	0.135	2	0.24	0.639
RESIDUAL	11			8		

SOURCE OF VARIATION	DIN df	F	P	PHOSPHATE df	F	P
(A) DAY	2	7.18	0.020	2	0.49	0.628
(B) LOCATION	1	9.12	0.019	1	1.47	0.259
(C) HABITAT	1	3.86	0.090	1	0.00	0.965
A*B	2	0.55	0.601	2	0.54	0.601
A*C	2	0.56	0.593	2	0.84	0.468
B*C	1	0.89	0.378	1	1.18	0.309
A*B*C	2	4.31	0.076	1	1.09	0.328
RESIDUAL	8			8		

SOURCE OF VARIATION	TOTAL NITROGEN df	F	P	TOTAL PHOSPHATE df	F	P
(A) DAY	2	1.88	0.195	2	3.83	0.075
(B) LOCATION	1	0.03	0.866	1	0.70	0.429
(C) HABITAT	1	2.38	0.149	1	1.42	0.273
A*B	2	0.83	0.461	2	0.06	0.815
A*C	2	0.08	0.922	1	0.35	0.571
B*C	1	0.25	0.626	2	0.00	1.000
A*B*C	2	1.75	0.215	1	0.35	0.571
RESIDUAL	9			7		

SOURCE OF VARIATION	TEMPERATURE df	F	P	DISSOLVED OXYGEN df	F	P
(A) DAY	2	166.45	0.0001	2	3.79	0.191
(B) HABITAT	1	5.78	0.047	1	0.36	0.607
A*B	2	4.14	0.081	2	2.43	0.259
RESIDUAL	3			3		

SOURCE OF VARIATION	CHLOROPHYLL A df	F	P	BOD_5 df	F	P
(A) DAY	2	2.73	0.218	1	0.28	0.691
(B) HABITAT	1	0.64	0.483	1	0.84	0.528
A*B	3	2.25	0.262	1	1.65	0.421
RESIDUAL	3			1		

APPENDIX 2.3 ANALYSIS OF VARIANCE RESULTS

SPATIAL STUDY

SOURCE OF VARIATION	NITRITE+NITRATE df	F	P	AMMONIA df	F	P
(A) LOCATION	5	5.46	0.031	5	4.56	0.048
(B) DEPTH	1	1.23	0.308	1	14.02	0.079
(C) SITE(LOCATION)	6	1.22	0.409	6	4.12	0.316
A*B	5	1.51	0.314	5	11.178	0.176
B*C	6	1.02	0.442	6	0.18	0.944
RESIDUAL	21					

SOURCE OF VARIATION	DIN df	F	P	PHOSPHATE df	F	P
(A) LOCATION	5	5.61	0.021	5	8.89	0.010
(B) DEPTH	1	1.01	0.287	1	0.02	0.882
(C) SITE(LOCATION)	6	1.22	0.409	6	0.11	0.992
A*B	5	4.51	0.376	5	0.12	0.984
B*C	6	0.88	0.765	6	3.21	0.021
RESIDUAL	31			21		

SOURCE OF VARIATION	TOTAL NITROGEN df	F	P	TOTAL PHOSPHOROUS df	F	P
(A) LOCATION	5	1.73	0.261	5	0.48	0.779
(B) DEPTH	1	0.41	0.548	1	0.00	0.956
(C) SITE(LOCATION)	6	0.41	0.852	3	1.04	0.522
A*B	5	0.21	0.948	1	0.53	0.544
B*C	6	2.68	0.042	2	2.18	0.194
RESIDUAL	22			6		

SOURCE OF VARIATION	DISSOLVED OXYGEN df	F	P	TEMPERATURE df	F	P
(A) LOCATION	5	1.98	0.134	5	1.35	0.291
(B) DEPTH	1	0.02	0.886	1	1.79	0.199
A*B	5					
RESIDUAL	22			6		

SOURCE OF VARIATION	BOD_5 df	F	P	PARTICULATE NITROGEN df	F	P
(A) LOCATION	5	0.76	0.607	5	0.78	0.598
RESIDUAL	6			6		

APPENDIX 4.1.: RESULTS OF 24 HOUR STUDY UNDERTAKEN ON THE 2ND JUNE 1989 AT GREEN ISLAND.

				WIND		WAVE											
LOCATION	HABITAT	REP	TIME	DIRECTION	SPEED	DIRECTION	HEIGHT	OXYGEN	TEMPERATURE	NO_2+NO_3	NH_4	DIN	PO_4	TN	TP	SS	CHLOROPHYLL *a*
			hrs	degrees	m/ms	degrees	metres	mg/l	°C	uM	uM	uM	uM	uM	uM	mg/l	ug/l
Time Period 5: 2110 High Water																	
a	f	1	2110	100	175	190	0.10	6.8	25.1	0.23	-	-	0.54	5.7	-	17	-
a	f	2	2110	100	175	190	0.10	-	-	0.27	0.00	0.27	0.20	7.9	0.5	-	-
a	s	1	2100	100	175	190	0.10	7.0	25.1	0.39	1.60	1.99	0.17	3.6	-	15	-
a	s	2	2100	100	175	190	0.10	-	-	0.31	-	-	-	4.9	-	-	-
b	f	1	2132	100	175	190	0.10	7.5	25.1	0.37	-	-	-	10.3	0.3	17	-
b	f	2	2135	100	175	190	0.10	-	-	0.30	-	-	-	8.3	-	-	-
b	s	1	2130	100	175	190	0.10	7.8	25.2	0.23	-	-	-	6.0	-	14	-
b	s	2	2130	100	175	190	0.10	-	-	0.31	-	-	0.21	7.9	0.2	-	-
Time Period 6: 2405 Ebbing tide																	
a	f	1	2405	180	178	180	0.10	6.4	24.7	0.19	0.63	0.82	0.17	6.6	-	18	1.20
a	f	2	2405	180	178	180	0.10	-	-	0.28	0.11	0.39	0.14	5.4	-	-	-
a	s	1	2350	180	178	180	0.10	7.5	25.0	0.31	-	-	-	10.7	-	23	-
a	s	2	2350	180	178	180	0.10	-	-	0.34	-	-	-	5.3	-	-	-
b	f	1	2435	180	178	180	0.10	-	-	0.33	0.48	0.81	0.17	5.3	-	17	4.92
b	f	2	2435	180	178	180	0.10	-	-	0.31	0.75	1.06	0.36	7.4	-	-	-
b	s	1	2425	180	178	180	0.10	7.7	24.9	0.28	0.67	0.95	0.11	0.0	-	17	-
b	s	2	2425	180	178	180	0.10	-	-	0.24	-	-	-	6.0	-	-	-
Time Period 7: 2700 Low Water																	
a	f	1	2700	170	196	170	0.10	4.8	24.0	0.37	1.07	1.44	0.14	5.7	-	19	-
a	f	2	2700	170	196	170	0.10	-	-	0.32	1.47	1.79	0.30	0.0	-	-	-
a	s	1	2735	170	196	170	0.10	7.9	24.6	0.32	-	-	-	5.5	0.2	16	-
a	s	2	2735	170	196	170	0.10	-	-	0.39	-	-	-	5.7	-	-	-
b	f	1	2800	170	196	170	0.10	-	-	0.41	1.63	2.04	0.22	8.3	0.3	16	-
b	f	2	2800	170	196	170	0.10	-	-	0.14	-	-	-	6.3	-	-	-
b	s	1	2745	170	196	170	0.10	7.4	24.7	0.25	0.42	0.67	0.17	6.3	-	20	-
b	s	2	2745	170	196	170	0.10	-	-	0.37	-	-	-	5.1	-	-	-
Time Period 8: 3000 Flooding tide																	
a	f	1	3000	170	210	190	0.10	6.1	24.3	0.34	-	-	-	5.6	-	18	-
a	f	2	3000	170	210	190	0.10	-	-	0.28	0.57	0.85	0.08	37.4	0.60	-	-
a	s	1	3015	170	210	190	0.10	6.6	-	0.24	-	-	-	5.3	-	18	-
a	s	2	3015	170	210	190	0.10	-	-	0.27	-	-	-	5.3	-	-	-
b	f	1	3105	170	210	190	0.10	6.2	-	0.28	-	-	-	7.5	0.3	18	-
b	f	2	3105	170	210	190	0.10	-	-	0.32	-	-	-	5.6	-	-	-
b	s	1	3045	170	210	190	0.10	6.9	25.1	0.30	0.46	0.75	0.21	4.4	-	18	-
b	s	2	3045	170	210	190	0.10	-	-	0.29	0.00	0.29	0.22	6.0	-	-	-

APPENDIX 4.2.: RESULTS OF DIEL STUDY UNDERTAKEN FROM THE 2ND JUNE TO 4TH JUNE 1989 AT GREEN ISLAND.

LOCATION	HABITAT	REP	WIND DIRECTION	WIND SPEED	WAVE DIRECTION	WAVE HEIGHT	OXYGEN	TEMP	NO_2+NO_3	NH_4	DIN	PO_4	TN	TP	PN	CHL*a*	BOD_5
			degrees	m/ms	degrees	metres	mg/l	°C	uM	uM	uM	uM	uM	uM	uM	ug/l	mg/l
Day 1: 2/6/89 Time: 0710																	
a	f	1	160	215	160	0.15	6.8	24.7	0.28	0.34	0.62	0.12	6.1	0.2	16.0	-	-
a	f	2	160	215	160	0.15	-	24.9	0.23	0.08	0.31	0.11	4.9	-	-	-	-
a	s	1	160	215	160	0.15	7.4	24.6	0.31	-	-	-	4.6	-	15.0	-	0.0
a	s	2	160	215	160	0.15	-	24.8	0.24	0.00	0.24	0.12	6.5	-	-	-	-
b	f	1	160	215	160	0.15	-	24.5	0.35	0.56	0.91	0.14	4.9	-	18.0	-	0.4
b	f	2	160	215	160	0.15	7.6	24.6	0.27	0.53	0.80	0.22	4.9	-	-	-	-
b	s	1	160	215	160	0.15	7.7	24.8	0.35	-	-	-	5.3	-	17.0	-	0.5
b	s	2	160	215	160	0.15	-	24.3	0.31	-	-	-	10.6	0.2	-	-	-
Day 2: 3/6/89 Time: 0753																	
a	f	1	130	295	180	0.20	8.6	26.8	0.40	0.59	0.99	-	7.1	0.3	16.0	0.5	1.2
a	f	2	130	295	180	0.20	-	-	-	0.43	-	0.25	6.1	0.3	-	-	-
a	s	1	130	295	180	0.20	7.7	26.2	0.33	0.57	0.90	0.19	12.3	0.4	16.0	0.4	0.5
a	s	2	130	295	180	0.20	-	-	0.31	0.48	0.79	0.14	8.7	0.4	-	0.4	-
b	f	1	180	287	180	0.25	-	-	0.49	1.09	1.58	-	7.5	0.3	12.0	0.4	-
b	f	2	180	287	180	0.25	-	-	0.41	1.32	1.73	0.38	6.0	0.3	-	0.4	-
b	s	1	180	287	180	0.25	-	26.1	0.17	0.92	1.09	0.20	6.3	0.3	17.0	0.7	0.2
b	s	2	180	287	180	0.25	-	-	0.37	0.93	1.30	0.27	6.6	0.4	-	5.1	-
Day 3: 4/6/89 Time: 0837																	
a	f	1	170	307	170	0.40	-	-	0.41	-	-	0.25	7.1	0.3	13.0	-	-
a	f	2	170	307	170	0.40	-	-	0.42	0.48	0.90	0.01	7.5	0.3	-	-	-
a	s	1	170	307	170	0.40	-	-	0.23	0.51	0.74	0.28	7.0	-	18.0	-	-
a	s	2	170	307	170	0.40	-	-	0.31	-	-	0.25	6.3	0.3	-	-	-
b	f	1	170	307	170	0.40	-	-	0.31	1.35	1.66	0.37	4.1	0.2	12.0	-	-
b	f	2	170	307	170	0.40	-	-	0.33	0.63	0.95	0.35	9.8	0.3	-	-	-
b	s	1	170	307	170	0.40	-	-	0.51	1.11	1.61	0.17	6.7	0.2	14.0	-	-
b	s	2	170	307	170	0.40	-	-	0.31	1.25	1.56	0.36	11.3	0.4	-	-	-

APPENDIX 4.3.: RESULTS OF SPATIAL STUDY UNDERTAKEN ON THE 4TH JUNE 1989 AT GREEN ISLAND.

				WIND		WAVE											
LOCATION	HABITAT	REP	TIME	DIRECTION	SPEED	DIRECTION	HEIGHT	OXYGEN	TEMPERATURE	NO_2+NO_3	NH_4	DIN	PO_4	TN	TP	PN	BOD_5
			hrs	degrees	m/ms	degrees	metres	mg/l	°C	uM	uM	uM	uM	uM	uM	uM	mg/l
Location A																	
1	1	1	1025	130	295	90	0.20	7.7	26.2	0.33	0.57	0.90	0.19	12.3	0.3	16.0	0.5
1	1	2	1040	130	295	90	0.20	-	-	0.31	0.48	0.79	0.14	8.7	0.4	-	-
1	2	1	1030	130	295	90	0.20	7.8	26.3	0.25	0.70	0.95	0.17	3.9	-	-	-
1	2	2	1045	130	295	90	0.20	-	-	0.26	1.13	1.39	0.24	4.7	-	-	-
2	1	1	1040	130	295	90	0.20	7.7	26.2	0.26	0.46	0.72	0.14	4.6	-	14.0	0.1
2	1	2	1040	130	295	90	0.20	-	-	0.25	0.51	0.76	0.20	4.3	-	-	-
2	2	1	1040	130	295	90	0.20	7.9	26.3	-	-	-	0.17	14.7	0.3	-	-
2	2	2	1040	130	295	90	0.20	-	-	0.24	0.53	0.77	0.27	6.4	0.4	-	-
Location B																	
1	1	1	1110	180	287	180	0.25	8.0	26.1	0.17	0.92	1.09	0.20	9.0	0.4	12.0	0.2
1	1	2	1110	180	287	180	0.25	-	-	0.37	0.93	1.30	0.27	6.3	0.3	-	-
1	2	1	1115	180	287	180	0.25	9.2	26.3	0.25	0.63	0.88	0.26	6.6	-	-	-
1	2	2	1115	180	287	180	0.25	-	-	0.31	0.59	0.90	-	2.8	-	-	-
2	1	1	1135	180	287	180	0.25	10.5	26.7	0.33	0.66	1.00	0.14	5.1	-	10.0	2.5
2	1	2	1135	180	287	180	0.25	-	26.7	-	0.56	-	0.23	0.0	-	-	-
2	2	1	1140	180	287	180	0.25	8.4	26.2	0.30	0.64	0.94	0.13	7.7	0.4	-	-
2	2	2	1140	180	287	180	0.25	-	-	0.42	1.03	1.45	0.27	6.6	0.3	-	-
Location C																	
1	1	1	1200	180	287	180	0.25	8.1	26.1	0.18	0.59	0.77	0.13	5.1	-	16.0	0.7
1	1	2	1200	180	287	180	0.25	-	-	0.17	0.54	0.71	-	4.4	-	-	-
1	2	1	1200	180	287	180	0.25	8.3	26.1	0.23	0.69	0.91	0.11	7.7	0.4	-	-
1	2	2	1200	180	287	180	0.25	-	-	0.23	0.64	0.87	0.15	5.5	-	-	-
2	1	1	1210	180	287	180	0.25	8.1	26.6	0.34	2.15	2.49	0.11	5.3	-	12.0	0.3
2	1	2	1210	180	287	180	0.25	-	-	0.22	0.51	0.73	0.25	4.4	-	-	-
2	2	1	1220	180	287	180	0.25	8.8	26.2	0.23	-	-	0.17	8.3	0.3	-	-
2	2	2	1220	180	287	180	0.25	-	-	-	0.59	-	0.09	0.0	-	-	-

APPENDIX 4.3.: RESULTS OF SPATIAL STUDY UNDERTAKEN ON THE 4TH JUNE 1989 AT GREEN ISLAND.

				WIND		WAVE											
LOCATION	HABITAT	REP	TIME	DIRECTION	SPEED	DIRECTION	HEIGHT	OXYGEN	TEMPERATURE	NO_2+NO_3	NH_4	DIN	PO_4	TN	TP	PN	BOD_5
			hrs	degrees	m/ms	degrees	metres	mg/l	°C	uM	uM	uM	uM	uM	uM	uM	mg/l
Location D																	
1	1	1	1245	180	287	180	0.25	8.7	26.3	0.43	0.72	1.15	0.23	5.6	-	66.0	1.1
1	1	2	1245	180	287	180	0.25	-	-	0.27	1.54	1.80	-	7.2	-	-	-
1	2	1	1250	180	287	180	0.25	8.2	26.1	0.37	1.08	1.45	0.30	5.9	-	-	-
1	2	2	1250	180	287	180	0.25	-	-	0.35	0.50	0.85	0.16	9.1	0.3	-	-
2	1	1	1310	180	287	180	0.25	-	26.6	0.46	1.92	2.38	0.13	4.6	-	12.0	0.7
2	1	2	1310	180	287	180	0.25	-	-	0.30	2.20	2.50	0.07	3.2	-	-	-
2	2	1	1310	180	287	180	0.25	8.3	26.2	0.51	-	-	0.28	5.6	-	-	-
2	2	2	1310	180	287	180	0.25	-	-	0.39	-	-	0.24	4.3	-	-	-
Location E																	
1	1	1	1605	120	267	90	0.20	8.6	26.4	0.44	0.04	0.48	0.11	4.6	-	12.0	1.0
1	1	2	1605	120	267	90	0.20	-	-	0.38	-	-	0.01	8.1	0.4	-	-
1	2	1	1615	120	267	90	0.20	8.1	26.4	0.37	-	-	0.11	15.0	0.3	-	-
1	2	2	1615	120	267	90	0.20	-	-	0.38	0.34	0.72	0.17	5.3	-	-	-
2	1	1	1630	120	267	90	0.20	8.6	26.4	0.44	0.03	0.47	0.12	6.8	0.4	16.0	1.2
2	1	2	1630	120	267	90	0.20	-	-	0.34	0.61	0.95	0.41	9.1	0.5	-	-
2	2	1	1635	120	267	90	0.20	8.1	26.4	0.26	-	-	0.04	7.5	0.9	-	-
2	2	2	1635	120	267	90	0.20	-	-	0.33	0.96	1.30	0.04	6.7	-	-	-
Location F																	
1	1	1	1655	120	267	90	0.20	8.1	26.5	0.40	0.08	0.48	0.10	7.3	0.3	13.0	0.6
1	1	2	1655	120	267	90	0.20	-	-	0.32	2.29	2.61	0.15	6.6	-	-	-
1	2	1	1655	120	267	90	0.20	9.1	26.5	0.34	0.56	0.90	0.21	10.7	0.3	-	-
1	2	2	1655	120	267	90	0.20	-	-	0.32	1.45	1.77	0.10	4.6	-	-	-
2	1	1	1710	120	267	90	0.20	8.0	26.5	0.44	-	-	0.18	11.1	0.4	15.0	0.4
2	1	2	1710	120	267	90	0.20	-	-	0.46	-	-	0.27	9.0	-	-	-
2	2	1	1710	120	267	90	0.20	8.9	26.5	0.20	0.86	1.06	0.20	7.7	0.4	-	-
2	2	2	1710	120	267	90	0.20	-	-	0.30	0.91	1.20	0.07	14.7	0.2	-	-

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