WORKSHOP SERIES No. 10

NUTRIENTS IN THE GREAT BARRIER REEF REGION

Proceedings of a Workshop held in Townsville, Australia, 26 and 27 November 1987
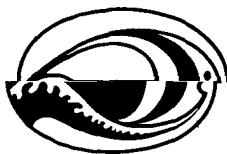
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PREFACE

The Authority gratefully acknowledges the valuable contribution made by all Workshop participants. The Nutrient Workshop provided an opportunity for" sharing of information and ideas on nutrients in the Great Barrier Reef Region. The findings as recorded in these proceedings are an important reference point in our understanding and will assist in providing direction for management of this aspect of the Great Barrier Reef Marine Park.

The Authority would particularly like to recognise the assistance of the speakers and of the authors for their contribution to this publication. The skilled guidance of the chairman, Dr Don Kinsey, ensured workshop objectives were met. The assistance of the Working Group leaders, Dr Des Connell, Dr Leon Zann, and Ms Claudia Baldwin for maintaining direction during discussion and of the rapporteurs, Mr Peter McGinnity, Mr Grahame Byron, and Mr Jon Day in synthesising discussion are greatly appreciated.

Ms Christine Dalliston, Mr Peter McGinnity, and Mr Jon Day provided logistical support for the Workshop. Actual publication of the proceedings was arranged by Ms Gillian Matthew. Special mention should be made of typing assistance by Beryl Dennis, Kay Bye and Sandra Anderson.

Further information on any aspect of this report, or of the workshop generally, may be obtained from:

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EXECUTIVE   SUMMARY

In response to a perceived problem regarding nutrient levels at
localised sites in the Great Barrier Reef Marine Park, GBRMPA
held a Workshop on Nutrients in the Great Barrier Reef Region on
26 and 27 November 1987. Over forty participants attended the
Workshop, including researchers in the disciplines of biology,
chemistry, engineering, geology and oceanography as well as State
and Commonwealth government water quality and marine park
managers.

The Nutrient Workshop provided a forum for examination of roles
and responsibilities regarding water quality; an opportunity for
discussion and interchange of ideas on a technical level
regarding research undertaken; and guidance to the Marine Park
Authority in relation to management of enhanced nutrients in the
Marine Park.

Nineteen papers were presented on the first day of the Workshop
in relation to: coastal processes, effect of nutrients on coral
reef communities, nutrient distribution and fluxes, movement and
chemical processes.

On the second day participants were divided into three working
groups to discuss management issues and the need for research and
monitoring in: the Green Island area, the Whitsunday area, and
the inshore GBR Region. These working groups were valuable in
consolidating ideas on the need for. concern about nutrients in
the GBR Region and for advising on the future direction that
management should take.

ROLES   AND   RESPONSIBILITIES

Two main organisations are concerned with water quality
management in the GBR Region: GBRMPA under the Great Barrier
Reef Marine Park Act 1975 (Cwlth) and Queensland Water Quality
Council (QWQC) under the Queensland Clean Waters Act 1971-82.

The Great Barrier Reef Marine Park Act provides for the
regulation or prohibition of acts (whether in the Marine Park or
elsewhere) which may pollute water in a manner harmful to plants
or animals in the Marine Park. Those wishing to discharge
household, commercial or industrial waste into the Marine Park
need to apply for a permit. To date, in the absence of
alternative acceptable standards, GBRMPA has accepted Queensland
Water Quality Council guidelines for waste discharge in relation
to point source discharges from tourist resorts. The Marine Park
Authority also recognises a need to address non-point sources of
nutrients in the future.

The Queensland Clean Waters Act seeks to protect all waters
(underground, surface, and the sea, within Queensland) by
controlling discharge of all kinds of waste capable of causing
pollution, through two separate provisions: licensing discharges
and "duty of care" provisions. Licensing is based on effluent
standards, and provides exceptions for septic tanks serving less
than 100 persons, stormwater run-off uncontaminated by domestic

sewage, and agricultural run-off. To date, the approach taken by QWQC has been a problem-oriented response. As with the Marine. Park Authority, regulation of non-point sources has not been attempted." Nutrient removal from waste'occurs only in highly populated areas of south-east Queensland.

COASTAL PROCESSES

A number of participants discussed the input of nutrients from mainland' sources.

Rasmussen established a relationship between nutrients in the Barron River discharge and the Low Isles environment by analysing coral cores.

Nitrogen'appears to be the nutrient limiting phytoplankton biomass in pelagic shelf waters. The total 11-year, monthly mean flows from all major rivers from the Barron to the Burdekin were summed in Mitchell's studies, estimating that "10,000 tonnes of NO_3^-N is released annually along this coastal area. The need to monitor flood events was stressed. Since much of the river water is constrained within the near-shore region (20 kilometres offshore) by long-shore currents, Mitchell estimated that the nitrogen flux from river inputs in nearshore regions 'could account for as, much as 50 per cent of the total N, significantly affecting phytoplankton productivity in the inshore GBR.

While dissolved nutrientsmay be dispersed further from the shore, Johnson's work indicates that most nutrients attached to , suspended materials are deposited initially close to shore, within 15 kilometres offshore in water depths of less than 20 metres.

Alongi indicated that nutrient fluxes from GBR sediments are naturally enhanced during periods of extensive river run-off and storm surges(cyclones) which generate sediment resuspension. It has been predicted that resuspension of 1 centimetre of GBR inshore sediment leads to moderate increases in water column nutrient concentrations, particularly for nitrogen species.

Concern regarding input of nutrients from mainland agricultural lands were confirmed by Prove's research. Soil erosion rates in a cane growing area of between 50 and 500 t/ha/year using conventional cultivation techniques were found. Preliminary results indicate that concentrations in run-off water from farm plots range from 84 to 1000 mg/L of total inorganic nitrogen and 1.6 to 34 mg/L of inorganic phosphorus. Erosion can be significantly affected by zero tillage and residue retention practices, but there is little evidence to suggest that nutrient concentrations would vary by adoption of conservative farming practices.

Boto suggested that the ability of a mangrove system to absorb and ameliorate nutrient inputs will depend on placement, timing, quantities, and nature of such input. There is little evidence to suggest any appreciable net exchange between mangroves and surrounding coastal waters in the tidally dominated systems, and it is suggested that direct inputs of nutrients into these mangrove waterways could lead to rapid and substantial eutrophication, particularly where tidal flushing may be limited.

A paper by Cosser included in the proceedings, but not presented at the Workshop, summarises the inputs from two different sources: point sources as continuous, insignificant quantities overall, but high loading in limited areas; and run-off which is episodic, quantitatively significant, but generally low loading per unit area. In order to evaluate the relative importance of respective sources, information as to quantities, real and temporal loading characteristics, sinks, and the pathways of biological assimilation is required for each. He stressed the importance of storm flow in nutrient flux and attempted to estimate riverine phosphorus loading to the Cairns Section of the Great Barrier Reef Marine Park based on export coefficients observed in southern Queensland, yet to be verified.

NUTRIENT MOVEMENT

A major source of enhanced nutrients is thus seen to be from mainland sources and processes such as cyclones in the GBR Region which cause resuspension of nutrients. Within the system, nutrient movement can be predicted to some extent.

Three main types of nutrient movement were discussed by Wolanski: through river floods, of a baroclinic coastal boundary layer of width increasing northward and breaking up in patches; circulation around reefs of non-buoyant nutrients which may become trapped in lagoons and near separation points such as illustrated by the CORSPEX model; and buoyant nutrients like sewage where waste is concentrated along topographically-controlled fronts.

Furnas discussed how nutrients are dispersed by water movement and transformed by planktonic organisms. Inputs of nitrogenous nutrients lead to increases in phytoplankton and can develop into blooms within 2-3 days if sufficient nutrients are available. However additions of nutrients to GBR waters may not necessarily be observed as an increase in dissolved nutrient levels. Rather, local or regional increases in phytoplankton biomass would be an obvious sign. Such enhanced phytoplankton biomass levels would affect coral reefs either through increases in 'surplus' water column phosphate concentrations, or indirectly in community changes resulting from shading, sedimentation, and proliferation of benthic filter feeders.

EFFECT ON CORAL REEF COMMUNITIES

A large proportion of the papers dealt with effects of nutrients on coral reef communities. It has been established, primarily in overseas studies, but also in research undertaken on the GBR, that corals have a low tolerance to elevated nutrients.

Kinsey's experiments at One Tree Island illustrated that addition of nutrients N and P on a daily basis over 8 months increased primary productivity but had no visible effects on the community structure. However, coral calcification rates had reduced by 50 - 60 per cent. Suppressed community calcification will result in decreased real growth and structural maintenance. It seems that

reefs **may** tolerate elevated nutrient levels well above the natural range for **significant** periods of time. In this situation the **nutrients,** and the organic loading (phytoplankton) which they, generate, impose a chronicstress **leaving** the reef vulnerable to non-recovery after an acute event such as freshwater **input,** crown of thorns kill and coral bleaching events.

Coral 'cores were analysed by Rasmussen for **phosphate levels on** an **historical basis.** Through laboratory experiments she has shown that increased **phosphate** flux contained in mainland run-off hindered the ability of corals to operate at equilbrium resulting in alteration to the crystal morphology of the coral skeleton, decrease in skeletal density, and increase in skeletal fragility.

Morrissey described the nutrient history of the Coral Reef Tank at the GBR Aquarium by following temporal changes in nitrate concentrations. High mortality rates of scleractinian corals, especially Acropora, **occured** at times of elevated nitrates, with widespread death at above 2.5 μM (of nitrate). **When** corals are at their temperature tolerance limits, they are more susceptible to stress by high nutrient levels.

Connell proposed a preliminary set of tolerance levels of corals to nutrients, suggesting that **a 20** per cent decrease in growth rate should be deemed the threshold level for coral. Primarily based on overseas studies, he indicated that an increase in total phosphorus and nitrogen of 2 to 3 times background levels can lead to increased plankton productivity, higher sedimentation rates, benthic algal enhancement, and coral death.

A conservative approach to tolerance levels of **corals due** to the synergistic effects of phosphorus and nitrogen were espoused by Bell and Greenfield. Levels corresponding to a 10 per cent increase in background P^-PO_4 and inorganic N were recommended performance standards.

Their evidence implies that denitrification and phosphorus removal are necessary treatment requirements if acceptable levels of waste discharge after dilution are to be achieved in the vicinity of coral reefs. Management strategies are discussed, however, significant effort is required to gather relevant evidence on both microscale and macroscale effects of nutrients in the Great Barrier Reef Marine Park before major changes in management are implemented.

Richards has monitored a reef that is being used by a tourist operation and expressed concern that, observed increased algal growth may have been related to enhanced nutrient levels:

Coral and algae are not the only reef 'biota affected **by enhanced** nutrients. Rasmussen, for example, is investigating a link between 'crown of thorns and enhanced nutrients.

Zann's multidisciplinary study of the ecology, hydrography and fisheries of a lagoon in **Tonga** illustrated the catastrophic effects of recentgeologic uplifting, intensive fishing **and,** particularly, increased-nutrient discharge directly **and** through the groundwater. resulting from urbani'sation and changes in **land** use.

Work by Risk looked at the relationship between increased coastal productivity at nearshore reefs, and accelerated bioerosion leading to weakening of the coral community. Isotopic tracer methods appear to be powerful tools in the study of coral metabolism.

Jones' work concerned mobilisation of toxic metal ions in inshore GBR caused by the planktonic community. He highlighted processes involving Trichodesmium blooms; input of sediment (through erosion or dredging); sewage; and metal wastes. In comparison with discharge from tourist resorts, waste discharge into the Marine Park from the mainland was seen as a major input, with particular reference to waste water discharge from Townsville and Thuringowa.

McConchie explained that nutrients can be transported in the natural environment as ions adsorbed onto colloids and clay minerals. Colloids that influence the rate of increase of adsorbed chemicals to other parts of the systems were described.

WORKING GROUP RECOMMENDATIONS

Each Working Group was asked to work to similar guidelines and allow for discussion on the need for concern regarding enhanced nutrients in the Great Barrier Reef Marine Park, management recommendations, research and monitoring strategy.

There was general concern that inshore waters of the Great Barrier Reef appear to have elevated nutrient levels, and in localised areas may be reaching an undesirable threshold.

It was felt that main geographical areas of concern were the inshore reefs close to mainland sources and subject to additional stresses from tourism activities. Of particular mention were waters north of Cairns where the Reef is close to shore and there is a northerly flow of water concentrating nutrients inshore; the Townsville - Magnetic Island area where sewage discharges reaching the Great Barrier Reef are likely to be significant; and the Whitsunday area where there are a number of tourist resorts and intensive tourism activity in a small area with a complex circulation pattern.

As a result it was recommended that an appropriate monitoring strategy be established. Research and monitoring programs need to address the ambient water quality of inshore waters, and differentiate between input from the mainland (urban discharge and agricultural run-off) and input from island resorts and other tourist activities. Priority should be given to data collection in areas of major geographical concern.

In terms of management, it is suggested that standards of waste discharge to be adopted could be based on achieving not more than a 20 per cent decrease in coral growth or 10 per cent increase in nutrients over ambient levels. These standards would have to be applied with caution in different sections of the reef recognising that natural variation will be appreciable.

Two other recommendations worthy of consideration are that **GBRMPA** should have a representative on the Queensland Water Quality Council, and an advisory committee should be set up to advise GBRMPA oh the'nutrient problem.

OPENING ADDRESS

Graeme Kelleher
Chairman, Great Barrier Reef Marine Park Authority

Welcome. For some of you it is the first time you have attended a workshop sponsored by the Great Barrier Reef Marine Park Authority.

Others may have attended one of our previous workshops on Coral Trout Assessment Techniques, Cyclone Winifred, Contaminants, and Fringing Reefs. Of importance too will be our next workshop: on Innovative Planning and Management in July 1988.

These workshops have an important role in assisting the Authority, to carry out its function of managing the Marine Park. Workshops are a mechanism for experts to work together to ensure that:

> all available information can be identified and assessed, and

> areas requiring further research are identified.

A GBRMPA management objective is to maintain the natural qualities of the reef while allowing reasonable use.

This workshop is being held in response to higher than average levels of phosphorus and nitrogen in some areas of the GBRMP. The sources of these nutrients are probably sewage outfalls and mainland run-off.

The natural qualities of the Reef are affected by nutrients. For example we know that most corals cannotsurvive chronic enhanced nutrient levels. Effects on other biota, such as crown of thorns starfish are not clear. Effects of enhanced nutrient levels and subsequent eutrophication in fresh and estuarine waters are widely known,

As managers, the Authority must know the sources and effects of nutrients to justify any regulation. We aim to minimise regulations consistent with maintaining the quality of reef resources.

The Contaminants Workshop in 1984 focused on heavy metals, hydrocarbons, PCBs and other organo-chlorines. It was concluded that the levels were so low as to be barely measurable. It was suggested at that Workshop that nutrients or sediments, primarily from mainland sources were more likely to have a greater 'impact on the Reef and should be a research priority. Subsequent research sponsored by the Authority, and data from monitoring of sewage outfalls indicate that levels of nutrients in some localised areas are high and increasing.

This workshop has been organised to first, give you all an opportunity to put forward any information and views that you may

have about this matter and second, to have you focus (through working groups) on the matter at a reef wide level and also for two locations: the Whitsunday Islands and Green Island.

The objectives of the workshop are:

To review briefly, and assess the status of knowledge concerning nutrients in the Great Barrier Reef Region and related research, in particular:

  i)   types and sources of nutrients
 ii)   the effects of enhanced nutrient levels on GBR biota and other coral reef biota
iii)   baseline and enhanced levels in inshore waters of the GBR Region.

To identify information gaps in our knowledge of nutrients in the GBR.

To determine whether there should be concern about the levels of nutrients in the Great Barrier Reef Region.

If concern is warranted, to determine a strategy for, and components of a management program that could include monitoring levels and effects of nutrients at specific sites and over the whole GBR Region.

To determine the feasibility of establishing a permissible level of nutrients in waste discharge and coastal run-of-f--i-n-to---t-he-Great Barrier Reef Marine Park.

To review and advise on waste disposal practices and permitted activities.

To determine any other management implications.

We in the Authority greatly appreciate your participation in this workshop. Please help us to focus on the particular issues that are identified in the above objectives.

WASTE DISCHARGE IN THE GREAT BARRIER REEF MARINE PARK

Claudia Baldwin, Peter McGinnity, and Grahame Byron
Great Barrier Reef Marine Park Authority,,'

BACKGROUND

In May 1984 the Marine Park Authority sponsored a Workshop on Contaminants in Waters of the Great Barrier Reef Marine Park. The Workshop concentrated on heavy metals, polychlorinated biphenyls (PCBs) and other organochlorines, and hydrocarbons. In attempting to assign priorities to areas of further research, participants, noted that sediments and nutrients were more likely to be of greater concern to the Reef than the three contaminant groups considered at that workshop. In particular, an area recommended for further research was:

> "the effects of agricultural fertilisers and other nutrients exported to the GBR from the mainland."
> (Dutton, 1985, p.iii)

Interest in nutrient and sediment input has continued in the Authority. 'We are assessing an increasing number of permit applications for waste discharge into the Marine Park from island resorts and other tourist facilities such as pontoons and the floating hotel. As part of this assessment, we have had to determine discharge standards appropriate for marine coastal waters. A recent report to the Authority on waste discharge guidelines by Greenfield, et al. (1987) highlighted a need to examine the tolerance level of corals to nutrients in particular, and suggested standards for waste discharge into reef waters.

Internationally, concern is also being expressed about nutrient levels in freshwater and groundwater systems, and estuarine and coastal environments.

As a result of a recent review of wastes and their disposal in the marine environment, the U.S. Office of Technology Assessment' concluded after investigating other options such as ocean dumping, that "with regard to impacts caused by waste disposal activities and run-off, the only policy choice available to maintain and improve the health of estuaries and coastal waters' is to minimise pollutant inputs to these waters," by either maintaining or expanding the current system of pollutant controls or establishing additional site specific controls on waste disposal and non-point pollution where needed (O.T.A., 1987, p.13).

The Australian Environment Council has also reviewed the problem of deterioration of streams and lakes in Australia due to overfertilisation by nutrients (1987). Eutrophication of lakes, rivers and estuaries, (taste and odour problems in country town water supplies and stock deaths attributed to blue-green algae) have all been documented. However, the impacts of nutrients on coastal waters have yet to be adequately determined.

A wide range of sewage impacts on coral reef communities has been reported in various parts of the world. Little or no impact has been observed on some reefs in well-flushed waters that have received small quantities of effluent, whereas large discharges of effluent into poorly flushed lagoons and bays have caused major changes in species composition and abundance (Pastorak, 1985).

It is expected that lethal and sublethal impacts of nutrients on corals will be addressed more extensively during the Workshop.

SOURCES OF NUTRIENTS IN THE MARINE PARK

There are many sources of nutrient rich waste entering the Great Barrier Reef Marine Park each requiring some consideration. The point sources are obvious and more readily managed than the diffuse or non-point sources.

To date management has focused on point source discharges directly into Marine Park waters such as sewage outfalls from island based resorts. Many resorts already have secondary treatment plants and others are in the process of upgrading.

These outfalls are cur-rently regulated under conditional permits issued by the Authority and under licences issued by Queensland Water Quality Council. Through the permit system we are able to regulate the quantity, quality and point of discharge for effluent as well as stipulating monitoring procedures. It is recognised though that the standards are not necessarily appropriate for coral reefs or open waters. While we accept that these controls have not significantly reduced the total amount of nutrients entering the Marine Park, they do enable us to more adequately assess and monitor the situation and to regulate any future expansion of wastes disposed.

As a growth industry in Queensland, tourism will have more and more of an impact on Reef waters. It may be helpful to briefly outline some of the trends in resort tourism that have convinced the Authority of the need to come to terms quickly with impacts from effluent discharge.

To give an idea of the number of visitors generated by type of facility, a comparison of visitor days in the Marine Park by facility isillustrated in Table One.

TABLE ONE

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Facility	Visitor Days
Island resorts	790 000
Charter boats	1 274 000
Private boats	690 000

(Driml, 1987)

There are 21 resort islands in the GBR Region. Of these, the bulk of island accommodation, with 73% of available rooms, is located in the Central Section. Islands of the Mackay/Caprjcorn Sections provide a further 23% and islands of Cairns Section contribute 4% of island resort rooms (Driml, 1987).

Green Island is the single most heavily visited reef, with an increase of 12% in visitors.between 1985/86 and 1986/87, to total 19'3,500 visitors in 1986/87.

Growth in visitor nights at island resorts has accelerated in recent years with a 17.5% increase from 1983/84 to 1984/85. The year 1984/85 to 1985/86 saw more moderate growth with a 6.5% increase in visitor nights. This is still substantial. A considerable amount of investment is currently being made in building new island resorts and in the redevelopment and' extension of existing resorts. Plans to build or extend resorts are reported to exist for 14 islands and have been projected to' lead to a doubling of rooms within a few years (Driml, 1987).

While we progress towards better control of point source discharges directly into the Marine Park, it is important not to ignore non-point or diffuse source discharge.

Of concern in this category is the ever increasing boating activity within the Marine Park. Between 1980 and 1984/85 the number of commercial vessels operating to take passengers to the, Great, Barrier Reef more than doubled to approximately 275 (Driml, 1987). Whilst many of the larger vessels including the large catamarans have holding tanks, they legally discharge untreated waste while underway.

Fish feeding is part of the visitor entertainment at a number of resorts and pontoons. To give an idea of the magnitude of the situation, preliminary estimates ,by Q.NPWS indicate that 47 tonnes of bread and food scrap was fed to fish by the combined operators at Green Island in 1987 (pers. comm., T. Stevens), This may also contribute to enhanced nutrient levels.

In the same 12 month period from July 1986 to end of June 1987 recreational boating increased between 5% and 7%. Very few of these vessels have holding tanks for wastes.

Most large cruise vessels and cargo ships which transit through the GBR have holding tanks, however, many have limited capacity. A recent incident in Whitsunday Passage where a large passenger liner purged its tanks helps to highlight the potential for significant problems.

Wastes are discharged into the Park via rivers or creeks. The expanding population on land adjacent to the GBR has made disposal of waste increasingly problematic. Many of the population centres on the North Queensland coastline are presently incapable of suitably handling the volume of human and industrial waste generated. Many of these wastes are high in nutrients and usually discharge indirectly via creeks and coastal waters into the Marine Park.

wastes that are typically high in nitrogen and/or phosphorus and are generated adjacent to the Marine Park are domestic sewage,those generated by feedlots, fertiliser production and use in agriculture, meat processing, milk processing, and commercial launderies.

Run-off and groundwater from agricultural areas can contain very high levels of nutrients either from fertilisers or decomposing matter. It is possible that nutrient rich discharges to the Marine Park will increase with the onset of the wet season in northern regions, particularly in those areas that have been subject to drought or cyclonic events.

In addition, with the expansion of the mariculture industry, one might speculate that the use of high protein feeds could add to nutrient levels in receiving waters.

Many would argue that the level of dilution of all these wastes in receiving waters should be high enough to raise little concern. There may however be some cause for debate on this issue.

LEGISLATIVE MANDATE FOR GREAT BARRIER REEF MARINE PARK

The Great Barrier Reef Marine Park Act 1975 Section 66(2)(e) provides for the regulation or prohibition of acts (whether in the Marine Park or elsewhere) which may pollute water in a manner harmful to animals and plants in the Marine Park.

The Regulations, drafted in accordance with the Act, specify that the written permission of the Authority is required prior to discharging or depositing "household, industrial or commercial waste in the Marine Park", with the following exceptions:

        a) where a Zoning Plan provides for the Zone to be used or entered for that purpose;

b)   the discharge of human waste from a vessel or
       aircraft which does not'contain a storage tank of a
       kind designed,for the storage of human waste;

c)   offal from fish caught in the Marine Park;,

d) other biodegradable "waste from a vessel or aircraft
   which is more than 500 metres seaward from the
   seaward edge of a reef.

The provision that sources of pollution "in the Marine Park or
elsewhere" may need to be considered, is of particular'
significance as it is one of the few provisions of the Act
relating to management of activities which are not entirely
within the bound'aries of the Marine Park.

In all normal circumstances the Authority would not seek to use
this regulatory mechanism but instead would prefer to collaborate
with other relevant agencies to achieve a common goal of
protection of the environment. Other legislative- controls
relevant to waste discharge in the Great Barrier Reef Region
include :

a.) Queensland Clean Waters 'Act 1971

Administered by'the Water Quality Council of Queensland, the
provisions of this act regulate discharges'which are likely to
cause 'damage to the environment of the territorial waters of the
State of Queensland.

b) Commonwealth Environment Protection (Sea Dumping) Act 1981

Administered by the Department of the Arts, Sport, the
Environment, Tourism and the Territories, this legislation
regulates, amongst other things, the dumping of wastes and other
matter from vessels, aircraft and structures into Australian
waters. For the purposes of this Act dumping does not include
discharge of human waste from a vessel, aircraft or structure
where that activity is incidental to normal operations.

c) Commonwealth Protection of the Sea Legislation Amendment Act
    1 9 8 6

This legislation will give force to Annex IV of the International
Convention for' the Prevention of Pollution from Ships. Annex IV,
propose's the introduction of a requirement for ships of 200 tons
gross tonnage and ships which are certified to carry more than 10
persons to have holding tanks for wastes and to discharge wastes
only outside of the Great Barrier Reef Region, for example,
through a facility at a port. This Act will only take effect
once the Annex has been ratified by 50% of nations representing
50% of world shipping'tonnage; expected to take several more
years.

The impact of the latter legislation, when and if it comes into effect, will be significant, not just for ship-owners, but also for coastal communities which may need to provide sewage treatment facilities for more than just a local population.

Like the Great Barrier Reef Marine Park legislation, the administration of the above Acts relies principally on the regulation of waste discharges through permits or licencing. It is perhaps the common objectives of the legislation and a similar approach to regulation which has resulted in the close liaison and cooperation between staff of each of the various agencies.

NEED FOR AGENCY LIAISON

The cooperative approach adopted by the various agencies is perhaps best illustrated by the example of the Four Seasons Floating Hotel. The Hotel itself is to be located at John Brewer Reef, in Commonwealth waters beyond the three mile territorial sea. It will cater for about 450 to 500 guests, staff and day visitors. Wastes, other than discharge of hypersaline water from the water desalination plants, are not to be released into the John Brewer Reef lagoon. The proposal is to carry out secondary treatment of wastes on site, incinerating sludge and transporting the treated effluent by barge to a dump site outside of the John Brewer Reef lagoon. The developer is also required to monitor effluent discharge and impact on the reef through an Environmental Monitoring Program approved by the Marine Park Authority.

As the principle agency responsible for approving the operation of the Floating Hotel, the Authority has been required to consider all aspects of -waste disposal, including the treatment methods, proposed standards and the means and locations for disposing of the treated wastes. In carrying out this review the Authority has sought and received extensive advice from staff of the Queensland Water Quality Council, the Commonwealth Department of the Arts, Sport, the Environment, Tourism and Territories,, oceanographers and various other scientists.

THE FUTURE

To date this Authority has focussed on the regulation of discharges from identifiable point sources. Standards adopted have generally been those applied to waste discharged in Queensland waters, in most cases equivalent to secondary treatment. The problems to be faced in the future are far more complex and must consider such matters as non-point source discharges, from land run-off, groundwater, and discharges into adjacent waters not within the Marine Park. In addition, discharges from vessels, both those transiting the Marine Park and those operating regularly within the waters of the Park must be considered. It is hoped that this workshop will provide guidance to the Authority with regard to both the threshold or critical levels for nutrients in GBR waters and appropriate management of sources of those nutrients.

The Authority has as one of its aims, "to protect the natural qualities of the Reef, whilst providing for reasonable use of the Reef's resources".

Recent surveys of tourists, and divers in particular, have indicated that Barrier Reef water quality and marine life are important features for most tourists (Pearce, 1987).

'It would not be difficult to argue that the natural qualities of the Reef would command a h'igh'value. In fact,' the economic value of tourism, for example, to the Re'ef Region measured as gross output is around $220 million per annum. This value is increasing in real terms by 10% per annum. (Driml, 1987). This figure represents strictly that expenditure involved in visiting the offshore islands and reefs.

It is the intention that this Workshop will function to enlighten Park managers on the direction we should take in regard to nutrients.

We need to know more about the effects of enhanced nutrient levels on Great Barrier Reef biota.

We need to consider acceptable levels for waste discharge and coastal run-off in the Marine Park and to determine management strategies to achieve those levels.

We may need to consider implementation of a monitoring programme and select appropriate components.

Any such programme will have to be implemented with limited resources and must be "spot-on" to reduce scientific uncertainty to the point where a management solution is clear. It must also provide results in time to enable management to take, action to prevent detrimental impacts.

By concentrating on the conditions that managers are attempting to maintain in a park and that users expect, the central question for resource managers should be "How much change is acceptable in the marine environment?". And then, "How do we maintain the quality that is desired?".

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WASTE DISCHARGE CONTROLS UNDER THE CLEAN WATERS ACT

Robert A. Craswell
Senior Water Quality Engineer
Department of Local Government

1. INTRODUCTION

Water pollution control relating to the waters of the State of Queensland is the responsibility of the Water Quality Council, a statutory body' set up under the Clean Waters Act 1971-82. This Act and its Regulations provide the statutory powers to control water pollution in Queensland.

The Act is of relatively recent origin having come into effect following its proclamation in 1973. It is an Act for the restoration preservation and enhancement of the waters of the state. Its existence can be traced to a manifest need for water pollution control in Queensland at that time. This need was demonstrated by the occurrence of anaerobic conditions in some of the state's waters, an industry survey to identify the scope and potential impact of waste discharges there-from and an absence of simple effective legislation to enable the situation to be rectified. At that time there was a world wide clamour for water pollution control and, this was reflected by local agitation for it here' in Queensland.

Within the framework of the then existing conditions, priorities were readily identified and the act framed accordingly.

2. SCOPE OF THE CLEAN WATERS ACT

The Clean Waters Act is intended to apply to the whole of the water segment of the environment - underground and surface waters, rivers, (both the bed and the banks) lakes, water storages and the sea. The Act embraces all uses of water - agriculture, irrigation, livestock, industry, public water supply, navigation, recreation, waste disposal, wildlife, fish and other aquatic life. It seeks to protect these waters and uses of water in a variety of ways, including the control of waste discharges from buildings, lands, drains, sewers, refuse tips, vehicles and vessels. The term waste is not restricted to sewage, garbage and material of no value, but includes any solid, liquid or gas which is capable of causing water pollution. The term discharge includes any escape; '@howsoever caused or occasioned". Provision is made for the promulgation by Regulation of water quality plans and water quality objectives which will apply to catchments or regions or, in some cases, to the whole State.

The Act is binding on all persons and bodies, including the Crown, and, subject to specific exceptions, its provisions prevail over those of any other State Act whenever the latter are inconsistent with the former. The exceptions are:

(a) Existing agreements under Section 10A of the Health Act, of which only one remains in operation;

(b) Five existing agreements made under Special Acts applying to mining developments which agreements pre-dated the Clean Waters Act;

(c) The Pollution of Waters by Oil Act.

(d) The discharge of wastes from vessels into tidal waters.

Both (c) and (d) are basically concerned with maritime matters and impinge on national and international agreements.

3. THE CLEAN WATERS ACT 1971-82

The Act is administered by the Water Quality Council of Queensland supported mostly by the Water Quality Section of the Engineering and Technical Services Division of the Department of Local Government, subject to the Minister for Local Government, Main Roads and Racing. The Council which is representative of State Departments, Local Government, Industry and Conservation comprises 19 members.

The Clean Waters Act seeks to control water pollution by two separate groups of provisions:

(i) 'The licensing provisions centered on Section 23 where the occupiers of premises are required to hold licences for discharges, subject to their meeting conditions attached to the licence.

(ii) The "duty of care" provisions of Section 31 where an occupier is required to so use premises that water pollution does not occur.

The licensing provisions provide exception for the following categories of discharge:

(i) if such wastes comprise stormwater runoff uncontaminated by domestic sewage or trade wastes!

(ii) if such wastes comprise stormwater runoff from agricultural lands and the--occupier-o-f-the.. premises complies with any specific or general requirements of the Council for controlling the contamination of such wastes;

(iii) discharges from septic tanks serving less than 100 persons.

In the case of (iii) Water Quality Council may impose other general or specific conditions to be observed by Local Authorities in granting permits for septic tanks under the Standard Sewerage By-Laws.

The "duty of care" or other provisions are currently implemented by:-

(i) inspecting premises to ensure occupiers are operating in accordance with Section 31, viz. in such a manner as to avoid the discharge of wastes to waters;

(ii) reviewing planning and other reports, such as environmental impact assessments, for new works and developments under Section 32; and

(iii) reviewing Local Authority proposals for refuse tips, strategic plans, town planning schemes, development control plans and by-laws under Section 36 and 37.

4. THE LICENSING PROVISIONS OF THE ACT

Section 24 of the Clean Waters Act contains the main provisions relating to licensing discharges.

Council may grant, refuse or grant subject to sudh conditions 'as it thinks fit, an application for a licence or for renewal or transfer thereof.' It may also revoke or vary any conditions applied to a licence or attach new conditions to a licence during its currency. In considering an application Council must have regard to, amongst other things, the character and flow of the receiving water, the best available practicable methods of treating the wastes, the present and future requirements for quality and quantity of such water, any prescribed water quality plans and Government policies, any conditions of a mining lease, the combined effects of the discharge and any other existing or future discharges to such waters and any other relevant information. Licences expire on the 30th June in each year and attract annual fees which are usually based on the quantity of wastes discharged. By definition, compliance with the licence conditions cannot be construed to be water pollution under' the Act and conversely, failure to comply with licence conditions is an offence covered by special penalties.

Each licence application is considered on its merits relative to the assimilative capacity' of the receiving waters. Neither the Act nor the Regulations lays down discharge standards apart from the General Standard' prescribed in the Regulations. Each licence may , for example, stipulate the daily quantity, quality and location of the discharge and may also lay down conditions including outfall submergence, initial dilution and on occasions restrictions relating to tidal or other factors limiting the duration of discharge. There are basically two alternative philosophies to setting effluent standards

        (i) Technology based; and
       (ii) Water quality based.

Technology based standards stipulate the degree of treatment to be achieved before discharge is permitted e.g. secondary treatment by biological means. The effluent quality would bear little relationship to the assimilative capacity of the receiving waters but would be consistent throughout an industry.

Water quality based standards stipulate the effluent quality required to achieve some minimum acceptable quality in the receiving waters.

Water Quality based standards can be imposed by the application of effluent standards on the dischargers or by requiring that the receiving waters be 'managed to maintain certain minimum ambient water quality levels.

The Clean Waters Act is water quality based but the powers of the Water Quality Council are so wide in the conditions it may attach to a licence that it could embrace technology based standards if it saw fit.

5. THE "DUTY OF CARE" PROVISIONS

Section 31 of the Clean Waters Act outlines procedures for the prevention of water **pollution** from premises other **than from discharges which** are **licensed.**

Section 31 requires the **occupier of any** premises **to keep** or **use such premises and** to operate **his** trade or industry **and** control **equipment in such** a manner as to **avoid the** discharge **of** wastes therefrom **to any** waters. **In addition, any** matter whether **solid, liquid** or **gaseous must not be placed in** or **on such** premises **in such** a manner that water **pollution is** or **is likely to be caused by any** part **of the** matter.

The provisions **of this section** are **aimed at the avoidance of the** discharge **of wastes** therefrom to **any** waters. **This is quite** different from the aim **of the licensing** provisions where water **pollution** is prevented **by** control **on the quantity and quality of the** discharged wastes.

To date these provisions **have been used** routinely **for schemes** for **land disposal of wastes** where **the** Water **Quality Council has** refused to grant **a** licence for discharge to wastes. **Supplementing this a number of highly polluting** primary industries **have been handled by the** provisions **of Section 23 (2)** (b) **(vii) and** controlled through **the use of guidelines** e.g. piggeries **and feedlots. Coal mines and** other **developments subject to the Environmental Impact Assessment** procedures **have also been handled** under **Section 31 and its** complementary **Section 32 which** require **the notification of the intention** to carry **out** works at **premises.** The final area **of application** arises **when pollution complaints** are received **and abatement means** are required e.g. extractive industry in water storage **catchments. This is not an all** embracing list **of situations** where **Section 31** provisions **have been used but it is a good indication of the** activities-of---**the** Water **Qua-lity- Council-in -this.** area.

There **is some debate as** to whether **these** provisions'of **the Clean** Waters **Act could be used** to control **non-point** source **pollution** generally. **Two** problems arise **in such** a general **application:**

(i)   **the** current **lack of any definite data to** prioritize **potential wastes** sources, **and thus justify the cost to the community of such** control **measures;**

(ii)   **the cumbersome** procedures where

(a) **each** premises **must be investigated** to allow **the** Water **Quality Council** to determine its **opinion on** the compliance with the provisions **of Section 31,**

(b) **the requirement that each** occupier **submit** grounds supporting his **belief that he is complying with the provisions of the Section where the** Water **Quality Council** holds a contrary **opinion, and**

(c) **the** Water **Quality determining the efficiency of such and** where necessary **imposing its own conditions on such** occupiers.

The exemption of the discharges **of wastes** from agricultural **land** from **licensing** provisions shows the **intention** of those drafting the legislation **to, impose** controls **in that industry. The imposition of** controls was **expected to be** through **the** normal farm advisory procedures **i.e. Department of** Industries **extension** officers.

Nutrients

The Water Quality Council initially saw its immediate role in the, control of oxygen demanding substances, heavy metals and pesticides in point source dischages. In recent years the incidence of algal blooms and oxygen super-saturation in estuaries and the abundance of macrophytes in some non-tidal streams has focused the Water Quality Council's attention on the nutrient enrichment of the state's waters. In view of the Water Quality's reluctance to impose conditions not adequately justified by evidence of problems to support their imposition it has moved cautiously to require nutrient removal having firstly indicated to some licensees its opinion that controls may be imposed at a later date. This was followed by the requirement for nitrogen removal and most recently by requirements for both phosphorus and nitrogen removal. All these related to specific point source discharges and in each case the requirement was supported by evidence to the Water Quality Council of the likely problems were these measures not to be implemented.

In the study of the trophic status of estuaries, assessment of the impact of non-point source pollution has been made. In no case to the present time has the Water Quality Council moved to directly control input of nutrients from non-point sources in the catchment as part of its management of any river. Its activities under the Duty of Care provisions have indirectly addressed this issue.. It is the lack of evidence specifically relating nutrients from these sources to manifest water pollution problems which lies behind the Water Quality Council's approach to date.

Conclusions

(i) Water pollution control to date in Queensland has been in response to manifest or identifiable problems

(ii) These problems have been addressed to date by the control of oxygen demanding and toxic components in point source discharges to waters.

(iii) Non-point source pollution control has, in the main, been restricted to industry other than intensive animal husbandry but'even then problem areas have received priority.

(iv) Work of the Water Quality Council to date has necessitated the imposition of nutrient removal on some point source discharges mainly in the highly populated areas of South East Queensland.

(v) Continuing studies will be needed to justify any move towards the widespread control of non-point sources pollution.

RIVER INPUTS OF NUTRIENTS

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INTRODUCTION

The interest of scientists at AIMS in river inputs of nutrients relate to their importance in determining the levels of phytoplankton primary production within the GBR ecosystem. General nutrient levels on the shelf and adjacent Coral Sea have been examined for some years and mechanisms for introducing nutrients onto the shelf investigated (Andrews and Gentien, 1982, Andrews, 1983, Andrews and Mitchell, 1986 and Wolanski, 1986). One such mechanism is upwelling along the shelf break which transports nutrients from the Coral Sea. Research into this process suggests it should be possible to budget these nutrient inputs using temperature and wind data (Andrews and Furnas, in prep). Shelf sediments hold a very large pool of nutrients from which remineralisation processes feed nutrients back into the pelagic zone (e.g. Ullman and Sandstrom, 1987). It is also known, from research following Cyclone Winifred last year, that cyclones can resuspend much sedimentary material from in and around reefs and thereby introduce large amounts of nutrients into the pelagic zone (Furnas et al, in prep). Data is lacking on a third likely source of additional nutrients, that from coastal rivers.

Nutrient sampling from rivers was commenced late last year and has continued this year as a relatively small research project. This effort comprises spot sampling at irregular intervals from 5 river systems (Figure 1) along the near-northern coast by ourselves and by individuals from local organisations. We have been sampling at the highway crossings of the Herbert, Murray, Tully and South Johnstone rivers. Brian Prove, (Department of Primary Industries, South Johnstone) has made collections in the South Johnstone and a major tributary, Bamboo Creek. John Reghenzani (Bureau of Sugar Experimental Station, Tully) has recently begun taking samples from the Tully River and a number of smaller creeks which feed it (Jarra, Boulder and Banyan Creeks). David Amos (Queensland Water Resources Commission, Ayr) is collecting samples from the Burdekin River.

Standard analyses done on these samples include major inorganic nutrients, NO , NO_2, NH_4 (constituting DIN - Dissolved Inorganic Nitrogen), PO_4, $Si(OH)_4$, DON (Dissolved Organic Nitrogen) and DOP (Dissolved Organic Phosphorus) as well as filtration of suspended particulate matter for PON (Particulate Organic Nitrogen). DON and DOP have presented some early analytical problems and are not discussed here. The PON samples remain to be analysed. This paper discusses the set of inorganic nutrient data so far obtained. Data is also available from the Queensland Water Quality Council on some creeks and rivers in this region, but is not discussed here.

Water collections were made from bridges using a clean Kinsey sampling bottle or bucket, sampling the top metre of water. A comparison of triplicate surface and near-bottom samples from the Murray River confirm that flowing river water is well mixed horizontally and vertically, so the surface sampling strategy appears valid. Water for nutrient analyses is filtered through GF/F filters into acid-washed vials and frozen for later analysis (within 2-3 months). For PON, known volumes are filtered onto pre-combusted GF/F filter , which are then retained frozen until analysis. All samples are filtered in duplicate. Methods of nutrient analysis used are described in Ryle et al (1981).

Figure 1.   River   sampling   sites.

River concentrations of inorganic nutrients are compared here with streamflow records from the QWRC for these river. As streamflow records for all sampling days are not yet available, monthly means from 1974 to 1984 have been used. A regional estimate of nutrient fluxes using these mean streamflows is calculated.

NUTRIENT RESULTS

For the present analysis, the nutrient data are divided into two sets, the first from the four northern rivers, the Herbert, Murray, Tully and South Johnstone and the second from the Burdekin River. Samples from smaller creeks are not included, as some of these show peculiarly high or low levels. Data from the four northern rivers have been combined and mean monthly concentration values plotted against the 11 -year monthly mean river flow for these rivers. The data for nitrate (NO_3) is shown in Figure 2 on a monthly base. Each bar represents the mean of 2 to 12 monthly values. NO_3 generally accounts for about 75 % of DIN and a seasonal trend with significantly higher NO_3 concentrations during the summer period of peak river flow is apparent. The seasonal pattern of DIN, comprising NO_3 and NH_4 (Figure 3), is similar to this seasonal trend. PO_4 concentrations (Figure 4), are quite variable throughout the year and never very high. From this small data set, a seasonal trend cannot be discerned. Silicate (Figure 5) concentrations are highly variable, with some suggestion of higher levels in the periods of greatest river flow.

Data from the Burdekin River were collected at about fortnightly intervals. Discharge volume was measured concurrently. In Figure 6, discharge volume is plotted against NO_3 and DIN concentrations through the period sampled. There again appears to be a trend of higher NO_3 and DIN levels during periods of peak river flow. For PO_4, shown in Figure 7, fairly steady, low levels are seen for most of the sampling period with only one elevated value. Studies in other regions have shown that very high levels of PO_4 may be flushed down at the beginning or peak of a river flood with much lower concentrations before and after. Silicate (Figure 8) shows some indication, from three values, of higher levels during flood periods.

CONCLUSIONS

The objective of this study is to obtain reasonable estimates of nutrient inputs from coastal rivers to the shelf ecosystem, in particular N species, since N appears to be the nutrient limiting phytoplankton biomass in pelagic shelf waters. In attempting a first-order estimate, the total 11-year, monthly mean flows from all the major rivers from the Barron down to the Burdekin, a coastal distance of -300 km, have been summed. Using mean, monthly DIN values obtained to date and a simple concentration-flow relationship, it is estimated that -10,000 tonnes of NO_3-N is output annually along this coastal area.

DON values are not reported here, but assuming a DON:DIN ratio of 2.3 obtained from other tropical rivers (Mkybeck, 1982), it is estimated that this would provide -2 µM-N per litre per year when averaged over the whole adjacent shelf. In terms of phytoplankton C fixed, this would account for ~3-4 % of annual shelf production. However, since much of the river water is probably constrained within the near-shore region by long-shore currents (Wolanski and Van Senden, 1983; Wolanski and Thomson, 1984), a reduced shelf area of influence, approximately 20 km offshore in width may be assumed. The calculated N flux could then support as much as 50% of the total N requirements. It must be noted that these estimates are based a very small data set, with extrapolation over some missing months, the use of an averaged 11-year flow record and the above assumption of a DON:DIN ratio. Furthermore, while some of the summer samples were taken from rapidly running creeks and rivers soon after rain, none were obtained from rivers at flood peaks.

Figures 2-5.   Mean monthly **dissolved inorganic nutrient concentrations in the South J'onstone, Tully, Murray** and **Herber Rivers during** 1986-87 (solid bars) **in** relation **to 11-year mean of summed monthly'** discharge **rates** (open circles).
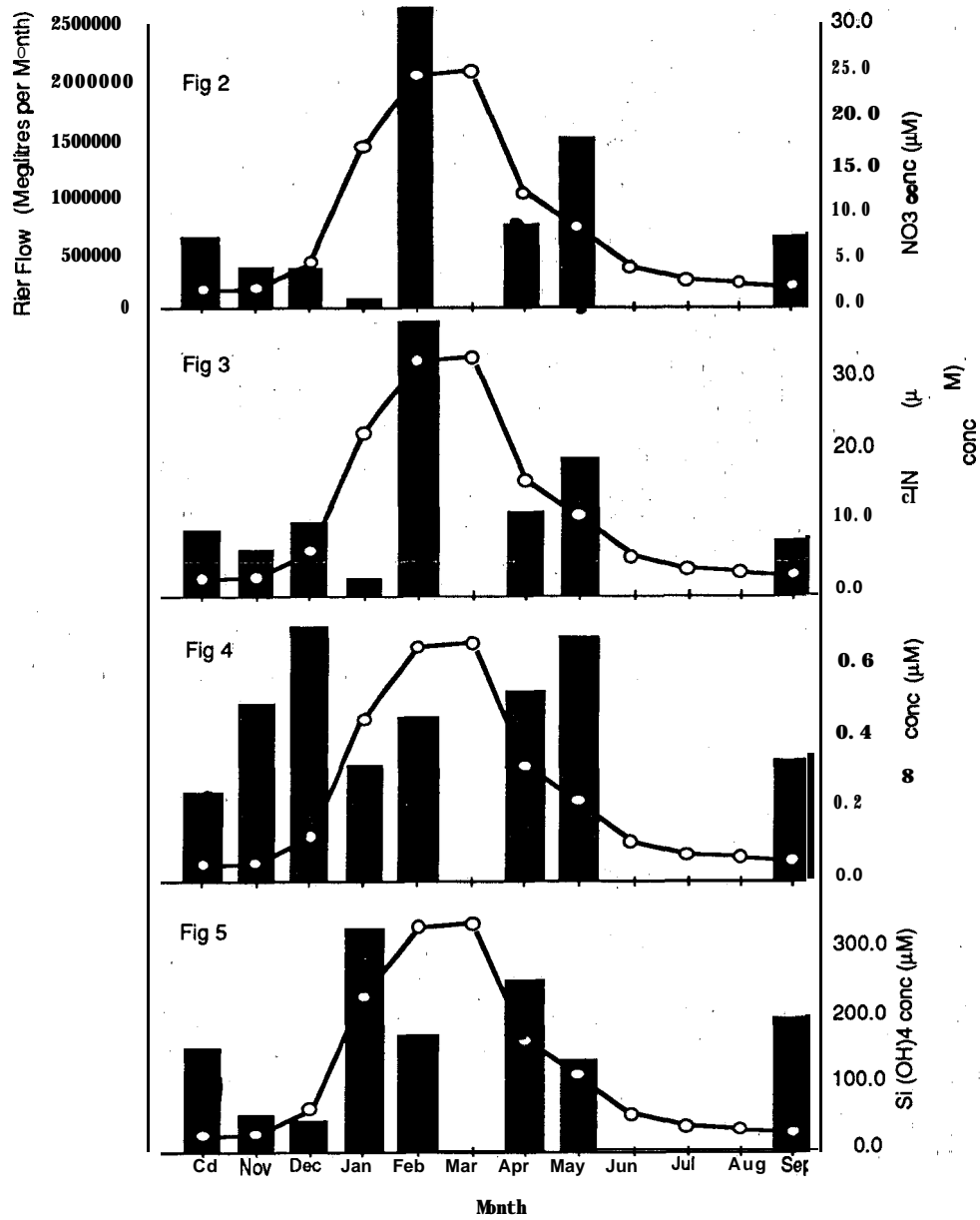
Figures 6-8. **Discharge volumes and dissolved inorganic nutrient concentrations in the Burdekin River during 1987.**
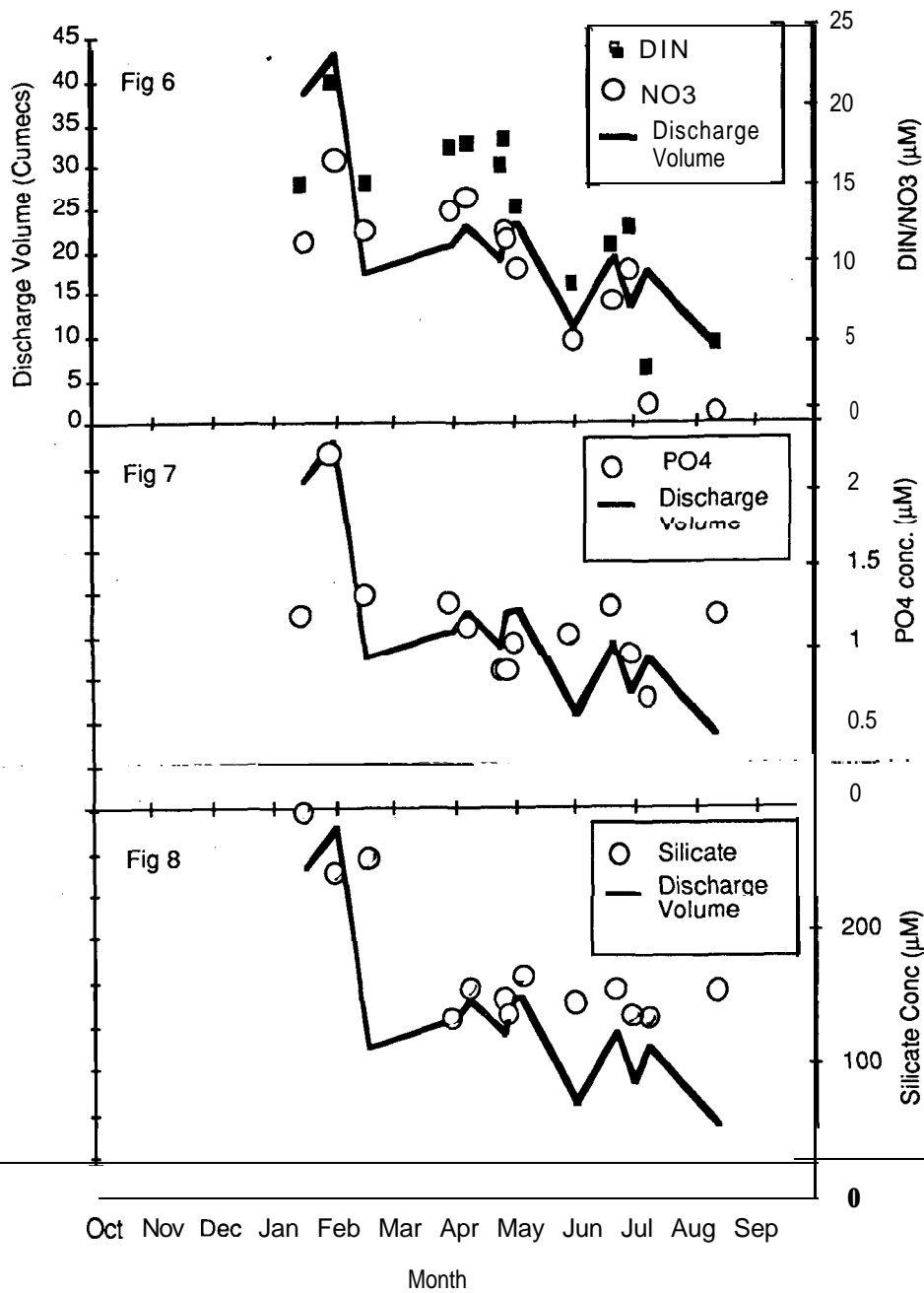
RIVER VARIABILITY

Finally, a comment should be made about the variability in flow **of** North Queensland rivers. While most flow occurs in the summer months, it can be extremely variable on day to day time scales. An example is the Herbert River before and after Cyclone Winifred (Figure 9). In the 5 days following this cyclone, 5 1% of the 1986 annual flow of the Herbert River was recorded. Considering such flow variation, it is important to monitor large flood events to see, whether higher nutrient levels occur during these periods. Though a sampling programme of this nature is difficult to organise, we plan to attempt event sampling.

Water flows also vary enormously from year to year. Figure 10 shows the annual flow in the Burdekin River in 1974, a wet year and in 1982, an "El nino" drought year. The 1974 flow, in which nearly 30 million megalitres was recorded in the month of January, was 28 times higher than the 1982 flow and 19 times higher than the 11-year mean used herein. Considering such year to year variability in river flow rates, large flood events could introduce large nutrient loads into relatively small areas of the shelf over a small time frame. . The results of such "event-scale" inputs of nutrients might range from effects on exposed benthic organisms to the promotion of phytoplankton blooms and subsequent enhanced survival of larval organisms.

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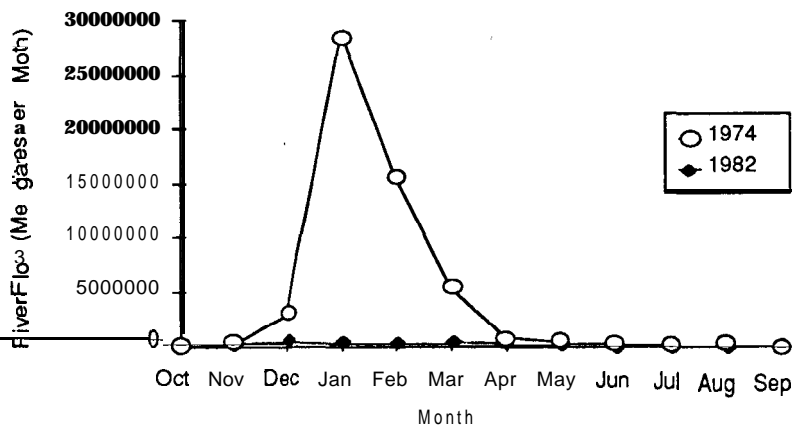**Figure 9. Discharge from the Herbert River resulting from cyclone Winifred.**
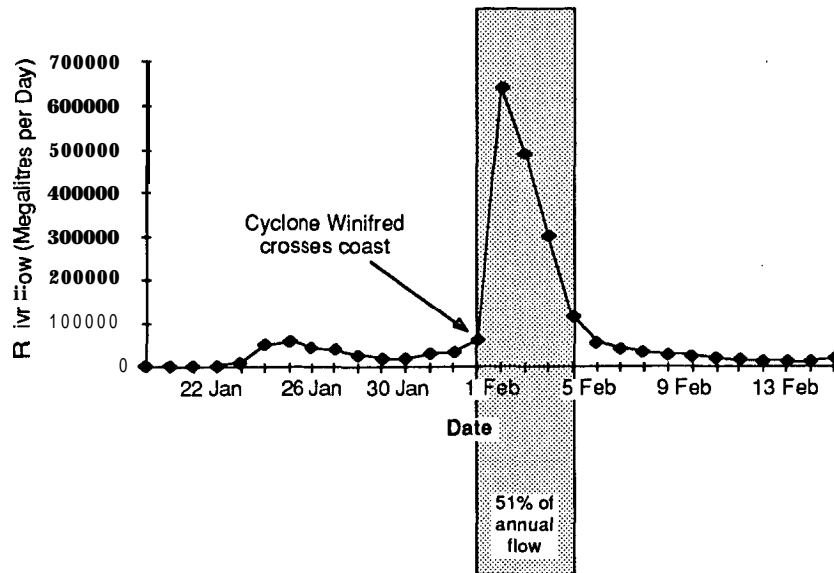
Figure 10. Discharge rates in the Burdekin River over two years, 1974 and 1982.

SEDIMENTARY EVIDENCE ON THE SEAWARD LIMITS OF SUSPENDED MATERIALS FROM RIVERS

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INTRODUCTION

The Marine Geoscience Group has been researching sedimentation.on the central Great Barrier Reef shelf for several years, concentrating on the sector from Cape Upstart to Cape Tribulation. The programme has two major themes : sea-level history and transgressive sedimentation during the last post-glacial sea-level rise, and the patterns and processes of modern sedimentation, particularly the transition from terrigenous sediments nearshore to carbonate sediments offshore. These studies have utilised a wide range of equipment, mainly shallow seismic (Uniboom and 3.5KHz) profilers, vibracorers and a frame-supported grab for recovering undisturbed samples of the sea-floor.

The central Great Barrier Reef shelf is up to 120km wide, with a reef tract occupying the outer shelf 30-50km offshore, in water depths of 40-80m. The middle shelf is a broad, featureless plain with a thin veneer of relict sediment covering the Pleistocene surface. The inner shelf is the area of active modern terrigenous input and extends up to 15km offshore to water depths of ca. 20m. Fringing reefs surround many of the bedrock islands on the inner shelf, and are subject to river influx, in contrast to the shelf reefs offshore which are beyond most river influence. A summary of recent work on shelf sedimentation is given by Johnson, Belperio & Hopley (1986).

This paper summarises some evidence on the seaward limits of deposition of suspended sediment introduced to the marine realm by rivers. While dissolved nutrients may be dispersed further in the water, it is clear that most nutrients attached to suspended materials are deposited initially very close to shore.

SEDIMENTARY EVIDENCE

Sedimentary Facies

Modern coastal deposition in the Bowen-Ingahm area has formed a seaward-thinning wedge of terrigenous sediment up to 20m thick, and up to 15km wide, consisting of an inner platform'of more. sandy sediment, overlying a thin wedge of muddy sediment (Johnson & Searle, 1984) (Fig.1). More recent, unpublished data has confirmed this pattern off Cape Tribulation (Johnson & Carter, 1987), off Innisfail (Gagan, unpubl. data), in Cleveland Bay off Townsville (Carter & Johnson, unpubl. data), and off the Burdekin Delta (Way, 1986). This wedge of inner shelf sediment displays, seaward-dipping seismic reflectors which indicate deposition at present sea-level.
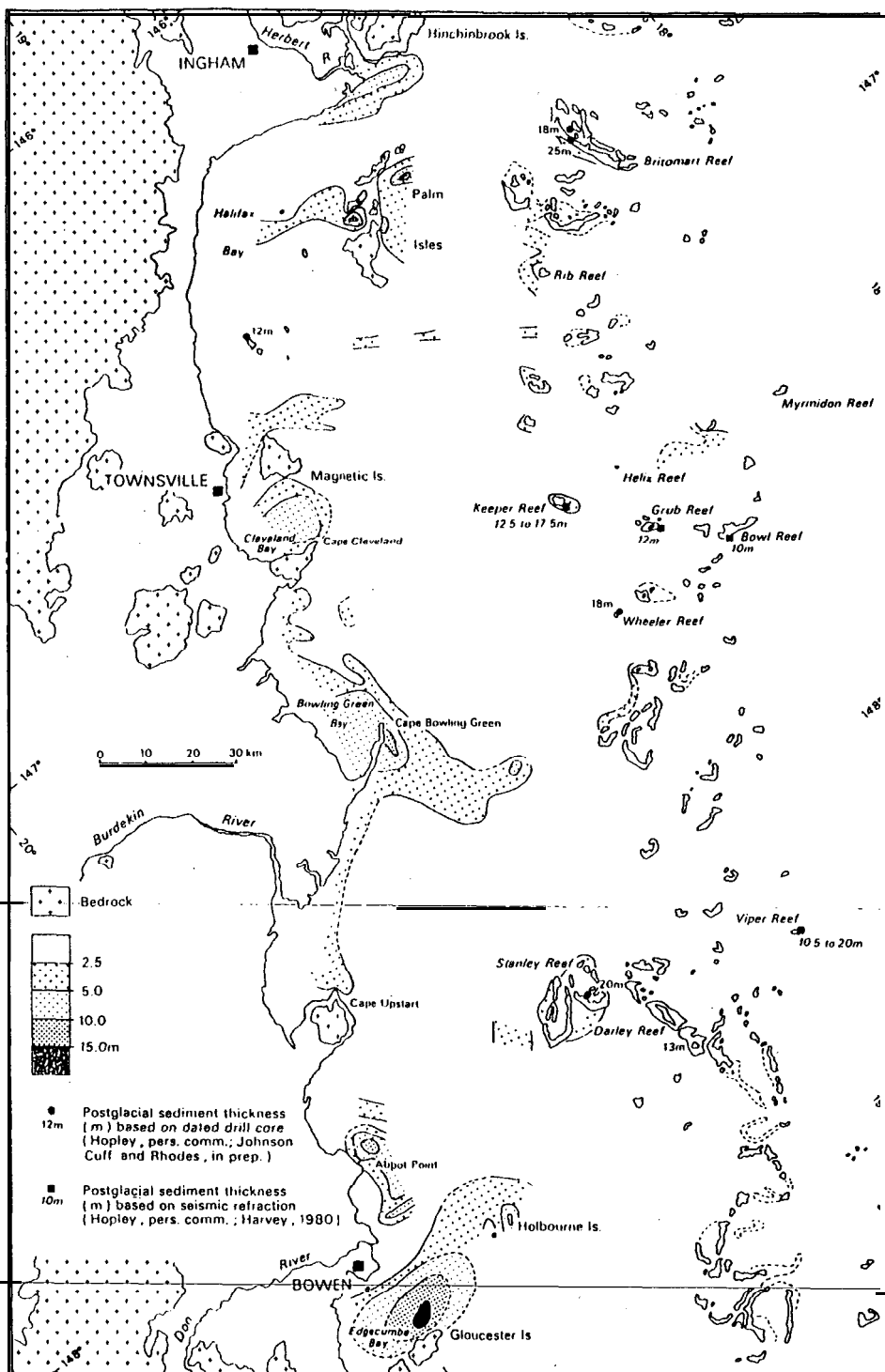
Figure 1. Isopach map showing distribution of post-glacial sediment on part of the central Great Barrier Reef shelf. **Note** the wedge of sediment nearshore (from Johnson & Searle, 1984).

Sediment brought to the coast by rivers tends to stay nearshore for the following reasons. Sand is deposited on river mouth bars due to the drop in river velocity and the onshore transport induced by waves. Longshore drift of sand is predominantly northwards in response to the prevailing southeasterly weather (Belperio, 1983). Muddy plumes of suspended sediment extend further seawards but are generally also held nearshore by the weather (e.g. Belperio, 1983; Wolanski & van Senden, 1983).

Stable   Carbon   Isotopes.

,A study of the top 10mm of undisturbed sediment samples from the
shelf off Innisfail before and'after Cyclone Winifred crossed the
shelf on 1 February 1986 showed the seaward extent of deposition
of terrestrial organics (Gagan, Sandstrom & Chivas, 1987)'
(Fig.2). Terrestrial organics have a sta'ble carbon isbtope (del
13C/12C) ratio of about -26.5 per mil in this region., while the
shelf marine organics have a ratio of around -18 per mil. Figure
2 shows the mixing of these two end-member sources of organics to
give intermediate ratios for organics from samples across th.e
shelf. It is clear that significant amounts of terrestrial
orqanics do not extend more than 12km offshore since the isotope
ratios are essentially marine at this distance from the coast.
It is also clear that the distribution of orqanics is much the
same after as before the flood of terrestrial sediment caused by
rainfall associated with the cyclone.
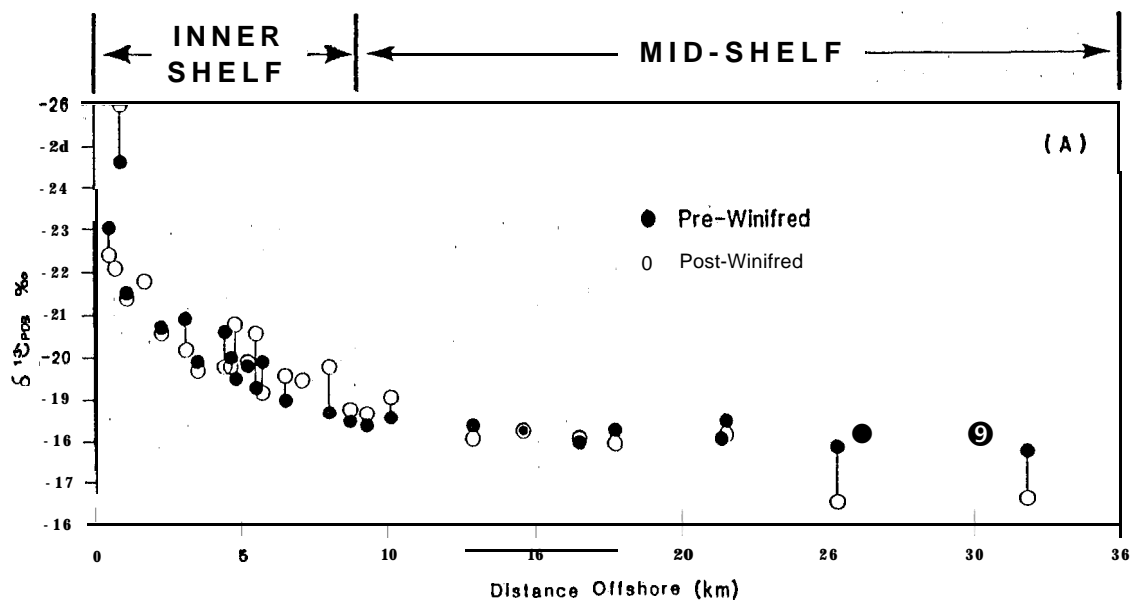
Figure 2. Comparison of the stable carbon isotope ratios of
organics from surficial shelf sediment before and after Cyclone
Winifred (from Gagan and others, 1987).

Evidence from Reefal Sediments

Analyses of reef cores confirms that terrigenous sediments are
largely restricted to inner shalf areas, and further that htis
has been the pattern during the Holocene, i.e. during the major
recent phase of reef accumulation. Isdale (1984) showed that
coral cores from inshore reefs preserved the influence of
terrestrial flooding as fluorescent bands, an effect very rarely
seen 'in offshore shelf reefs. Many'analyses of surficial
sediments from shelf reefs have'shown they are carbonate
sediments (e.g. Orme & Flood, 19801, with minor terriqenous
sediment, only in the deeper parts of cores (e.g. Johnson, Cuff &
Rhodes, 1984). These deeper sediments would have accumulated at ,
lower sea-levels when the coastline was, consequently closer. In
contrast the fringing reefs around bedrock islands on the inner
shelf contain up to 50% terrigenous sediment in the matrix

between larger coral and shell fragments (Johnson & Risk, 1987).
Further the terrigenous input has been essentially constant
during the Holocene.

CONCLUSIONS

(1) Sedimentary evidence from seismic profiling, isotope studies
of surficial sediments, and the nature of reefal sediments
indicates most suspended terrigenous sediment is deposited within
15km of the coast, and in water depths of less than 20m.

(2) However it may be that some of this sediment is moved
gradually across the shelf in the longer term, but present
evidence is that such amounts are insignificant under the wave-
dominated environment of the central Great Barrier Reef. Such
cross-shelf transport is more likely in areas with higher tidal
currents such as the Whitsunday region.

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BENTHIC NUTRIENT REGENERATION IN THE CENTRAL GREAT BARRIER REEF REGION

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Despite the acknowledged importance of the regeneration of dissolved inorganic nutrients from the benthos to the water column for primary production, it is astonishing that so little of such work has been conducted in the Great Barrier Reef province. A few studies have examined water column concentrations in relation to water mass movements (e.g. Walker and O'Donnell, 198 1, Andrews and Gentien, 1982), but only two published studies have examined benthic nutrient fluxes either in situ or in the laboratory (Hansen et al 1987; Ullman and Sandstrom, 1987).

From nearshore sediments of Bowling Green Bay (Central GBR Lagoon), Ullman and Sandstrom (1987) measured fluxes in laboratory cores ranging from -23 to 28, -154 to + 890 and -990 to + 1750 μmol-m^{-2}.d^{-1} for PO_4^{3-}, total nitrogen species (NH_+ + NO_- + NO_-) and $Si(OH)_4^-$, respectively. Similarly, in Davies Reef lagoon, Hansen et al (1987) recorded low and variable fluxes (-28 to + 1 for PO_4^{3-}, +57 to +806 for $Si(OH)_4^-$ and + 143 to +544 for ΣN).

Recent and ongoing nutrient regeneration experiments conducted by the author at AIMS have found similarly low and variable benthic fluxes measured from intact box cores and bell chambers taken from intertidal and subtidal sediments in the Hinchinbrook Island - Murray River - Brook Islands region. The results suggest that proximity to mangrove forests does not apparently result in greater rates of nutrient flux (Table 1).

Of greater significance is the fact that solute fluxes calculated using Fick's diffusive law (Bemer, 1980) predict generally higher rates of flux for all of the inorganic species compared to the measured fluxes (Ullman and Sandstrom, 1987; Alongi, in prep.). Taken together, our data reveal a strong vertical concentration gradient with sediment depth at Bowling Green Bay and in the Hinchinbrook region for all nutrients implying the existence of strong nutrient fluxes from the sediments to the overlying water.

Comparison of fluxes from the GBR province with those from temperate coastal and estuarine sediments reveals that the fluxes from the GBR are substantially below the mean fluxes observed in other environments, although there is a fair degree of overlap (Table 1). Why such low fluxes despite evidence of strong vertical concentration gradients? Two possible reasons are: dilution by terrigenous inorganic debris low in nutrients and relatively unreactive, and low rates of plankton detritus deposition coupled with high rates of benthic bacterial production. Indeed, bacterial production rates in the Hinchinbrook Island region range from 0.5 - 2.3 gC.m^{-2}.d^{-1} indicating that nutrient consumption is occurring at or near the sediment-water interface (Alongi, in prep.).

Table 1   DISSOLVED NUTRIENT FLUXES ($\mu mol \cdot m^{-2} \cdot d^{-1}$)

Location	PO_4^{3-}	Si	NH_4^+	$NO_2^- + NO_3^-$	Reference
Narragansett Bay (20°C)	160-7700	1800-1700	900-1800		Elderfield et al (1981)
Long Island Sound (22-27°)	60-320	0-19800	-1000-8000		Aller (1980); Aller and Benninger (1981)
Potomac Rivet (20°C)	-600-4000	1000-25000	-3100-26000		Callender and Hammond (1982)
Bowling Green Bay (22°)	-23-28	-990-1750	-160-760	-33-150	Ullman and Sandstrotn (1987)
Davies Reef Lagoon (22°C)	-28-1	+ 57-800	+ 143-544	0-10	Hansen et al (1987)
Missionary Bay · Murray River Region (20°C)	-34-79	+ 522-3144	-624-2469	-75-250	Alongi, in prep.

MANAGEMENT IMPLICATIONS

It is probable that nutrient fluxes from GBR sediments are enhanced only during periods of extensive river runoff (e.g. the Burdekin floods) and storm surges (e.g. cyclones) which result in significant sediment resuspension.   The calculations of Ullman and Sandstrom (1987) predict the resuspension of I cm of GBR inshore sediment would lead to moderate increases in water column nutrient concentrations, particularly for nitrogen species.   However, no simulation experiments have been conducted to test this hypothesis. It is evident that benthic nutrient fluxes in the GBR are finely tuned to physical processes occurring on land and in the water column.   However, before correct management decisions (e.g. waste disposal criteria) can be made, more observations, preferably of a long-term nature of benthic nutrient fluxes are necessary-particularly at or near sites of future anthropogenic input.

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SOIL EROSION RESEARCH IN CANE FIELDS ON THE WET TROPICAL COAST OF NORTH EAST QUEENSLAND

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INTRODUCTION
A research program was initiated in 1982 to develop appropriate minimium tillage and harvest residue retention practices to reduce soil erosion in sloping canelands. Previous estimates of soil *erosion* **in the area were as** high as 380t/ha after a mammoth January rainfall of 2742mm (Matthews and Hakepeace, 1981) but methods to combat the problem in north Queensl and have not been widely adopted,

The area has very high rainfall (>3000mm/annum), and steep and broken topography and the use of conven t i onal soil conservation structures is not of ten acceptable to the farmer because of the difficulty in achieving workable layouts. In the absence of protect i on, thunderstorms and a prolonged wet season cause large erosion losses in the intensively cultivated soils,

Trials were establi shed on commerc i al farms in each of the mi 11 areas where significant areas of sugar cane were grown on slop i ng 1 and. This was to ensure a high level of interest from local farmers and to facilitate the ex tensi on of the work in that area,.

This paper summar i ses the soil erosion measurements for different ti 11 age and residue retention practices and -reports. some prel iminary findings- --of nutrient concentrations in runoff water leaving the farm paddock. The results Of the so i i eros i on research are currently being written for submission a s a final project report to the National Soil Conservation Program and for submission to relevent scientific journals.

METHODS
Soil erosi on was measured using a prof i 1 emeter (Sal laway and Prove, 1983) which enables changes in the soil surface to be mon i tored prior to and subsequent to erosive rainfall events, Runoff was measured wi th a system of he i ght recorders and data loggers as. i t passed through a 75mm Parshall flume, Nutrient samples were col 1 ec ted from 1 arge set tl ing tanks at ttie bottom of the paddock and from the creek draining the farm, and analysed at the AIMS laboratory (Ryle et al., 1981).

RESULTS AND DISCUSSION
Soil Erosion
Soil erOsion rates between 50 and 500 t/ha/yr were measured under conventi onal cultivation practices depending on the severity of the wet season, the land slope, and time since cultivation before erosive rainfall occurred, In general terms, soil loss in the order of 150 t/ha can be expected in any year, At the site wh i ch recorded 500t/ha/yr, 400 t/ha was lost in two thunderstorms in October and November 1985. A further 100 t/ha was lost during the wet season, The reason for the heavy thunderstorm losses was that intensive cultivation was carried out prior to both storms.,

Under zero tillage and residue retention systems,' soil erosion rates have been reduced to 50 t/ha/yr or less, These much reduced soil erosion rates resulted primarily from the absence of tillage, thereby taking advantage of

the soil compaction associated with harvesting. operations. In addit ion:, protection was gained from increased levels of ground cover;.

Runoff

Total runoff volumes were largely unaffected during wet season rainfall even t's,'; As the soil is at,or above. field capacity during most of the wet 'season, high intensity rainfall causes overland flow (or runoff) to occur irrespective of the management practice. Management practices, however will influence the shape of the runoff hydrograph (Figure, 1). Response times for both the rising and falling stages of 'the hydrograph have been increased with residue retention and zero tillage, however peak rates have been decreased, thereby reducing the erosive potential of the runoff water'.

Nutrient' Levels

Preliminary results indicate that total inorganic nitrogen concentrations in runoff water from farm plots range from 84 to 1000mg/1. Total inorganic phosphorus concentratioris were from 1 .6 to 34mg/1. Concentrations of total inorganic nitrogen and phosphorus in the creek draining the farm ranged between 140 to 1540 and 3.1 and 15.5mg/1, respectively. No apparent differences between management practices were detected. Interpretation of this information must be carried out very cautiously as only single samples were obtained. No analysis of nutrients in bed load sediments has been carried out.

Adopt i on Rates

Extension activities have concentrated on increased awareness of soil erosion rates occurring annual l y from cultivated canefields and 'on management practices capapable of reducing these rates substantially. After five years of research and extension and associated industry organisation efforts, an adoption rate of 60% in all sloping caneland of the wet tropics region, using conservation farming techniques, is expected for the 1987-88 *cane season.

ACKNOWLEDGEMENTS

CONCLUSIONS

The large soil erosion rates (up to 500t/ha/yr) in intensively cultivated sugar caneland may be substantially reduced (<50t/ha/yr) by adopting' zero tillage and residue retention practices. Little information is available on nutrient levels in runoff waters leaving the farm, however it appears that no, apparent change in nutrient concentrations will occur with the adoption of these conservation farming practices. During the 1987-88 season, conservation farming practices are expected to be adopted on 60% of the sloping caneland on the wet tropical coast.

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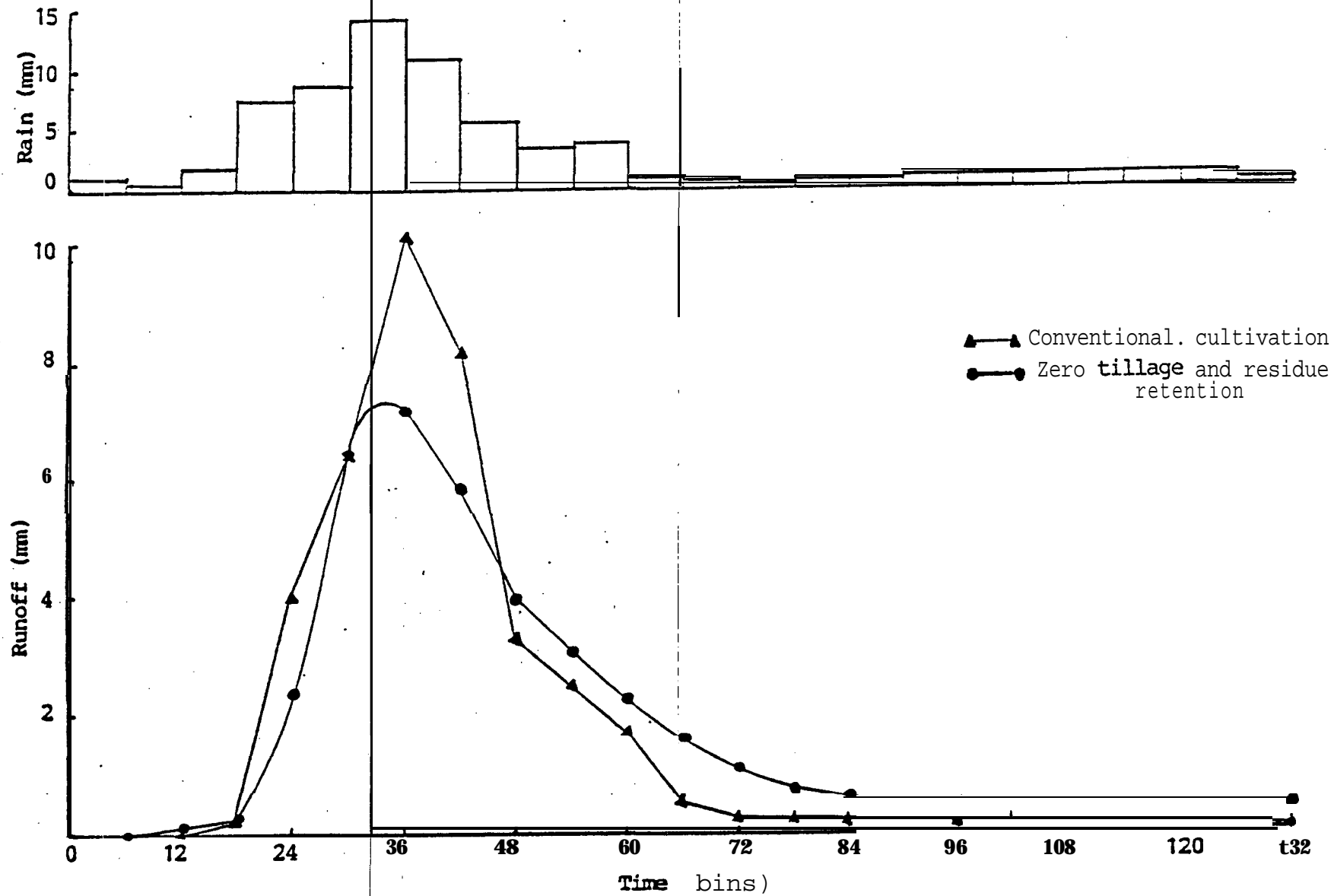
Figure 1

Rainfall Hyetograph **and** Runoff.Hydrcgraphs for a **0.08** ha Catchment in Innisfail **(21/1/86)**

NUTRIENT STATUS Ok MANGROVE SYSTEMS AND SOME POSSIBLE EFFECTS OF EXTRANEOUS INPUTS

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INTRODUCTION

Connections between mangroves and coral reefs have not been investigated in any detail. Indeed, it is difficult to conceive of a direct connection between these systems in the central and southern sectors of the Great Barrier Reef where the majority of the substantial reefs are situated tens of kilometers from the coastal mangroves. Nevertheless. the possible impacts of anthropogenic nutrient inputs into mangroves are of very direct importance to the discussions of this workshop. In practice. most of the resort and other developments in the region are situated on the coast or on coastal islands which contain, or are close to, substantial mangrove forests. Hence. the impact of these developments is likely to be felt first by the mangroves.

This paper briefly discusses some aspects of nutrient flows and seasonal variations in the concentrations of dissolved organic and inorganic forms of the major "macro" nutrients (carbon. nitrogen and phosphorus) in mangrove waters. This information, along with a limited amount of data concerning the capacity of mangroves to absorb nutrient loads, is then used to speculate on the possible effects of extraneous nutrient' inputs into these systems. Specifically, the questions to be addressed are:

(a) What are the ambient concentrations of nutrients in "pristine" mangrove waterways and how do these vary throughout the year?

(b) Are mangroves a source or sink for particular forms of nutrients? (Cf. the controversial "outwelling" concept which has been the subject of considerable attention in studies of, temperate salt marshes and critically reviewed by Nixon (1980)).

(c) Can mangrove forests absorb large nutrient loads and hence ameliorate their potential impact on coastal waters or other perhaps more fragile ecosystems (e.g. fringing reefs)?

RELEVANT DATA AND INFORMATION

Ambient nutrient levels
Most of the following data and discussion. except where otherwise specified'. is taken from a manuscript recently submitted for publication (Boto and Wellington. ms submitted).

The concentrations of some dissolved organic and inorganic materials. in a mangrove tidal channel (Coral Creek. Missionary Bay. Hinchinbrook Is.) have been shown to vary significantly over a 20-month period (Fig. 1). although the concentrations of all species were generally an order of magnitude lower than results reported for temperate salt marshes. Florida 'basin mangroves or an estuarine mangrove system in Malaysia (Nixon. 1980: Twilley. 1985: Nixon et al. 1984). In this regard. Coral Creek provides an interesting comparison with all other wetlands studied to date in that it is influenced' only by tidal action and is virtually free of any terrestrial/freshwater influences via river or groundwater inputs.. This factor alone probably accounts for the much lower ambient nutrient levels in these waters.

The concentrations of dissolved organic carbon (DOC). dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) varied significantly (one-way ANOVA. $p < 0.05$) throughout the study period but no seasonal trends were apparent. In the 1982-83 summer period. the inorganic nutrient (ammonium, nitrate: nitrite and phosphate) levels peaked during the period December to March and by July had decreased to levels near or, below
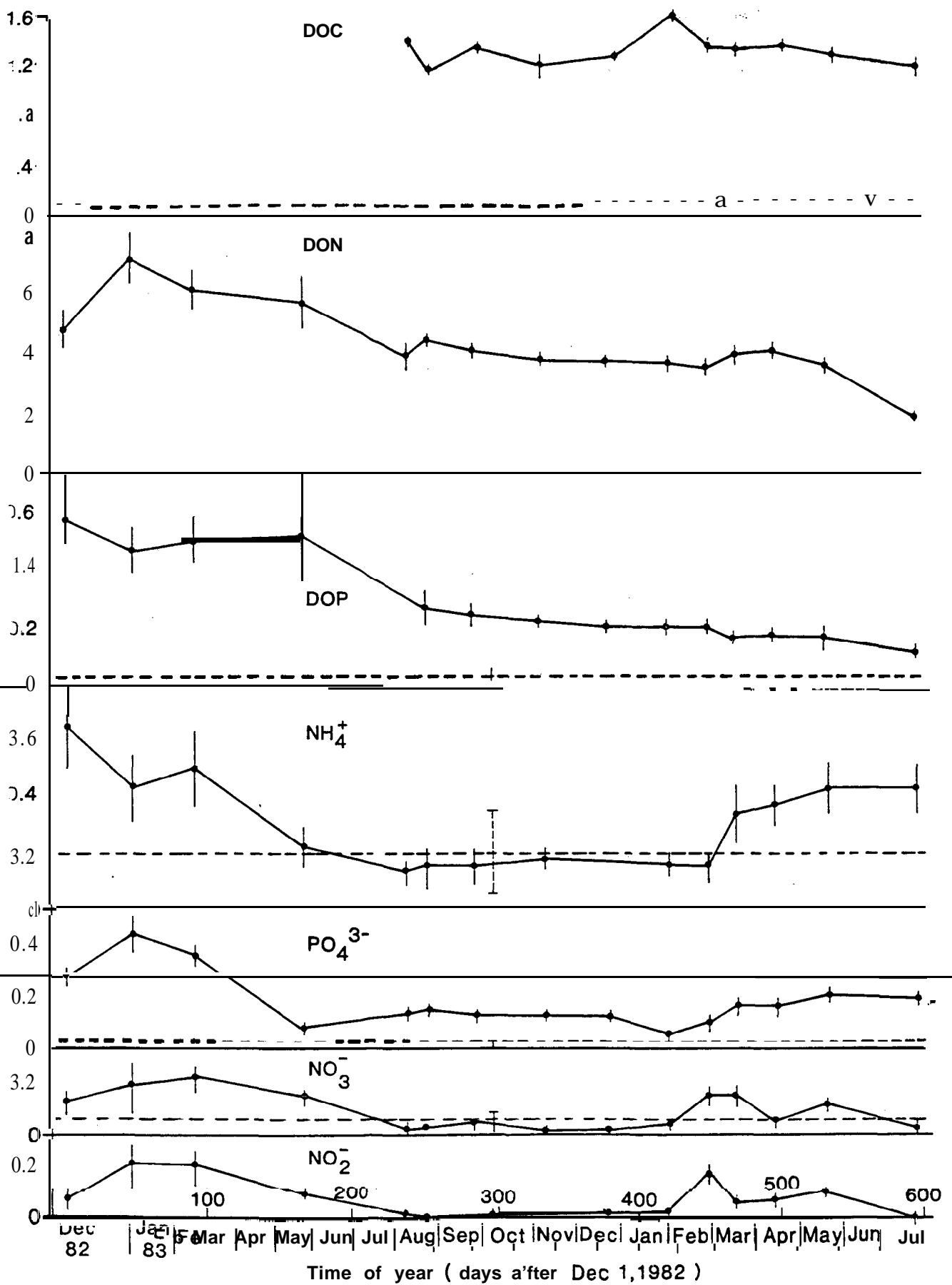
Figure: 1 Variation of the concentration (mean + 95% C.I.) of the dissolved materials in Coral Ck with time of-year. (Dotted lines indicate detection limits for the various entities).

the limits of detection. In the following year. however, the peak was later - February to July - significantly reduced in magnitude (l-way ANOVA, $p < 0.05$) and more prolonged, with ammonium and phosphate levels still significantly above detection limits in July.

Correlations between the concentrations of the dissolved materials, and some selected climatic data from a weather station in Coral Creek were examined. Most of the correlations were low ($/r/ < 0.65$) in absolute terms and it was readily apparent that the concentrations of most of these materials were only weakly (if at all) influenced by the macro-climatic variables examined in this study. A possible exception was foi the case of nitrate + nitrite where a good predictive multiple regression model could be, constructed using' solar radiation and water temperature as predictor variables. The utility of Such a model is questionable, however. as nitrate + nitrite account for only a minor fraction (2-3 %) of the total dissolved nitrogen in these waters,

Dissolved material fluxes

Only a few of the dissolved components gave statistically significant net flux estimates for individual tidal cycles. Further, even these components showed no consistent trend in net fluxes with all components except total dissolved phosphorus showing virtually zero net flux when the results for the 16 cycles studied were integrated over a full year (Table 1). Total dissolved phosphorus gave an annual net **import** amounting to ca. 24% of forest primary production requirements.'These results were consistent with previous studies which indicated that the mid- to high-intertidal areas of the forests in the Coral Creek system are P-limited (Boto and Wellington, 1983).

When these results are coupled with' previous estimates (Boto and' Bunt. 1981 with modifications according to the data of Robertson, 1986) of particulate matter **export** (mainly in the form of intact plant litter) amounting to ca. 35%, 9% and 10% of forest primary production C, N and P requirements respectively. it is immediately obvious that these forests generally export substantial quantities of organic carbon while N and P are almost completely conserved within the system. This tidally-dominated mangrove system therefore appears to be in a very finely balanced state as far as the macronutrients are concerned and, most pertinent to this discussion, there is no evidence to suggest that mangroves act as "sinks" for dissolved nutrients in the water column, except perhaps for total dissolved phosphorus.

Studies (Boto and Wellington. 1983) in which very large N and P fertilizer loadings were applied directly to the soils within the forests nevertheless demonstrated the ability of these forests to absorb high loadings of nitrogen and phosphorus, at least in the short term (one year). In that study. the forests showed either a significant positive growth response over 12 months or no response, depending on position within the intertidal zone. No detrimental effects were noted during that period.

DISCUSSION

It is important to stress at the outset of this discussion that the data obtained for Coral Creek can not be considered to be typical of the estuarine mangroves of the northern coastline in which the nutrient status is probably much more influenced by the associated riverine input than by the presence of the mangroves per se (Boto and Wellington? ms submitted; Nixon et al. 1984). The discussion by Mitchell (this volume) on river inputs of nutrients is therefore more relevant to the estuarine mangroves where the presence of the 'mangrove vegetation may act as a ."sink" to reduce somewhat the impact of river-borne nutrients on coastal waters (e.g. see Kennedy. 1984) although this latter feature has never been effectively demonstrated.

The Missionary. Bay mangroves (including Coral Creek) are. however, typidal of some of the larger mangrove forests of this region e.g. those situated at the, southern end. of Hinchinbrook channel. Bowling Green Bay. Trinity, Inlet. Port Douglas. Lockhart River (mouth) and Newcastle Bay. Because of their considerable areal extent. therefore. these

tidally-dominated systems can be considered to exert a significant influence on the coastal. and perhaps shelf. waters of the GBR lagoon.

It is reasonable to propose. from the information gained in the Coral Creek studies, that the effects of extraneous nutrient inputs to the mangrove systems, and their ability to absorb and hence ameliorate subsequent impacts on surrounding waters, will depend strongly on the placement, timing and quantities of such inputs.

For example, the consistently very low levels of dissolved organic and inorganic nutrients in the waters would suggest that major direct inputs of nutrient-laden effluents to the waters would be expected to be very detrimental to the water column nutrient status. Relatively minor loadings would have a significant effect on the dissolved nutrients in the waters and the potential for eutrophication must be considerable. Other discussions at this workshop may' focus on such effects and some local case history studies. Placement of the effluent directly into mangrove waterways may have less impact if carried out during flood tides. preferably spring tides. In this situation? the waters have a greater chance of coming into contact with the mangrove forest sediments and to be taken up by the trees, before the waters are then dispersed into the surrounding coastal waters during the ebb cycle.

Fairly obviously. the preferred mode of input would be directly onto the mangrove forest sediments and at an elevation high in the intertidal zone. This would give the greatest chance for the nutrients to be taken up by the trees and sediments and would enhance forest growth in the usually hypersaline high intertidal zone by lowering the soil salinities as well as increasing the phosphorus status of the soils which are likely to be P-deficient in this zone.

Even if the most efficient input mode can be achieved, it would be crucial to minimize the loadings and to monitor the nature of the effluent. There are definite limits to the long term ability of the trees and soils to absorb inorganic nutrients. This will be mainly determined by the forest growth rate i.e. if nutrient supply chronically exceeds the rate at which the trees can incorporate them, the excess must eventually leach into the mangrove waterways. There are also limits on the ability of even Fe-rich soils to chemically fix phosphate. While very heavy P loadings can be tolerated in the medium term (e.g. up to 400 $kgP.ha^{-1}.y^{-1}$ for the first year - Boto and Wellington? 1983) owing to the phosphate-. fixing capacity of clay and silts in particular. this capacity will significantly diminish in the longer term (Holford and Patrick. 1978).

Organic-rich effluents with high biological oxygen demand probably present the greatest threat to the long-term viability of the forests. Many mangrove forests are likely to be at or near the limits of their ability to cope with soil anaerobiosis (Boto and Wellington, 1984; Smith, unpublished data) and increased organic loads are highly likely to significantly intensify soil anaerobiosis which will not only effect the trees but probably also the burrowing infauna which play such a crucial role in the mangrove ecosystem (Robertson, 1986; Smith, 1987; Smith, unpublished data). It would therefore be strongly recommended that effluents be subjected to preliminary treatment to reduce the organic matter content before addition to a mangrove forest. More details of the probable response of mangroves to sewage effluent are given in a review by Clough et al (1984).

In summary. the ability of mangroves to absorb nutrient inputs will be heavily dependent on the placement, timing. quantity and nature of the effluent, WHile mangrove trees and soils have a capacity to absorb fairly substantial inputs of inorganic nutrients. at least in the short to medium term. their waterways contain very low levels of dissolved nutrients. There is also little evidence to suggest any appreciable net exchange between mangroves and surrounding coastal waters in the tidally-dominated systems and. it. is suggested that direct inputs of nutrients into these waterways could lead to rapid and substantial eutrophication. particularly where tidal flushing may be limited.

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Table 1

Estimated net annual exchanges-of the dissolved components in Coral Creek and the proportion of net forest primary production requirements (Boto and Bunt, 198 1, 1982) represented by each (negative sign denotes net export).

Component	Net annual exchange	Proportion of primary production
	(kg C. N or $P.ha^{-1}.yr^{-1}$)	(%)
DOC	73.1	0. 8
DON	12. 6	4. 7
DOP	3. 7	17.9
NH^4	1.5	0. 6
$NO^3 + NO^2$	-0. 3	-0.1
PO^4	1. 3	6. 3
Total dissolved N	13. 8	5.1
Total dissolved P	5.0	24. 2

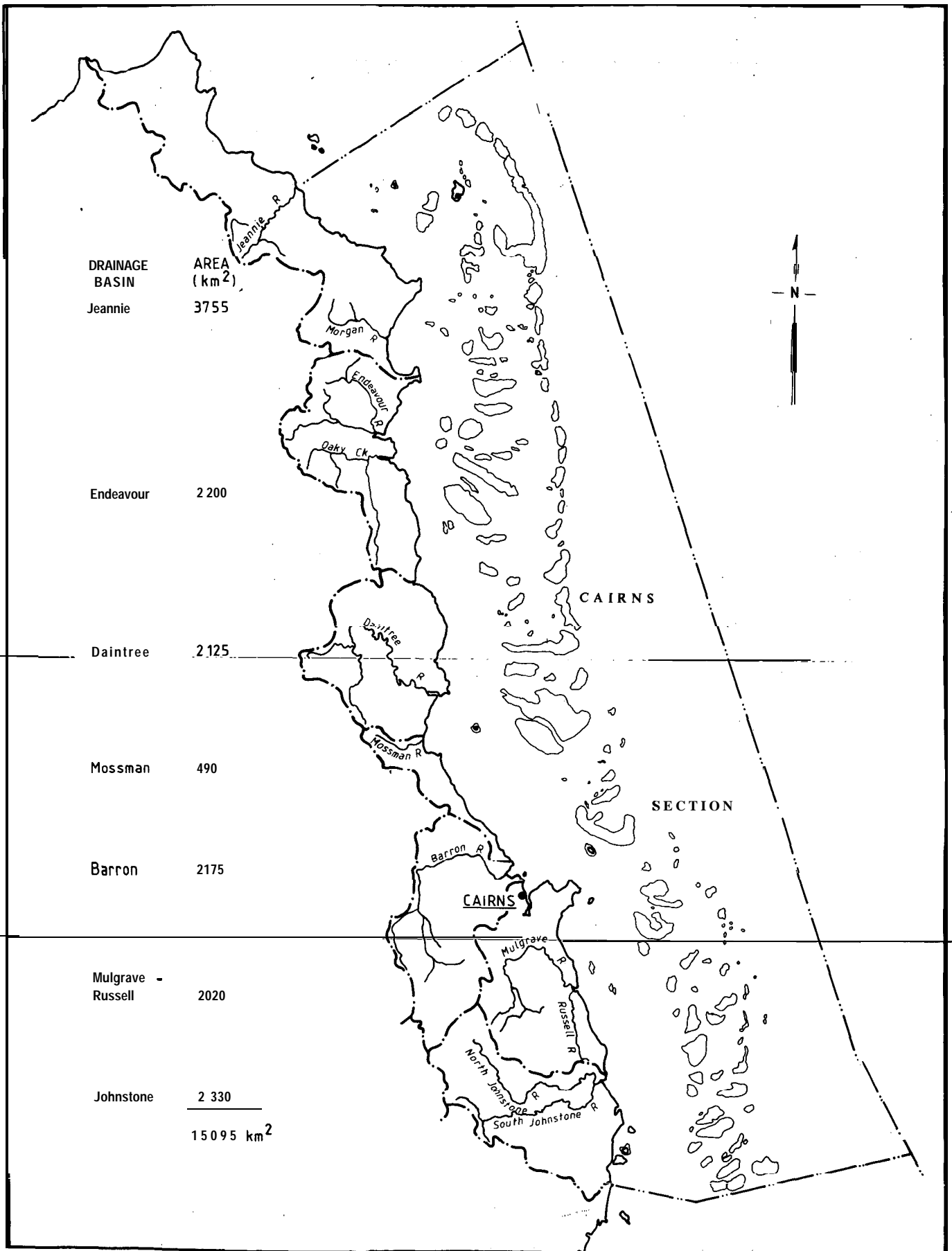| DRAINAGE BASIN	AREA (km^2)
Jeannie	3755
Endeavour	2 200
Daintree	2 125
Mossman	490
Barron	2175
Mulgrave - Russell	2020
Johnstone	2 330
	15095 km^2

CAIRNS

SECTION

CAIRNS

Figure 1. Location of drainage basins and major river systems discharging to the Cairns Section of the Great Barrier Reef Marine Park.

PHOSPHORUS EXPORT COEFFICIENT

Phosphorus load is equal to the product of concentration and discharge; estimates of both are therefore required for reliable load estimation. A reasonable estimate of load may be derived using the flow record in conjunction with an appropriate phosphorus 'export coefficient. However, very few load estimates for Australian rivers have been published, and of those which have (Cullén et al., 1978, Birch, 1982) the applicability of reported export coefficients to Queensland is questionable. The coefficients used in this paper are based on those measured during a 24-month study of phosphorus flux in the South Pine River (SPR), south east Queensland, by the author (Cosser, in preparation). Study objectives were to quantify phosphorus export and examine concentration-flow relationships; sampling was therefore appropriate to flux estimation, with high frequency sampling during stormflow. Concentration on flow regression models were developed independently for baseflow and stormflow, and for the latter, data were further stratified and separate models developed for rising and falling stages of the hydrograph to account for hysteresis behaviour. Flux estimates were calculated and export coefficients derived accordingly.

Export coefficients are frequently reported in terms of kg/km² yr-I. However, load is determined largely by discharge volume, and therefore stormflow load per unit area is dependent on the magnitude of the storm event. Export coefficients of this form are therefore inappropriate for comparative or predictive purposes as the value is volume dependent. A comparative basis is established, however, by using kg/km² mm^{-1} such that load is expressed per mm runoff per unit area. A stormflow total phosphorus export coefficient of 0.54 kg/km² mm^{-1} is proposed,. This value is marginally above the value of the mean stormflow coefficient observed in the SPR in order to compensate for the higher intensity of rainfall experienced in the north.

While the limitations of extrapolation to the Cairns region are recognised, similarities in catchment characteristics suggest that the value of the export coefficient will be of the approximate order. Both are subject to highly seasonal and intensive storm events which result in significant surface runoff and high water yield. Particulate entrainment and transportation is therefore high. The SPR catchment is largely (70%) under native dry and wet sclerophyll forest and is characterized by steep forested slopes and narrow V-shaped valleys. Stream gradients are high and channel lengths short. Similar features are evident in the northern river basins. Application ,of the coefficient to the larger southern river basins is less satisfactory.

PHOSPHORUS LOAD ESTIMATION

Phosphorus load was estimated for each drainage basin as the product of mean annual runoff (mm) and area (km²) multiplied by the export coefficient. Mean annual runoff for each of the major rivers in each drainage basin (QWRC, 1979) is assumed to be representative of the entire drainage basin. In the case of the Endeavour basin, two runoff values were used; one representing the Anna River and Endeavour River (946mm), 'and the other the Bloomfield River (2799mm). Each was applied to half the basin area. Stormflow resulting from major stormevents can typically constitute 75% to 85% of annual discharge, minor stormflow and baseflow accounting for the remainder. The stormflow export coefficient is therefore applicable to this fraction. A value of 80% of mean annual runoff was selected for load calculation. Total phosphorus load estimates are presented in Table 1.

The value of 9357 tonnes represents the estimated mean, annual riverine stormflow total phosphorus load to the Cairns Section of the Great Barrier

Reef Marine Park. This value will obviously vary from year to year depending on the number and magnitude of major storm events. The magnitude of variation will probably be similar to that of annual discharge.

The coefficient of variation, defined as the standard deviation divided by the mean, of annual discharge for rivers in this region is given as 0.5 by McMahon (1979). This suggests a standard deviation of mean annual phosphorus load of 4679 tonnes.

On the basis of the SPR research, baseflow and minor stormflow export coefficients may be only 5 - 20% of major stormflow values. Given the higher coefficient and the relative magnitude of stormflow discharge, the stormflow load estimate probably represents in excess of 90% of total annual load.

Table 1. Drainage basin area, mean annual runoff and estimated mean annual riverine stormflow total phosphorus load.

Drainage Basin	Area (km^2)	Mean Annual Runoff (mm)	80% of Runoff	Export Coeff. ($kg/km^2 mm^{-1}$)	Total Phosphorus load (tonnes)
Jeannie	1878	657*	526	0.54	533.0
Endeavour	1100	946	757	0.54	449.5
	1100	2799	2239	0.54	1330.1
Daintree	2125	1513	1210	0.54	1388.9
Mossman	490	1200	960	0.54	254.0
Barron	2175	449	359	0.54	421.9
Mulgrave-Russell	2020	3441	2753	0.54	3002.8
Johns-tone	2-330-	1964	1571	0.54	1976.9
				Total	9357.1

* Mean of Jeannie River (531mm) and McIvor River (783mm).

TEMPORAL DISTRIBUTION OF PHOSPHORUS FLUX

As a result of the hydrologic regime of north Queensland rivers, in which major stormflow may occur for less than 15% of the year but account for a significant percentage of annual discharge, phosphorus loading is typically episodic. Approximately 90% of annual phosphorus loading may occur in association with several major storm events between the months of January and April.

The significance of stormflow in nutrient flux is well established. Cullen et al. (1978) reported 67% of phosphorus flux to Lake Burley Griffin in 9% of the time in association with two major flood events.

THE FORMS OF PHOSPHORUS

The chemical properties of the orthophosphate ion cause it to react readily with various soil components, including aluminium and iron oxides, clay minerals and solid carbonates. Consequently, soil phosphate is present largely in association with particulate material. Solution phosphate concentrations are accordingly low. The aqueous and solid phase partitioning of phosphates has significant implications in terms of phosphorus flux. A number of studies have demonstrated that riverine phosphorus flux is largely attributable to the export of particulate associated phosphorus. While the relative fractionation is variable, on the basis of literature values and those observed in the SPR, 30% may represent the upper limit of the dissolved fraction during stormflow. The ratio is however influenced strongly by such factors as rainfall intensity

and.antecedent soil moisture, in addition to soil type and vegetation cover. Given local meteorological conditions, which result in significant surface runoff and high water yield, the particulate fraction' can be expected to constitute greater than 80% of the total phosphorus loading.

The significance of the relative fractionation of riverine phosphorus, relates to dispersion and' fate once discharged to the Barrier Reff Lagoon. These factors in turn determine the biological significance of-the input. Disperson of the finer suspended fraction can be quite extensive. The distribution of terrigenous sediments in the Cairns region of the Barrier Reef Lagoon indicates disperson across the width of the Lagoon (Wolanski et al., 1986). Sedimented phosphorus may therefore represent a significant source of phosphorus to the reef system However, while riverine flux is episodic, the processes of sedimentation and 'regeneration serve to distribute biologically available phosphorus throughout the year. Dispersion of the dissolved fraction follows that of the freshwater plume and may be spatially more extensive. Flood runoff may result in a marginal and transitory elevation in ambient concentration over a wide area. This fraction is immediately biologically available.

CONCLUSIONS

The estimate of riverine phosphorus load is based on export coefficients observed in southern Queensland, the validity or otherwise of extrapolation to north Queensland remains to be verified.

The utility of such estimates for environmental management purposes relates to both the evaluation of the quantitative significance of different phosphorus sources, and the capacity to identify perturbations to loading characteristics. The ability to detect change is necessary in order to identify the existence of a potential problem Detailed analysis of present flux characteristics provides a data base for future comparative studies. Identification of change above that considered within the realms of natural variability provides an indication as to possible perturbations prior to resulting biotic manifestations.

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PREDICTING THE MOVEMENTS OF NUTRIENTS IN THE GREAT BARRIER REEF

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ABSTRACT

An outline is given of the movement of nutrients in three cases, namely the case of river floods, the circulation around reefs for non-buoyant nutrients, and the fate of buoyant nutrients (coral eggs and sewage). In the first case, the river plume formation leads to a baroclinic coastal boundary layer of width increasing northward (for large river discharges) away from the river mouths. When the river flood ceases, baroclinic effects break up the plume in patches which are leaking along the coast. These patches drift more or less passively with the currents and can sweep over a considerable extent of the Great Barrier Reef. In the second case, non-buoyant nutrients are advected by currents around reefs and may be trapped in. lagoons and near separation points. The CORSPEX model can be used to predict these topographically-controlled flows as it has been successfully verified against extensive field data collected at three test areas, namely Rattray Island, the Ribbon Reefs and Bowden Reef. In the third case, buoyancy-induced secondary flows are expected to have a dominant influence as they result in concentrating the coral eggs, oil and buoyant waste along topographically-controlled fronts. This process is not predicted by any available classical two-dimensional models. These models are still extensively used, though they are -invalid, in determining the fate of nutrients, coral eggs, oil and sewage near reefs.

WATER COLUMN NUTRIENT PROCESSES IN GREAT BARRIER REEF WATERS

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‘I

INTRODUCTION

The development of rational policies for the management of inputs to and nutrient levels within a large, nominally oligotrophic ecosystem such as the' Great **Barrier** Reef (hereafter GBR) requires an understanding of nutrient dynamics at the system level. In developing such an understanding, the role of water column processes is central, as most nutrient additions to the GBR ecosystem through human activities will likely come via the water column, **be** dispersed by water movements and, be transformed by planktonic organisms.

A **Schematic for a Water, Column Nitrogen Budget**

With the last several years, an attempt has begun to develop a quantitative. nitrogen budget for shelf waters of the GBR. Figure 1 presents a schematic depiction of water' column pools of nitrogen, both in living and non-living forms and the pathways whereby nitrogen is added to, removed from and transformed by pelagic organisms. The focus is strictly upon water column processes. Coral reefs and the soft; inter-reefal benthos, both with equally complex nitrogen dynamics are shown as "black boxes" exchanging N with the water column. The development of models,. whether schematic as shown or numerical, provide a focus for the identification of key system pools and pathways, and a means for integrating results from a range of focused investigations.

Historical studies and data sets (eg. Andrews, 1983; Andrews and Gentian, 1982; Bellamy et al., 1982; Fumas and Mitchell, 1984; Furnas and Andrews, 1986, in prep.; Thomson and Wolanski, 1984; Wolanski and Jones, 198 1), have now established regional and seasonal variations in concentrations of dissolved inorganic nutrient species in the GBR waters, temperature-nutrient relationships in Coral Sea water masses interacting with GBR shelf waters and functional relationships whereby shelf-scale inputs of nutrients from intrusions of Coral Sea water may be estimated.

Work in progress is now directed toward quantifying seasonal and regional variability in concentrations of particulate nitrogen (PON) in shelf waters, inputs of nutrients from rainfall and coastal rivers, sedimentation of organic nitrogen from the water column, nitrogen uptake by phytoplankton and remineralization of nitrogen by water column biota (e.g. Ikeda et al., 1982).

A variety of evidence suggests that the inter-reefal pelagic ecosystem of'the GBR is nitrogen', rather than phosphorus or silicon limited. It is important, however, to note that this limitation is biomass, rather' than kinetic' limitation. Direct and indirect measurements of phytoplankton growth rates in situ (Table 1) indicate phytoplankton populations can grow at rapid rates (> 1.5 doublings day-i), despite low nutrient, particularly nitrogen concentrations. Importantly, within these populations, a number of individual phytoplankton species are frequently growing at rates in the range between 2 to 3 doublings per day and do so at DIN concentrations of 0.2 µM or less (Fumas, in prep.). Concentrations of dissolved inorganic phosphate (DIP) and silicate are almost always measurable, while concentrations of dissolved inorganic nitrogen (DIN) species

Figure 1. A schematic model for water column nitrogen pools and fluxes in GBR shelf waters.
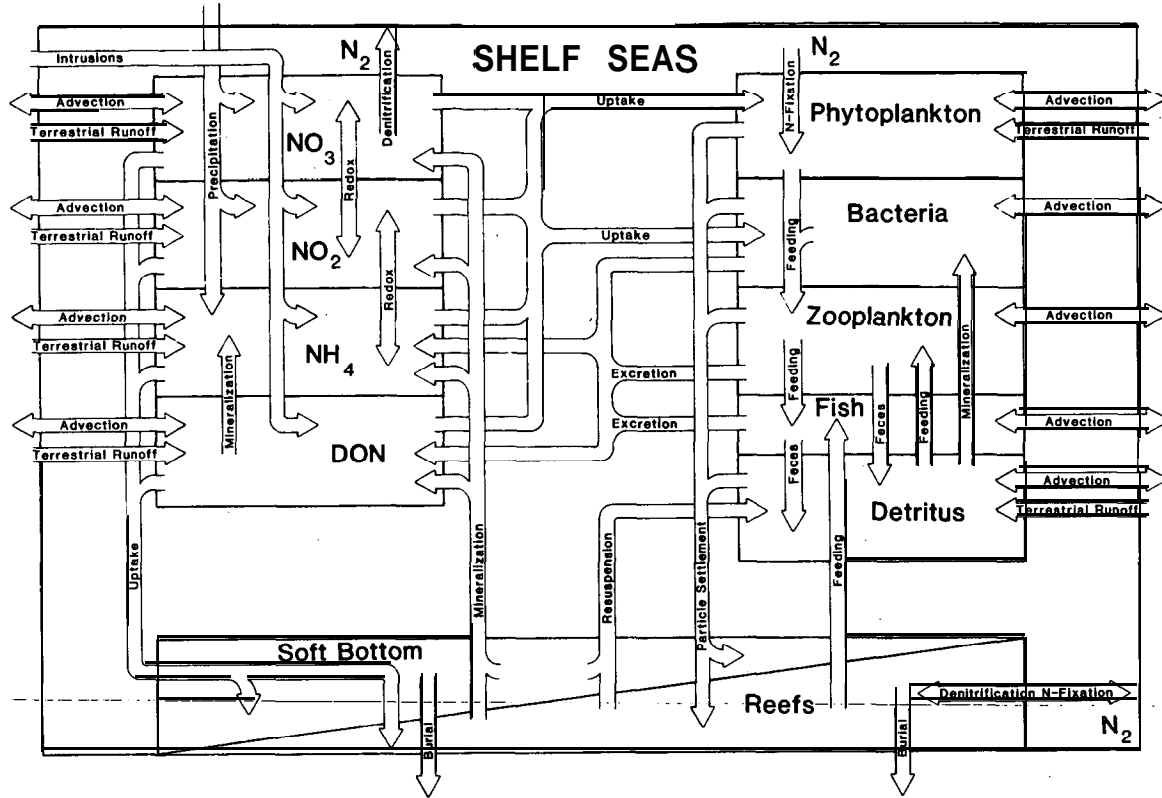
are frequently at or below the limits of detection (now ca. 0.05 μM). Concentrations of DIN, and DIP in shelf waters generally have a DIN/DIP ratio on the order of 1, far less than the Redfield N:P ratio (15-16) characteristic of marine phytoplankton. The low DIN/DIP ratio means that in the absence of external nitrogen additions, available nitrogen will be exhausted before phosphate and silicate are depleted.

Direct comparisons between water column stocks of DIN and estimates of nitrogen present in the form of phytoplankton biomass (Figure 2) indicate that soluble inorganic pools are similar in magnitude to or smaller than biomass-N pools. As a rule of thumb, to estimate phytoplankton biomass N, 1 μg of chlorophyll is equivalent to 1 ug-at of biomass N (e.g. Fumas, 1983). Large changes in water column pools of biomass-N and DIN only occur in GBR shelf waters when additional amounts of nitrogenous nutrients are added (in the case shown), by intrusions from the Coral Sea to the ecosystem, river runoff or cyclonic disturbances of shelf sediments.

Nitrogen Uptake by Phytoplankton in the GBR

Direct measurements of nitrogen uptake by phytoplankton, made using ^{15}N tracers, indicate rapid uptake and recycling of nitrogenous nutrients. When presented with nitrate at uptake saturating concentrations (ca. 2 μM), near-surface phytoplankton from the GBR lagoon are capable of doubling their standing stock of particulate nitrogen in less than one hour (Figure 3 Top). Preliminary kinetic analyses of uptake rates in relation to nitrate concentration and light intensity indicate half-saturation coefficients, the level at which uptake occurs at half the maximal rate, are <0.5 μM NO_3-N and 10% of normal surface light levels.

Time courses of ammonium uptake, as measured by ^{15}N uptake (Figure 4) confirm rapid turnover of water column ammonium pools. Where a ^{15}N-NH_4 spike considerably in excess of the ambient concentration is added to a sample (Fig 4 Top and solid lines, Bottom), linear uptake occurs for periods of at least 4-6 hours. When a spike closer to normal ambient concentrations (ca. 0.2 μM) was added to inshore samples with higher standing crop levels, uptake slows within 1-2 hours, indicating either depletion of available ammonium in the sample, and/or isotope dilution of the added spike by mineralization processes within the incubation bottle.

The Role of Disturbances in Shelf-scale Nutrient Processes

Oceanographic observations made shortly after the passage of cyclone Winifred over a section of the GBR in 1986 illustrate the role of disturbances in shelf-scale and local nutrient processes and the effect of nutrient loading upon concentrations and speciation of nitrogen in particular.

A hydrographic survey conducted after the cyclone showed the presence of high dissolved nutrient and phytoplankton biomass levels (Figure 5) throughout an area on the order of 10^4 km^2. Preliminary nutrient budgets for the event indicate that most of the phosphate and silicate added to the water column could be accounted for by inputs from rainfall, river runoff and porewaters in disturbed shelf sediments. In contrast, existing nitrogen stocks plus inputs from the above sources accounted for less than 25 percent of the nitrogen present in the post-cyclone water column. Partial mineralization of organic nitrogen in the column of shelf sediments resuspended by cyclone Winifred can easily account for the discrepancy. The high concentrations of nitrite and nitrate in shelf waters are indicative of waters receiving enhanced loading of organic nitrogen (e.g. McCarthy et al., 1984); When organic nitrogenous nutrients

Figure 2.   A comparison between integrated water column stocks of chlorophyll a and DIN (NH, + NO, + NO,) at mid- and outer shelf stations in the central GBR. Station 1 is in the GBR lagoon; station 4 at the shelfbreak. (From Fumas and Mitchell, 1986).
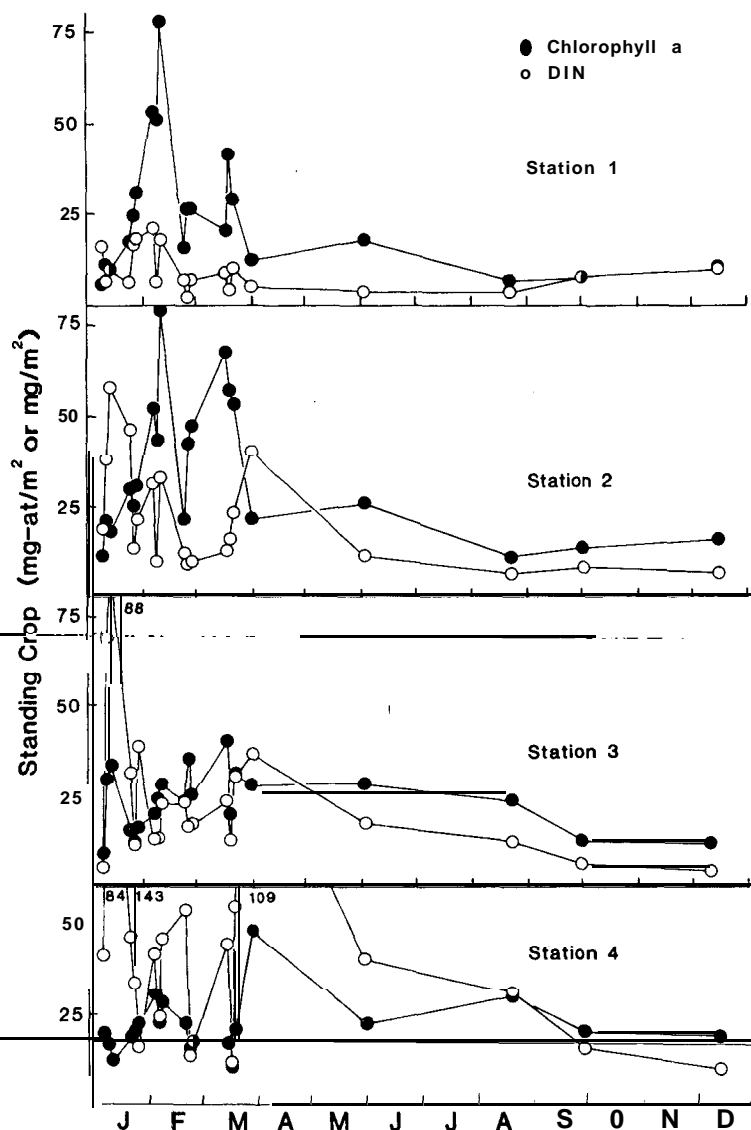
Figure 3. Uptake rates of nitrate, expressed as μM NO, taken up per μM of particulate N per hour · (hr^{-1}), in relation to nitrate concentration and ambient light intensity (as percent of surface irradiance) for near-surface phytoplankton from a mid-lagoon and an inshore site.
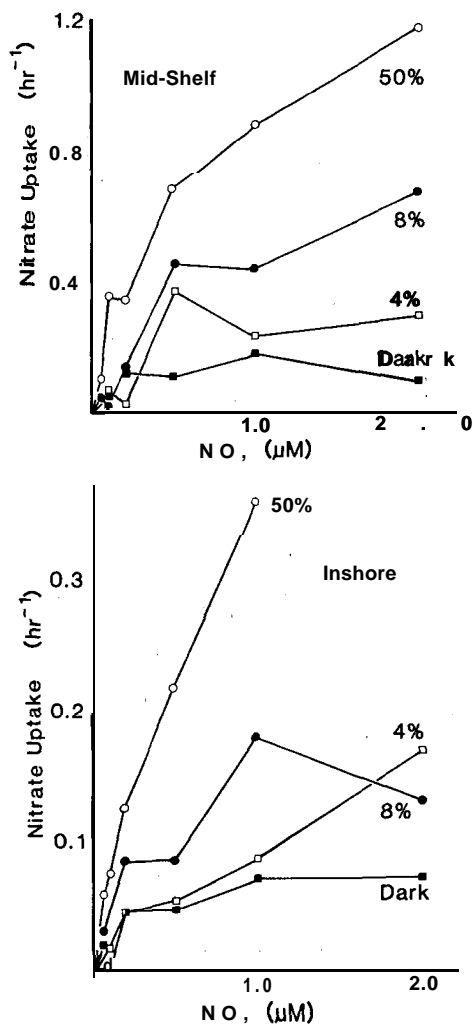
Figure 4.   Time courses of ^{15}N-NH$_4$ uptake, expressed as the atom percent excess of filtered particulate matter, by phytoplankton from the oceanic Coral Sea (Top, spikes > 1 µM) and from GBR shelf waters (Bottom, solid lines · midshelf and inshore experiments with spikes > 0.3 µM; dashed lines - inshore experiments with spikes < 0.2 µM).
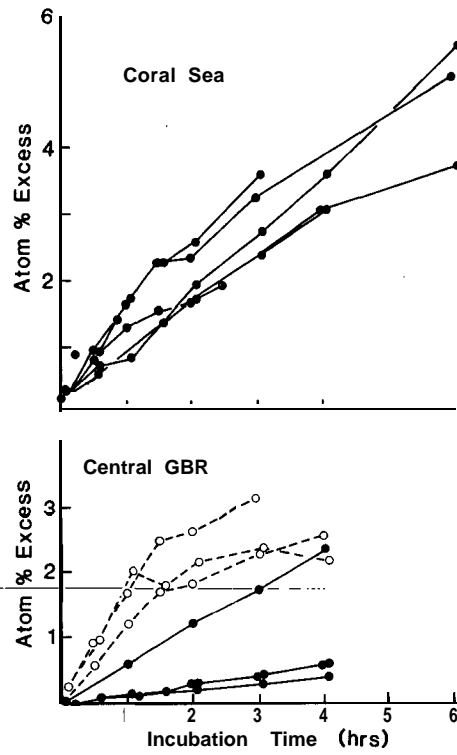
Figure 5.   Representative profiles of hydrographic parameters, chlorophyll and dissolved
nutrient concentrations in the cyclone affected area of the shelf (Fig. 5, 1986) and in similar
mid-shelf waters in the absence of cyclonic disturbance.
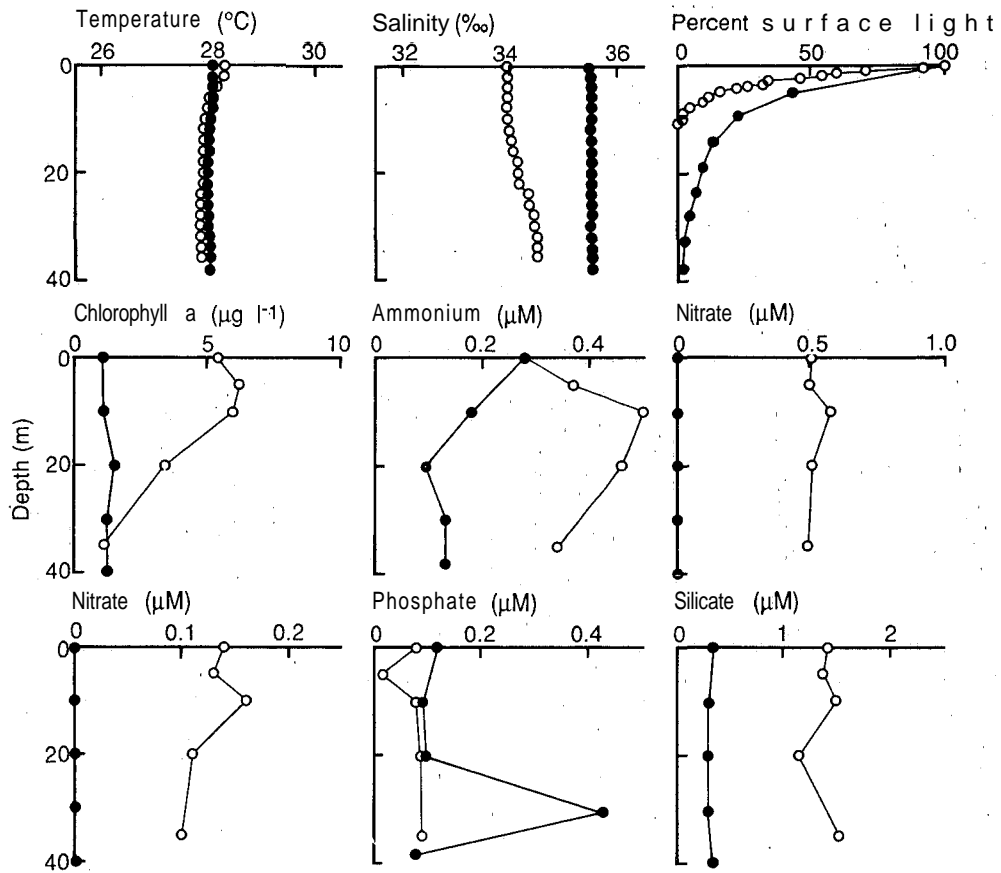
are added to GBR waters, mineralization by microbial processes proceeds at a rapid rate. Where mineralization of organic N to ammonium exceeds nitrogen demand by phytoplankton, "blooms" of aerobic nitrifying bacteria appear to develop as well, converting surplus ammonium to nitrite and nitrate.

Normal seasonal storm winds can lead to localized increases of dissolved nutrient concentrations and phytoplankton biomass in inshore water by resuspension of inshore sediments (Walker and O'Donnell, 198 1; Ullman and Sandstrom, 1987). Where the nutrient and organic content of coastal sediments are enriched by nutrient discharges, this effect may be exacerbated by concurrent mineralization of resuspended organic matter.

Some Implications of Water Column Nutrient Processes for GBRMP Management Planning

Phytoplankton biomass in inter-reefal waters of the GBR is N-limited. Inputs of nitrogenous nutrients will therefore likely lead to increases in phytoplankton and hence, plankton biomass in the affected area. Because of the high water temperatures (22-30C), high in situ light levels and rapid rates of nutrient recycling within the water column, phytoplankton populations can take up nitrogen equivalent to the standing crop within hours and can develop into appreciable blooms within 2-3 days if sufficient nutrients are available. As a result, human additions of nutrients to GBR waters may not necessarily be observable as an increase, either locally, or regionally, in dissolved nutrient levels. Rather, an obvious sign would be local or regional increases in phytoplankton biomass. Localized increases in dissolved nutrient concentrations would be most apparent where ratios of nutrients entering the ecosystem are unbalanced for phytoplankton growth (e.g. Goldman, 1976), resulting in the depletion of one nutrient before all are consumed and leading to buildups of "surplus" nutrients (e.g. DIN, phosphate or silicate) in particular situations.

The ability of phytoplankton to take up nitrogen and grow at near-maximal rates at ambient nutrient concentrations less than 1 μM -n ans that nutrient discharge/dilution standards should reflect these concentrations to prevent the development of localized, possibly deleterious algal blooms. Natural DIN concentrations in excess of 1 μM do occur within the GBR (e.g. Hatcher and Frith. 1985), but such situations appear to be restricted to highly enclosed reef lagoons and reef flat tide pools with very short to moderately short residence times.

Experimental and observational evidence suggests that phosphorus, not nitrogen is the macronutrient most directly detrimental to coral reef growth and health (e.g. Kinsey and Davies, 1979). The development of enhanced phytoplankton biomass levels as a result of local or regional eutrophication would affect coral reefs in a variety of ways, either through increases in "surplus" water column phosphate concentrations, or through indirect changes in reef community structure resulting from the growth of macroalgae, increased organic sedimentation from plankton blooms, shading of benthic autotrophs and fostering the proliferation of benthic filter feeders responding to increased plankton biomass and detrital particulate concentrations.

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Table 1. Doubling rates of chlorophyll (mean ±1 S.D., range) in diffusion chambers incubated under in situ conditions at mid- and outer-shelf sites in the central GBR.

Mid-Shelf	Outer-Shelf
Summer near-surface	Summer near-surface
0.8 ± 0.8 n = 7 0.0 - 1.6	0.2 ± 0.3 n = 5 0.0 - 0.7
Summer near-bottom	Summer near-bottom
0.6 ± 0.4 n = 5 0.0 - 0.9	0.4 ± 0.2 n = 5 0.2 - 0.6
Winter near-surface	Winter near-surface
1.1 ± 0.3 n = 3 0.8 - 1.3	0.8 ± 0.2 n = 4 0.5 - 1.0
	Winter near-bottom
	0.5 n = 2 0.0 - 1.1

RESPONSES OF CORAL REEF SYSTEMS TO ELEVATED NUTRIENT LEVELS

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INTRODUCTION

Coral reefs are dynamic systems. Fringing reefs in particular may be very effective in demonstrating many aspects of system and community behaviour because of the greater variability in environmental parameters to which they are likely to be exposed. In a recent workshop (Baldwin 1987) conducted by the Great Barrier Reef Marine Park Authority to consider the coastal fringing reefs of the Great Barrier Reef Region, a number of relevant and significant conclusions were indicated. They included:

- coral reefs, or at least fringing reefs, exhibit significant instability combined with a significant degree ofresilience

- fringing reefs exhibit a rather discontinuous existence with phases of very active development alternating with phases in which they are virtually **"dead"**

- nevertheless, fringing reefs exhibit very good **long-term survival**

- there are very sharp thresholds in stress response beyond which reef biota collapse

- coral reefs can be considered as exhibiting certain specific attributes:

  -they are normally subject to very low biological and chemical forcing functions

  -they have principally physical **controls, such as** turbulence, wave energy, storms, etc

  -they have an extremely high biological diversity which is an effective mechanism for handling the very low nutrient environment in which they are normally found

  .-they are **generally very** tolerant of stress

  -they exhibit rapid collapse when the stress exceeds a critical level

Stress to coral reefs can best be **considered** in two broad categories: acute stresses are those which kill at least the major groups of reef 'organisms; chronic stresses are those which the reef is able to withstand through extended time., Typically, a kill **by an** acute stress such as a major storm, freshwater input, or crown of thorns infestation is likely to be followed by rapid recovery in the absence of chronic stress;' A kill by an acute stress in the presence of chronic stress is likely to. lead to

non-recovery of the original reef community with a shift to a low diversity community better able to benefit from the chronic stress situation. I believe nutrients generally constitute a chronic stress, the presence of which may not be evident in community response for a long time.

Much of the Great Barrier Reef has been subject to only low level environmental stresses because of the magnitude of the monsoonal runoff during the wet season. The sediment and fresh water input from this runoff have been so great from time to time that they have caused most of the Great Barrier Reef system to develop seldom closer than 20 km and frequently more than 100 km offshore from the mainland.. Because of the separation of the reefs from the coast, the effects of the input of any threatening materials, including excessive nutrients, have been greatly attenuated by coastal dilution. Further, the Reef has not only been inaccessible for subsistence use, but until recently much of it has been remote even to the present population of Australia. The advent of faster vessels is changing this, but there has not yet been time for major effects to result.

Notwithstanding this apparent degree of protection of most of the reefs of the Great Barrier Reef Region, there are nevertheless many perturbations which can be considered, as possible indications of nutrient stress. The progressive degradation of some inshore reefs such as Low Isles (Rasmussen 1986) and the Green Island reef (summarised by Baxter 1987) is likely to reflect in part the influence of coastal water degradation (Hopley 1982) . In the case of Green Island at least, the influence of looalised nutrient enhancement from the island sewer outfall is also generally accepted as being pronounced. Clearly, the increasing use of the Region, its adjacent coastal-areas,--- and- its islands has the potential to lead to more degradation and careful management is essential.

My work has always emphasised the effects of stresses on the total system and has not considered in any detail the specific response of individual organisms. This paper, therefore, will stress system responses. I will discuss some effects of naturally elevated nutrient levels, experimentally enhanced nutrient levels, and the complex effects of treated sewage input on overall community structure and community metabolism (see also Kinsey 1987; in press).

THE NATURALLY OCCURRING SITUATION

The range of nutrient levels within which coral reef's occur is very broad (Smith and Jokiel 1975; Kinsey and Davies 1979; Smith et al 1981; reviewed by Kinsey 1985). They are by no means oases in the marine deserts of the world as they are often presented. In fact, it is probably reasonable to say that coral reefs occur throughout the naturally occurring range of surface nutrient concentrations found in the open tropical oceans of the world.

Reefs occur in waters with nutrient concentrations covering at least the range:

0 -- $4\mu M$ available nitrogen   0.05 -- 0.6p available phosphorus

It is interesting, however, to examine the carbon budget data available for complete reef systems throughout the reported nutrient range (summarised by Kinsey 1985). Most carbon budget data indicate that typical

complete systems are in almost perfect trophic balance, fixing almost exactly the same amount of carbon by photosynthesis as they release by respiration and exporting no more carbon than they receive in incoming plankton (there may be considerable spatial variability 'in this balance within the system, ie local source and sink areas); However, the Canton Atoll system reported by Smith and Jokiel (1975), and located in the general vicinity'of the equatorial divergence, is subject to incoming nutrient levels at the top of the naturally occurring range. This reef system was found to exhibit a clear' net production (though <5%), with photosynthesis exceeding respiration, and the system must be assumed to either accumulate organic matter or to export it in significant' quantity to the surrounding ocean.

THE EFFECTS OF EXPERIMENTAL NUTRIENT ENRICHMENT

A study of the impact of deliberate nutrient enrichment was carried out at One Tree Island reef (latitude $23°30'S$; 95 km offshore) in the Capricorn Group in 1971-72 (Kinsey and Domm 1974; Kinsey and Davies 1979). In these experiments a small lagoonal patch reef 25 m in diameter was subjected to concentrations of $20\mu M$ nitrogen (urea and ammonium) and 2 μM phosphate during the 3 hour ponded slack-water period of each daytime low tide. This experiment was carried out over a period of eight months. While ,the concentrations achieved were considerably above those occurring in reef areas naturally, the time of exposure each day obviously was very limited. The normal lagoon levels of nutrients in One Tree lagoon were less than $0.5\mu M$ nitrogen and about $0.05\mu M$ phosphorus.

Main reef-flat   Control reef-flat

Experimental reef-flat (1971)   Experimental reef-flat with fertilisation (1972)
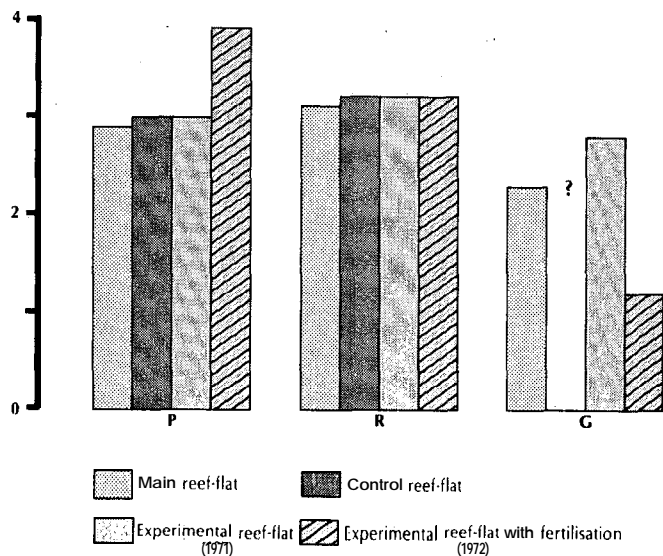
FIGURE 1. The effects of an eight month period of nutrient enhancement on community metabolism in a lagoonal patch reef at One Tree Island, Great Barrier Reef. The effects stabilised to the values indicated after about one month. The 'control reef flat' (on an adjacent patch reef) and the 'main reef flat' areas used for comparison were chosen to approximate the community structure of the experimental patch reef. Each of the sites included appreciable areas of unconsolidated sandy bottom.

P = Gross diel photosynthetic production (g carbon $m^{-2}d^{-1}$)
R = Gross diel respiration   (g carbon $m^{-2}d^{-1}$)
G = Net calcification   (kg $CaCO_3 m^{-2}yr^{-1}$)

The effects on community structure were undetectable, however, the effects on community production were appreciable and the effects were residual to the extent that they continued for at least a month after the cessation of nutrient addition.

Figure 1 'indicates the results of these experiments and it can be seen that the primary production of the system increased by approximately 25%, while consumption (respiration) appeared to be virtually unaffected. Thus, the system changed from being approximately in trophic balance to being significantly autotrophic. The fate of this excess production is not particularly clear. As indicated, there were no obvious changes in community structure. It is assumed that the excess production was either lost to the system as algal detritus, or was grazed from the system by itinerant fish and that this did not constitute a major addition to the in situ respiratory load.

The most dramatic effect of the nutrient enhancement was a 50-60% reduction in system calcification. This clearly implies the possibility of progressive long-term degradation of structural aspects of the reef, notwithstanding the apparent stability of the community structure.

Overall, a substantial increase in soluble nutrient levels would seem to be a chronic stress able to be withstood for quite extended time periods without visible effects. However, it is clear that enhancement of organic productivity certainly results and that calcification is severely inhibited.

TEE COMPLEX EFFECTS OF TREATED SEWAGE INPUT

Kaneohe Bay, Hawaii, is the best documented example of the effects of combined stresses on a coral reef system (eg Banner 1968, 1974; Kinsey 1979; Smith et al 1978; Smith et al 1981). Kaneohe Bay is quite frequently subjected to the acute effects of fresh water runoff on the reef flat environments. The potential for such events is clearly demonstrated in Table 1. This periodic destruction of reef communities has been tolerated throughout most of the Holocene, with rapid recovery after each event,

During this century, however, the bay has been subject to increasing levels of a series of chronic stresses. Figure 2 indicates the general configuration of the bay and its reef systems. Table 1 gives additional relevant information. The general circulation patterns prevailing and the location of the major streams are also indicated. Since the advent of man, increasing agriculture has occurred, particularly towards the northern end of the bay. This has resulted in substantial sediment runoff exceeding that which had previously occurred naturally. Additionally, urbanisation of the southern end of the bay (now 60,000 people) has resulted in substantially increased sediment runoff in that area also.

Substantial sewage input, representing the domestic output of 100,000 people by 1975, has occurred in the southern end of the bay at the points indicated in Figure 2. As the sewage was largely domestic and received secondary treatment it constituted principally a soluble nutrient input. The inputs are indicated in Tabie 2. However, the principal effect of this sustained nutrient input from a concentrated point source was to create a steady flow of phytoplankton and associated zooplankton in the water column. Thus, the coral reef systems actually were subjected as much to an organic particulate load as to a nutrient input.
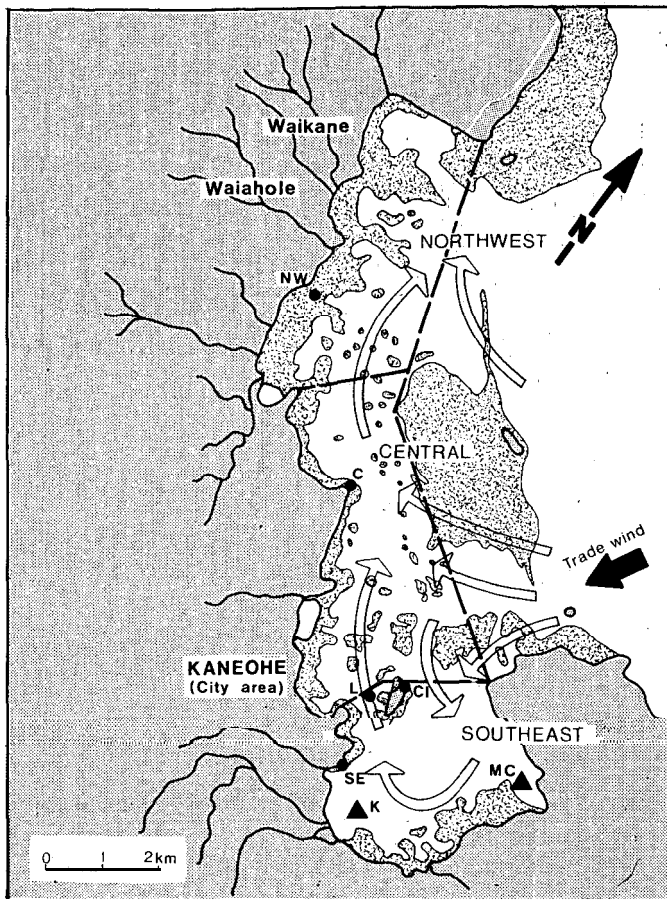
FIGURE 2. Kaneohe Bay on the island of Oahu, Hawaii. 'principal watershed 'streams and all major 'patch-reefs and fringing reefs are shown. The bay is semi-enclosed by a substantial barrier-reef/sand-bar structure and is considered functionally in three, indicated zones: northwest, central, and southeast. The two sewage outfalls, in use to the end of 1977, are indicated A . K is the Kaneohe city outfall and MC is the smaller Marine Corps base outfall. Reef-flat sites referred to in the paper are indicated ● ● General patterns of tide/wind driven circulation are also indicated.

TABLE 1. General information relating to Kaneohe Bay

Kaneohe Bay
      reef-flat area $9km^2$ at average depth 1m
      lagoon area $19km^2$ at average depth 15m
      --------------   -----

      total area $28km^2$

      water volume $270x10^6 m^3$
      flushing time   approx. 13 days,

Water-shed
      area $90km^2$
      average rainfall $1.7m$ y^{-1}

Freshwater input to bay $6m$ y-f

The concentration of both phytoplankton (as indicated by **Chl.a)** and of soluble nutrients as gradients away from the sewage outfall is given in Table **3.**

TABLE 2. Nutrient inputs to Kaneohe Bay in 1977 (mole per day)

	Total dissolved nitrogen	ammonium nitrogen	nitrate nitrogen	total dissolved phosphorus	inorganic phosphorus
Sewage	30000	16000		3300	3000
Streams	7000		5000	320	200

Note: Sewage inputs are continuous and point-source
Stream inputs are episodic and rather diffuse

TABLE 3. Nutrient and **phytoplankton*** (chlorophyll **a)** gradients resulting from treated sewage input to Kaneohe Bay, Hawaii in 1977

Site**	Avail. nitrogen (μM)	Avail. phosphorus (μM)	Chlorophyll **a** (mg m^{-3})
Oahu coastal	0.5-1	0.1	0.1
K (outfall)	4	1.2	10
·**SE**	4	0.7	8
L	3	0.6	5
CI	3	0.6	2
C	2	0.3	0.5
NW	1	0.2	0.5

Data after Kinsey **(1979),** Smith et al **(1978).**
* A gradient of associated zooplankton was also present.
** Site locations are shown in Fig. 3.

Figure 3 indicates the system metabolic response by **1977** to these compounded stresses.
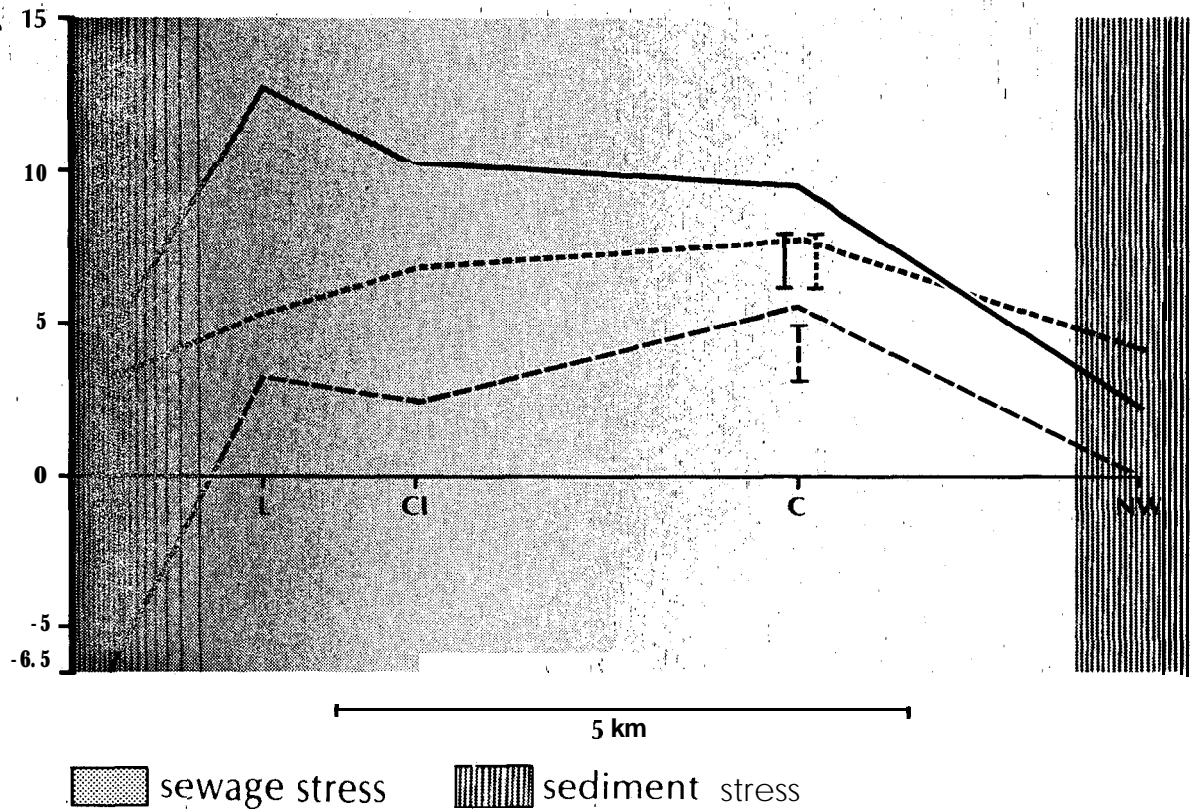
FIGURE 3. The effects on benthic community metabolism of sewage and sediment stress in Kaneohe Bay, Hawaii in 1976-7. Sewage stress in the form of a generated plankton stream and some residual nutrient enhancement applies principally south (left.) of the central site **(C).** The sewer outfall can be considered as the left axis. Sediment stress is most marked at the northwest site (NW) and in the southeast of the bay. The outer reefs in the north were subject to little stress of either kind. Data after Kinsey (1979, 1985, **1987).**

– – – – – –	Gross **diel** photosynthetic production	**(g** carbon $m^{-2}d^{-1}$)
——————	Gross **diel** respiration	(g carbon $m^{-2}d^{-1}$)
– – – –	Net calcification	(kg $CaCO_3 m^{-2}yr^{-1}$)

The vertical bars indicate the normal range for these metabolic parameters in hard substrate areas of natural, unperturbed reef flats (Kinsey 1983).

It is clear that, even in the central bay where the reef systems appeared to be reasonably normal, a slight degree of net heterotrophy existed **(R>P)** and slight enhancement of metabolic activity had occurred with respect to the normal levels found in coral 'reefs. Some algal enhancement occurred in, this area (dominated by **Dichtyosphaeria)** in response to the slight enhancement 'in nutrient levels. The net heterotrophy was reflected visually by slight increases in ,the populations of filter feeders.

The influence of sewage input to the Bay was considerable and resulted in a progressive decline in benthic primary production closer to the source, with a very great increase in community consumption (respiration). Calcification of the system also declined. While this latter outcome may, in part, reflect the direct effect of somewhat elevated nutrient levels (as previously discussed for the One Tree Island experiments), there was also pronounced overgrowth of the normal, calcifying reef communities and framework by particle feeding epifauna and **infauna.** This, in turn, prevented normal maintenance colonisation by coral and algal communities (the primary producers). A decade or so earlier, the alga **Dictyosphaeria** was a major component of the overgrowth community (Banner **1974**). By **1977**, heterotrophic communities were dominant. The principal members of these particle feeding communities were zooanthids, sponges, and barnacles. Very close to the sewage outfall the community consumption also declined. This was the result of the complete destruction of the physical substrate caused by boring, filter-feeding **infauna,** the activities of which are clearly indicated by the extremely negative calcification at that site. The overall effect near the sewer outfall was that the dense populations of filter feeding epifauna associated with other sites towards the southern end of the bay (eg sites L and CI) were no longer able to be supported by the unstable substrate. A further factor leading **to** an unsatisfactory substrate composition in the SE end of the bay was the continual input of terrigenous sediment.

Overall, with proximity to the sewage outfall, the benthic primary production declined because of the favouring of particle feeders, the loss of available substrate, and the reduction in light penetration caused by sediment and plankton in the water column. The community consumption increased where available substrate permitted colonisation by particle feeders. The community calcification.. declined because of substrate overgrowth, elevated nutrients, and direct destruction by infaunal boring.

At the far north end of the bay, on the inshore reefs (NW), it is clear that the heavy sediment overload in the relative absence of the effect of sewage input caused -a drop in all community metabolism parameters. However, the system became significantly net autotrophic. This response indicated a progressive loss of the normal coral communities and replacement of these with algal' communities established on the unstable sediment surface.

While the various extreme responses in the southern bay would appear superficially to be the direct result of progressive change under the influence of the compounded chronic stresses of nutrients, sewage and sediments, I believe that there is a clear indication that much of the response evident by **1977** in fact was developed during periods of recovery after acute fresh water kills. A large amount of the community shift occurred since a major surface reef kill in **1965** (Banner 1968, **1974).** I believe that it is true to say that the community structure so **well** established by **1977,'** indicates to a large extent a failure to recover from the **1965** kill because of the influence of the well established chronic stresses. This is borne out by the fact that the reef communities in the southern end of the bay, but below' the influence of the fresh water overlay in **1965,** survived quite well through to 1977 (personal observations) notwithstanding being subjected to the same chronic stresses as the reef flats: viz poor light penetration, elevated nutrients, and organic particle stress.

Nutrient/sewage loading, with its associated phytoplankton and **zooplankton production, has,** therefore, been a chronic stress. At low levels in the, central bay it has resulted in: increased benthic primary production; a shift to net heterotrophy; possible slight enhancement in calcification; and general, retention 'of approximately normal community structure. At high 'levels in the'southern end of the bay, the effects **are still** likely to have' been predominantly chronic and have been:' a reduction in available light; a substantial decrease in **benthic** primary production; a shift to 'considerable net heterotrophy; . an extreme reduction of calcification to become negative; a conspicuous shift in community structure towards dominance by heterotrophs'and particle feeders; and the virtual certainty of non-recovery of the natural community after acute stress.

Fresh water runoff is most likely to have been an acute stress, the recovery from which has been prevented by .the chronic stresses applying in recent decades.

At the end of **1977,** sewage was diverted from the southern end of Kaneohe **Bay.** Sediment input continued at approximately the 'same levels. Assimilable nutrient availability was at a substantially #elevated but decreasing level for several years because of release of combined nutrients from the bay sediments (Smith et al 1981). The community response to this decrease **in** the overall stress was marked.' ..

In the northern bay where the only significant stress was sediment, no changes have been evident.'

In the central bay where the community change in response to the earlier chronic stresses was not particularly marked, again the changes have not been particularly evident.

In the southern bay, by **1979,** changes in community structure were not marked though some of the filter feeders, particularly the sponges and barnacles had died presumably for the obvious reason that particulate plankton was no longer available in such quantity. Water clarity had improved considerably. By **1982** the previously heterotrophic reef flats had lost most of their filter feeders and the dead substrate of the early reefs **had** become totally covered with an algal population **dominated** by reds. By 1985, algal populations had declined. New: corals were in evidence over all the reef flats with a very high percentage cover .**in** intermediate areas, **(eg** sites L and **CI),** and the initiation **of** small colonies even in the dead crumbled substrate of the reef flats adjacentto the outfall. It was clear at that time that some recovery of all reef flats in south and central Kaneohe Bay was likely to result, from 'the **diversion** of the sewer from the bay.

However, in **1986** another major fresh water kill occurred causing the destruction of much of the new coral development in the shallow reef flat areas. There has not yet been time to **determine** recovery from this event, but in view of the clear recovery of the reefs between **1977** and 1985, it is reasonable to believe that complete, recovery of the **reef flats** to approximately normal reef community types should occur over the next several years.

SUMMARY

Coral reefs occur naturally in a relatively wide range of nutrient concentrations. However, the integral community function in reefs which occur at the more elevated nutrient levels differs from the typical balanced carbon budget so Often described for coral reefs. Such systems are likely to be net exporters of organic matter notwithstanding the fact that they may appear to support "normal" community structure.

It seems that reefs may tolerate elevated nutrient levels well above the natural range for significant periods of time. In this situation the nutrients impose a chronic stress leaving the reef vulnerable to non-recovery after an acute event such as a major storm, freshwater inundation, or crown of thorns kill.

Elevated nutrients may cause enhanced benthic primary production (net autotrophy), or, at higher sustained levels, may cause a. heavy phytoplankton production resulting in enhanced consumption (particle feeding; net heterotrophy).

Elevated nutrients will always result in suppressed community calcification resulting in decreased real growth and structural maintenance.

Community structure will be resistant to change and may not superficially reflect the chronic nutrient stress for a long time.

Rate of change in community structure may be dramatically accelerated by the occurrence of an acute event, the recovery from which will clearly reflect adaptation to the chronic stress of the elevated nutrient levels.

Recovery from such community structure modification can occur quite quickly if the chronic stress is removed and if good larval input is available.

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EFFECTS OF NUTRIENTS CARRIED BY MAINLAND RUNOFF ON REEFS
OF THE CAIRNS AREA: A RESEARCH PLAN AND PRELIMINARY RESULTS

Cecily Rasmussen

The ability of corals to record temporal variations in aspects of their environment has been well documented. For example , annual and lunar growth bands, atmospheric ^{14}C and oceanic temperature variations are all recorded in the coral skeleton (Buddemeier & Kinzie, 1976; Druffel, 1982; Schneider & Smith, 1982). Work by Isdale (1984) inferred a strong correlation between summer monsoonal rainfall. and mainland runoff and the intensity, timing and width of yellow-green fluorescent bands contained within the annual growth bands of the coral skeleton.

The ability of mainland runoff to transport large quantities of terrigenous material to nearshore reefs has been adequately described. Increased sedimentation, siltation, turbidity, salinity and temperature fluxes in coral reefs have been linked to anthropogenic changes of the adjacent hinterland (Maragos, 1974; Banner, 1974; Cortes & Risk, 1981). Similarly, inputs of nutrients into the marine environment have been shown to have a deleterious effect on marine communities (Maragos, 1974; Banner, 1974; Smith et al, 1977; Mergner, 1981).

Kinsey & Domm (1974) expressed concern that agricultural nutrients were adversely affecting 'coral reefs. Data from the experiments designed to test this hypothesis were re-examined by Kinsey & Davies in 1979. Calcification and skeletal density of the corals were shown to decrease with the addition of agricultural fertilizers. Kinsey & Davies were unable to differentiate between phosphatic'and nitrogenous influences, but expressed a preference for an inverse relationship between phosphate application and rates of calcification. Evidence from laboratory experiments (Simkiss, 1964; Wilbur & Simkiss, 1968; Yamazato, 1970; Lambert, 1974) suggests calcification in reef corals and molluscs can be markedly suppressed by large increases in phosphate levels in the surrounding water. Reitemeier and Buehrer (1983) studied the development of crystal morpho logy in calcium carbonates following the addition of various amount s of polyphosphates (one of the forms of phosphate present in trace amounts in the marine environment) and

concluded that distorted crystals were formed as the polyphosphate solution increased. Numerous chemical elements are incorporated into the coral skeleton at the time of deposition. Strontium, analyses of skeletal aragonite deposited by reef corals' has been 'conducted by researchers for many and varied reasons (Odum, 1957; Lowens'tam, 1963; Keith & Weber, 1965; Milliman, 1967; Schneider & Smith., 1982; Muir, '1984). Odum (1957) and Goreau (1961) reported the inability of corals to discriminate between strontium and calcium during the process of skeletogenesis. Other studies indicate a slight preference for strontium over calcium in the calcification process (Weber, 1973,).

Kinsman (1969) inferred from experimental evidence that reef coral aragonite is in equilibrium with seawater as far as strontium is concerned Experimentally precipitated aragonite indicated strontium incorporation is temperature dependent (Kitano et al, 1971; Houck et al, 1977). Smith, Buddemeier, Redalje and Houck (1979) subsequently devised a strontium-calcium thermometer for use in coral skeletons. Schneider and Smith (1982) investigated the use of the. strontium thermometer as a means of examining temperature records. preserved in the density bands of massive scleractinian corals. A variable was shown to exist which could not be explained by temperature variations (Schneider & Smith, 1982). Muir (1984) also investigated the suitability of using the strontium:calcium thermometer for seawater temperature inter-pretation. Results from this study indicated the strontium thermometer lacked a predictable pattern when external influences operated 'on the reef environment. Muir considered that factors, affecting the uptake of strontium could be the influx of periodic water masses from nearshore rivers and/or' inputs of chemical components into the reefal environment from anthropogenically altered coastal environs (Muir, 1984).

Rasmussen (1986) suggested that enhanced levels of nutrients from agricultural fertilizers were being transported to the reefal environment of the northern Great Barri'er Reef as, a component of mainland runoff. This author further suggested that the increased phosphate flux contained in this discharge hindered the ability of coral colonies to operate at equilibrium, thereby resulting in:

a)   a decrease in strontium values precipitated into the coral skeleton

b)   alterations to the crystal morphology of the coral skeleton

c)   a decrease in skeletal density; and

d)   an increase in skeletal fragility.

Recent 'research in temperate waters has documented the ability of commercially viable marine products to be reliant on a balanced interplay between mainland runoff and the marine environment. Alterations to the terrestrial regime are reflected in fluctuations in organisms of the marine environment (eg Skreslet, 1986).

Two hypotheses have been proposed that suggest Acanthaster planci outbreaks are a consequence of mainland influences. The larval recruitment hypothesis shows that larvae survivorship improves following lowered salinity and raised temperatures (Lucas, 1973, 1975; Pearson, 1975). While this hypothesis allows for the natural periodicity of monsoonal summer rains of the northern Great Barrier Reef, it also incorporates the proposition that human intervention in the catchments of mainland rivers significantly alters the amount and intensity of runoff delivered to the marine environment.

The second hypothesis, developed by Birkeland (1982) follows the larvae recruitment concept, but emphasises that the marine environment is altered chemically as well as physically by the input of nutrients transferred by terrestrial runoff into. the oceanic waters surrounding nearshore coral reefs. Birkeland suggests larva.1 food sources such as phytoplankton blooms are increased by the addition of mainland derived nutrients, thus promoting survivorship.

Both hypotheses rely on larval survival rates as opposed to a decrease in predator pressure. However, while these hypotheses relate to the direct effect of mainland influences on the Crown-of-Thorns starfish, it is possible that indirect effects are equally important. All organisms, including Acanthaster planci predators will be affected by changes in the chemical and physical conditions resulting from an influx of terrestrial products into the marine environment.

Records of   environmental influences contained in the coral skeleton will allow comparisons to be made between known Acanthaster planci population fluxes and environmental conditions operating 'at', the same time .

This study, therefore, suggests a number of proposals for' examining the hypothesis that the marine environment of the northern Great Barrier Reef is responding to anthropogenic interference of the nearby mainland.

PROPOSALS

1)   Variations in strontium levels,' precipitated into coral skeletons may provide an indication of the chemical factors and mechanisms operating in the marine environment at the time of coral growth.

2)   Variations in strontium may provide an indicator of terrestrial' alterations not previously recognized.

3)   Phosphate levels in oceanic waters around coral reefs aresufficient to affect the. precipitation of strontium into the coral skeleton. This change may have a deleterious effect on the corals themselves.

4)   Other marine organisms may also be adversely affected, either directly or indirectly, by anthropogenically enhanced nutrient levels. Records extracted from the corals should provide the temporal link between terrestrial alterations and artificially induced species adaptations of the marine environment, eg Acanthaster planci infestations.

A programme of research was subsequently devised .to test the above proposals.   Selection of Cairns and environs (Fig 1) as a suitable study site was dictated by three parameters:

1)   proximity of the reef to a significantly developed coastal environment

2)   the influence of a large drainage basin'anthropogenically altered for agricultural purposes
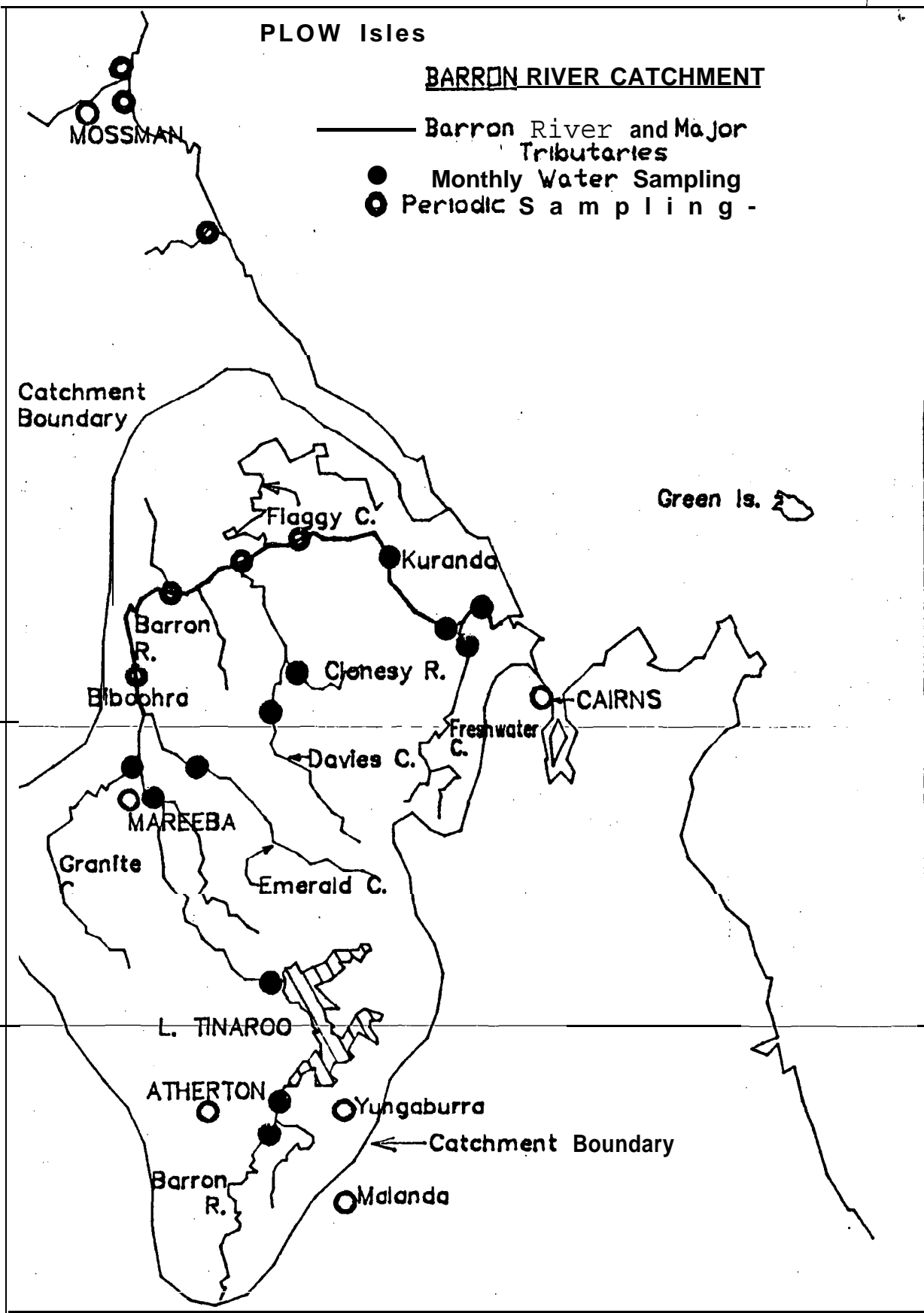
Figure 1. **Barron** River Catchment. Water sampling on a-monthly basis began from sites marked • in February 1986, and from site marked o in November 1986.

3)   the location of Green Island, suggested as the possible location
     of initial <u>Acanthaster planci</u> infestations.

PROGRAMME   OF   RESEARCH

The nature of the problem indicated two main fields of research   were
required.   Hence, a marine and a terrestrial programme were instigated.

Terrestrial   Environments

If enhanced nutrient levels in the marine environment are the result
of agricultural practices, then source and method of transport need
investigation.   Research methodology, therefore, should incorporate
a number of components:

1)   Collection of water samples on a monthly basis from the Barron
     River and its tributaries, as well as from short flowing streams
     of the nearby coastal hinterland (Fig '1).   To determine whether
     variations in stream nutrient levels can be ascribed to agricultural
     fertilizers, these will be analysed for PO_4, NO_3, NO_2, NH_4 and
     dissolved silica.

2)   Collection of sediment samples from the water sampling sites.
     These will be analysed to *determine the ability of particular
     dissolved chemical species to adsorb to clay and oxy-hydroxide
     particles carried as bed load.

3)   pH readings at water sampling sites.   Accurate interpretation
     of chemical equilibria in the water column is necessary if agricult-
     urally induced nutrient levels are to be separated from biological
     and geological alterations.'

4)   Collection of rainfall data.   These will be correlated with
     stream nutrient data as a simple means of estimating m e t h o d   o f
     nutrient' introduction to the stream channel, ie overland flow;
     ground water discharge; or combinations' of both.

5)   Collection of landuse, and land management information.   This
     would be analysed in conjunction with other 'data to determine
     spatial and temporal' influences on stream nutrient 'levels.

6) Int ens ive collection of water samples for a one monthly period from two agriculturally diverse locations. These will be collected using Garnet Automatic Water. Samplers placed at strategic locations - one in the pastoral area of the Atherton Tablelands, and one in the sugar cane growing coastal hinterland. These will be analysed in the same manner as other water samples, but specifically to determine whether a dual input of nutrients suggested by Rasmussen (1 9 8Fig ;2) *can* be isolated and allocated to particular land use practices. Timing of this water sampling programme will be determined by the indications 'from Figure 3, ie nutrients are reaching the marine environment twice yearly, mid-year (suggested as a response to sugar cane planting and associated fertilization) and early summer (suggested as a response to the land management practice of fertilizing dairy pastures in preparation for the monsoons).

Marine Environment

The concept that anthropogenically derived enhanced nutrient levels are adversely affecting the marine environment requires the programme of research be divided into five major sectors:

1) The attainment of corals from previous experimental areas such as the One Tree Reef project undertaken by Kinsey and Domm in 1974.

2) The collection of corals from areas of known anthropogenically derived elevated nutrient levels. For example, Kaneohe Bay and the Gulf of Aquaba.

3) The introduction of elevated levels of commercial superphosphate to Acropora and Porites species of corals grown under laboratory conditions.

4) To determine whether a decay or cumulative effect operates geograph-ically within the marine environment (effects which may be related to distance from input, marine vegetation, eddies, or sewerage outfall), the removal of coral cores from Porites species of
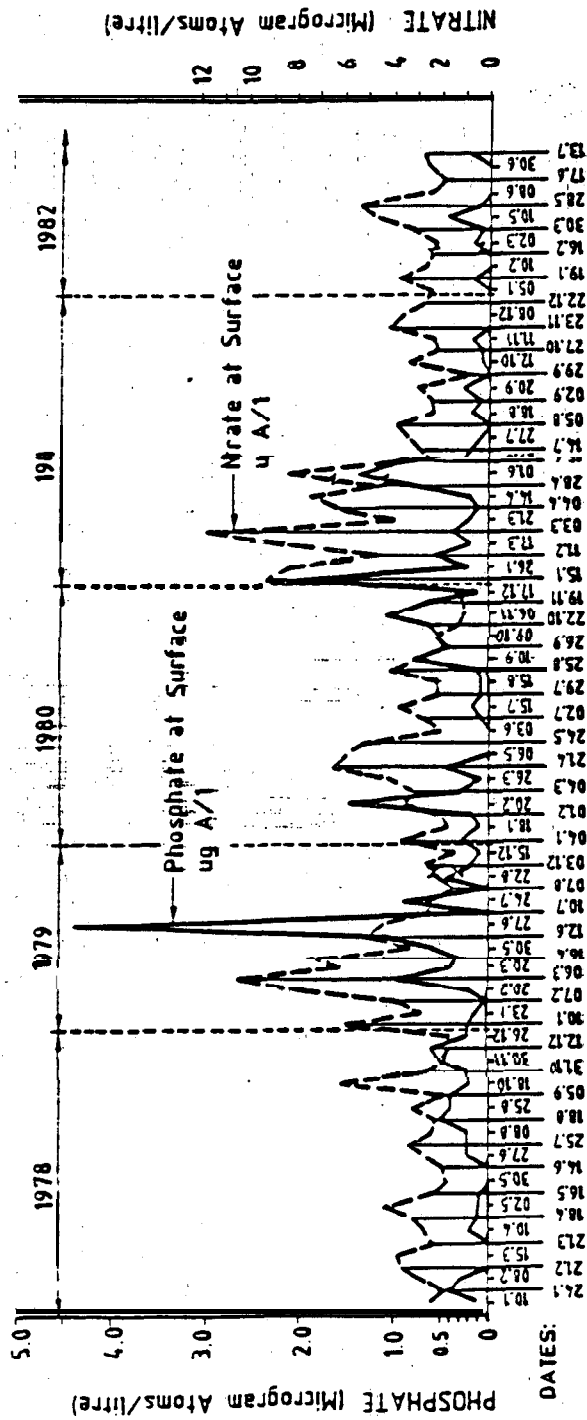
Fig 2. OCEANIC PHOSPHATE AND NITRATE LEVELS
Source : C.S.I.R.O. Dvision of Oceanography

LOW ISLES, NOR'HERN GREAT BARRIER REEF

Corals in a grid pattern radiating out from the mouth of the **Barron** River and extending as far north and south as financially possible will be undertaken (Fig 3). A control sample will, be removed from a **reefal** area sufficiently distant from mainland influences to be considered uncontaminated by anthropogenic interference **(eg** Myrmidon Reef).

5) Collection of samples of oceanic water will be undertaken by the Queensland National Parks and Wildlife Service' on a monthly basis from the entrance to Cairns Harbour across to the Green Island reef. Further samples will be collected on an intermittent basis from other reefs visited by Queensland National Parks and Wildlife Service. Fortnightly water samples will be collected from Low Isles by the Head Lighthouse Keeper. A further programme of collection has recently been planned for Agincourt Reef.

All oceanic water samples will be analysed for similar chemical species as the terrestrial samples. Correlations will subsequently be sought with events on the nearby mainland, weather regimes, tourism influx and dredging.

Corals obtained by the four methods listed above will be analysed temporally and spatially for variations in chemistry, crystal morphology, density, calcification, fragility, growth patterns and internal morphological characteristics.

Results obtained from this section of the programme will be analysed in conjunction with the terrestrial programme. The anticipated understanding of environmental records located in the coral skeleton will then be available for interpretation in conjunction with known Acanthaster planci biology, ecology, history and geographical distribution.

RESULTS

Water Samples

Results presently to hand indicate a strong correlation between raised stream nutrient levels and rainfall in associated areas with a lag of approximately one month (Figs 4 & 5). A further correlation exists
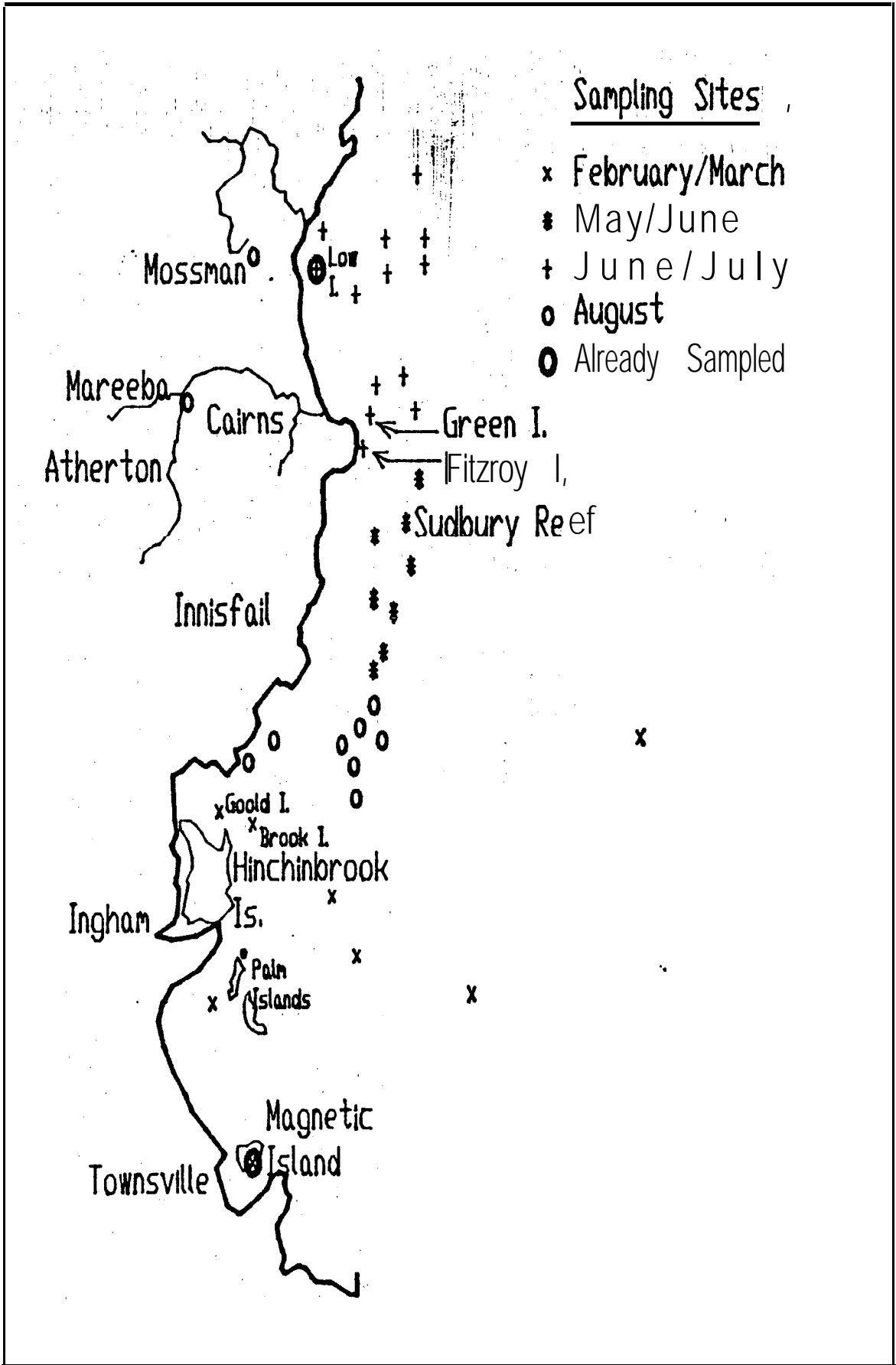
Figure 3. Proposed coral coring programme - northern Great Barrier Reef
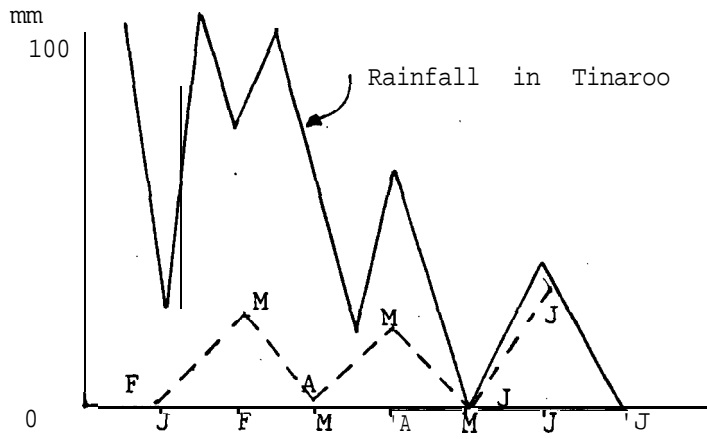
Figure 4. Rainfall data superimposed over NO_2 stream concentrations in the Tinaroo area - lag time = 1 month
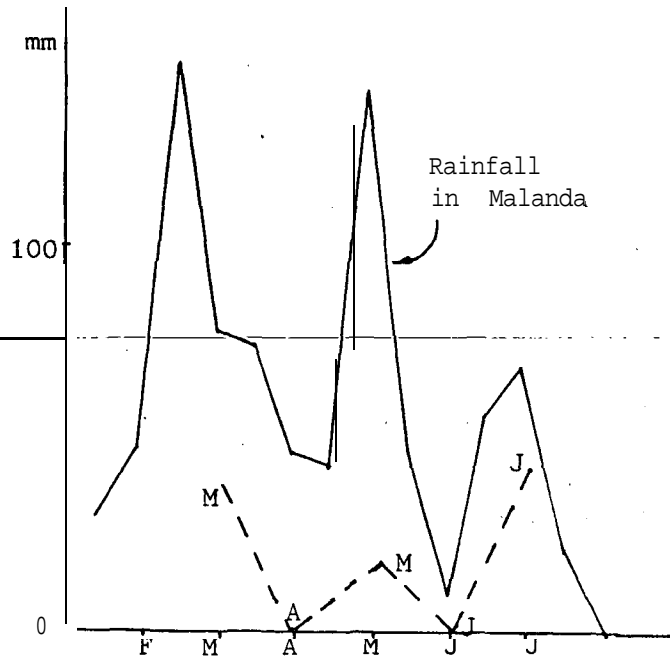
Figure 5. Malanda rainfall data superimposed over NO_2 stream concentrations in the Upper Barron River - lag time = 1 month
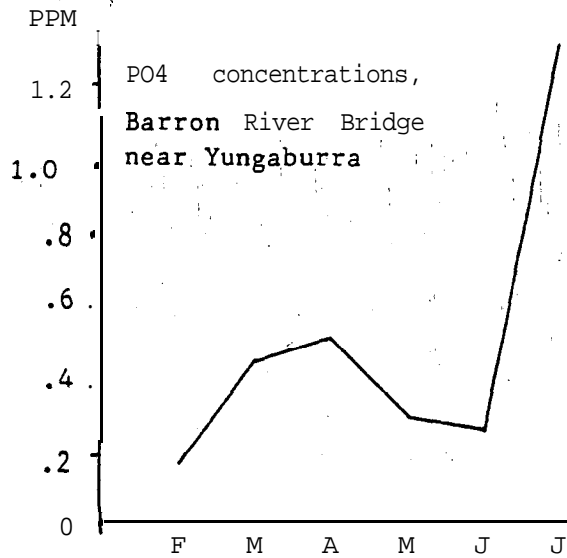
Figure 6.   Increased PO4 concentrations corresponding
with decreased rainfall and use of irrigation
as the major source of farm water supply   ·
(see rainfall pattern Fig 4)
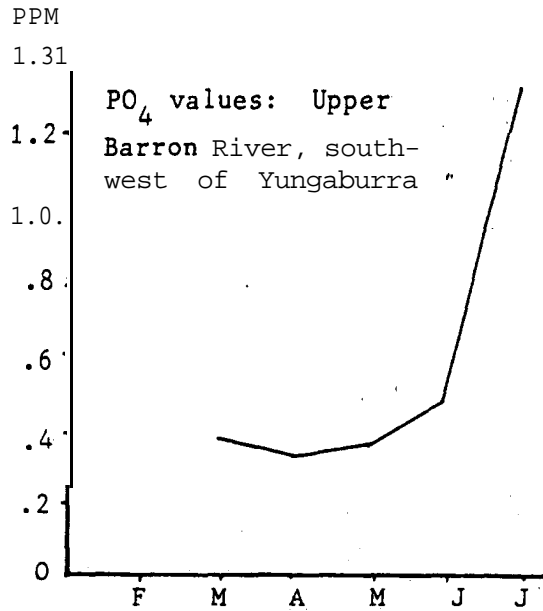
Figure 7,   Increased PO concentrations corresponding
with onset o4 irrigation **following** the decline
in natural precipitation (see rainfall pattern
F i g   5)

between land management practices and enhanced nutrient levels of the streams. For example, in the Yungaburra, Kairi and Tinaroo areas, irrigation began as rainfall decreased. This is reflected in the sudden flushing of nutrients into the associated streams draining these particular areas (Figs 6 & 7). Similarities are also suggested between stream nutrient levels, geographical location and landuse patterns. For instance, Davies Creek and Clohesy River (Figs 8 & 9) share similar nutrient -peaks, landuse patterns and geographical locations. These signatures are quite distinct to the dairying area of the Atherton Tablelands (eg Figs 6 & 7).

Experimental Corals

Two species of corals, Acropora formosa and Porites, were selected for experimentation. The ability to use the same Porites sample under a variety of geomechanical and geochemical techniques has provided researchers with an invaluable tool for unravelling the complexities of coral records. However , Acropora species of corals provide large -quantities. of coral shingle to the reefal environment. It is also considered aesthetically pleasing by tourists, hence its commercial value must not be overlooked. The rapid growth habits of Acropora formosa determined its experimental suitability.

Acropora formosa and Porites species of corals were grown in aquaria at the Orpheus Island Research Station. To mimic the marine environment as near as possible, unfiltered seawater was pumped into the tanks direct from the reef flat at a rate designed to provide an hourly turnover of marine water. Shade cloth covered the top and sides of the tanks to replicate oceanic conditions at a depth of approximately two metres. Commercial superphosphate of the composition described in Table 1 was dissolved in filtered seawater and added to the tanks by a drip system designed to maintain concentration within individual tanks of 2, 4 and 8 ugA/L PO4. Two tanks remained free of fertilizer as controls. Alizarin was used as a marker stain to provide a time basis for the experiment.

Figure **8.** Davies Creek

a)   PO$_4$ c o n c e n t r a t i o n s

b)   NO$_2$ concentration&
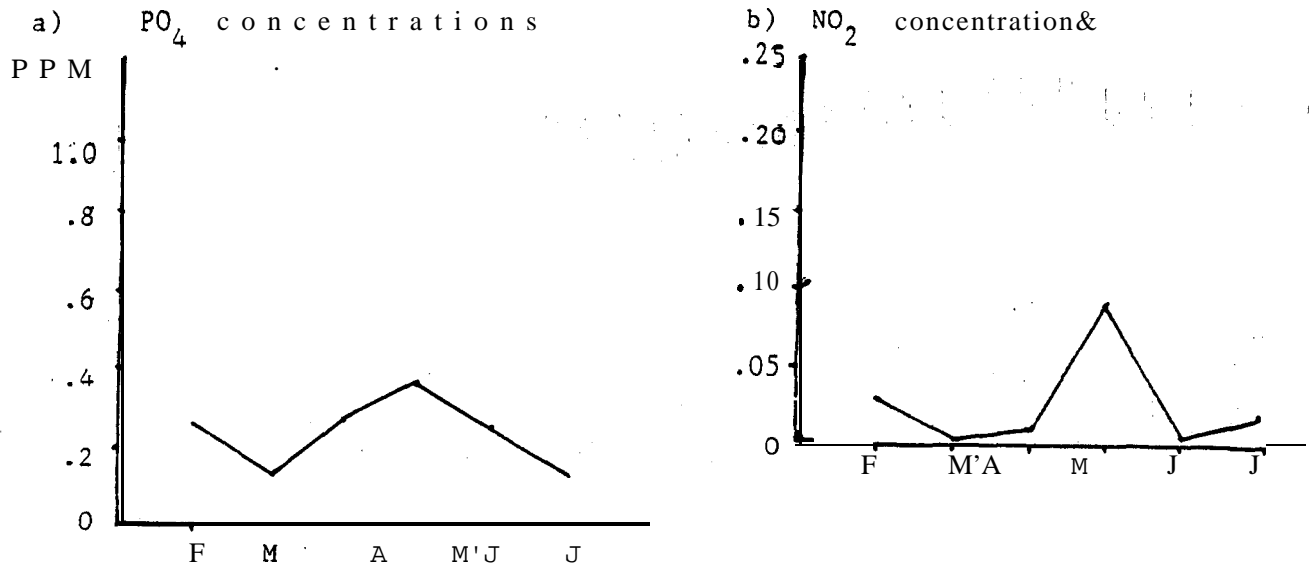
Figure 9.   Clohesy   River

a) **PO$_4$** concentrations
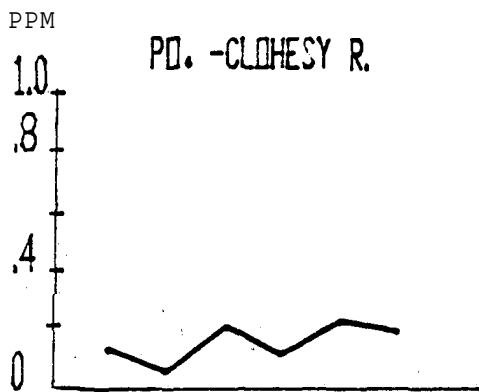
b)   **NO$_2$**
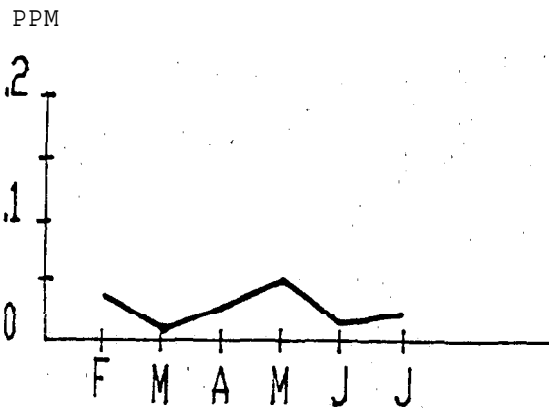
<u>Table 1</u>. Superphosphate Analysis
(weight percent)

Phosphorus 'P' (water soluble)	7.0%
Phosphorus 'P' (Citrate soluble)	1.5%
Phosphorus 'P' (Citrate insoluble)	0.5%
	9.0%
Sulphur 'S' as Sulfates	10.0%
Calcium 'Ca' as Superphosphate	20.0%

<u>Porites</u> species proved difficult to grow in experimental conditions. <u>Acropora formosa</u>, previously understood to be difficult to maintain experimentally (pers comm R Babcock; J Oliver) has proven extremely successful.

The <u>Acropora formosa</u> colonies were harvested on the night of coral spawning (9 November 1987) at Orpheus Island. Small *sections* were removed from each colony for examination of variance of spawning ability.

Growth-tips . from the remaining colonies were removed using n d tipped saw, and examined under the Scanning Electron Microscope for morphological and chemical variations. Plates 1, 2 and 3 indicate substantial alteration *to* the internal morphological structure of the skeleton has occurred. Skeletal walls have thinned and voids enlarged considerably with increased-addition of P04.

At present little is known of standard levels of strontium within <u>Acorpora</u> species of corals. However, although data are only preliminary, variation exists within the three samples indicating decreased levels of strontium following increased additions of PO4 (Table 2).

Coral Cores

Sections from two cores from Low Isles and Magnetic Island were made available by Dr Peter Isdale, Australian Institute of Marine Science. These samples were examined using x-radiography to determine annual growth bands and selected bands analysed using Atomic Absorption Spectometry, X-ray Diffraction and Scanning Electron, Probes to determine possible spatial and temporal variations in mineralogical and chemical precipitation into the coral cores..
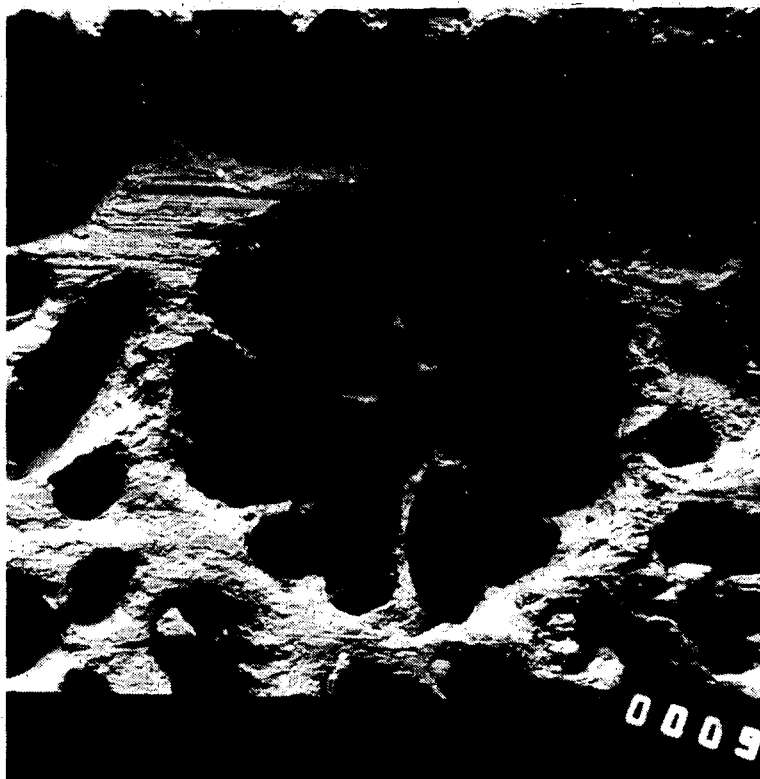
Plate 1. Growth tip, _Acropora formosa_. Control (Magnification **x** 40)
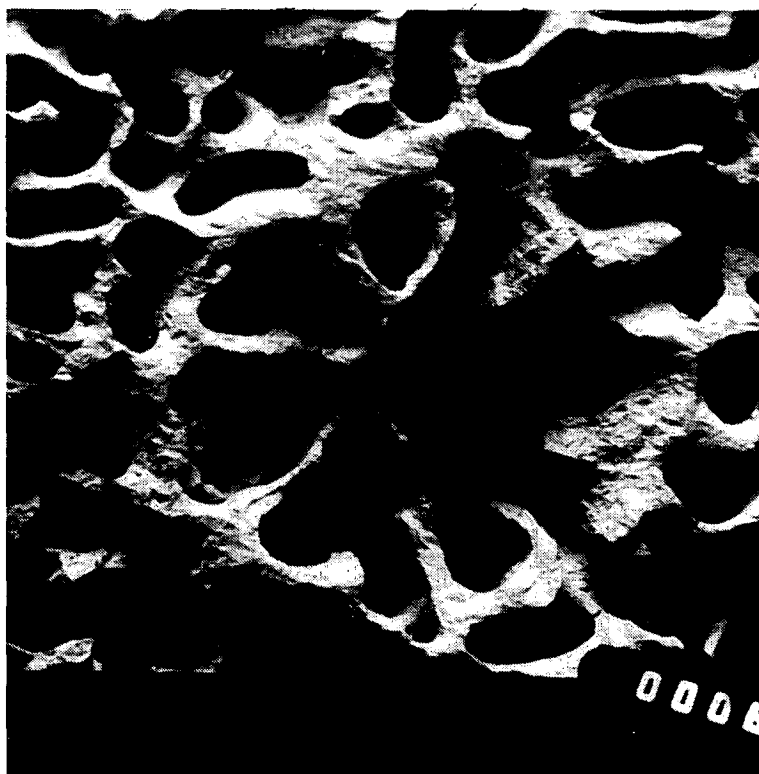
Plate **2.**   Growth **tip,** **Acropora** formosa, following the **addition** of 4 **ugA/L**
        PO$_4$ (Magnification,x '40).   NB **walls** beginning **to** thin

Plate 3.   Growth   tip,   <u>Acropora   formosa,</u>   following   the   addition   of   8   **ugA/L**
             PO$_4$.   (Magnification   x   40)   NB   Considerable   alteration   to
             <u>skeleton   morphology</u>;   _a)   -<u>excessive   thinning   of   internal</u>   walls;
             and b)   increase   in   size   and   number   of   voids

Table 2.   *Strontium* values, <u>Acropora formosa,</u> following the addition of
             controlled levels of **PO$_4$** **to experimental aquaria, Orpheus**
             ~~Island.. Values taken mid-way across tip using Electron Probe~~
             Analysis

                    PO4   CONCENTRATION   Sr VALUE

                    Control   7215
                    4 ugA/L   6820
                    8 ugA/L   6835

                        Preliminary   data   only

Strontium levels from both cores show a general decline over time, correlating with use of phosphatic type fertilizers in nearby terrestrial environments. Of particular interest is the different signature emanating from each coral core, thus establishing the individual alteration of the marine environment surrounding each coral colony rather than an overall steady decline in strontium availability. Further, the different signatures apparent in each core relate to known environmental histories of the different geographical locations of the two coral colonies.

Geographical variation, hydrological regime and landuse practices of the nearby terrestrial environment plays a significant role in determining the chemical composition of the corals. For example , it has been argued within this paper that the increased use of superphosphate is primarily responsible for a decrease in the amount of strontium precipitated into the coral skeleton.' 'Thus, when PO4 is added to the marine. environment via short runoff streams on a small is land draining pineapple farms (eg Magnetic Island) it would be 'anticipated s'keletal precipitation would be subjected to different variables than PO4 entering' the marine environment via a major river draining a large catchment substantially altered for agricultural purposes (eg Barron River). This geographical and environmental variation is recorded in coral skeletal material. As is evident in Fig 10 Townsville's 1946 flood served to dilute the amount of PO4 normally entering the marine environment only via a very few short runoff streams or through ground-water seepage, resulting in a strontium peak during this period,. Sewerage discharge from Ross River (Townsville) which replaced, fertilizer as the main source of PO4 in the Magnetic Island region following the decease of pineapple production, is similarly diluted by the heavy 1974 wet season, leading to 'a further strontium, peak at this time. In contrast, the Barron River catchment responded to the 1974 heavy wet 'by injecting large quantities of agricultural fertilizers into the marine environment around Low Isles. The substantial increase in PO4 led to a corresponding decrease in strontium precipitated into the coral skeleton during this period (Fig 11). It is significant to note that superphosphate is added to pastures in the Barron River catchment around October specifically in anticipation of the wet season. That superphosphate is reaching the rivers -following rainfall has been demonstrated above.
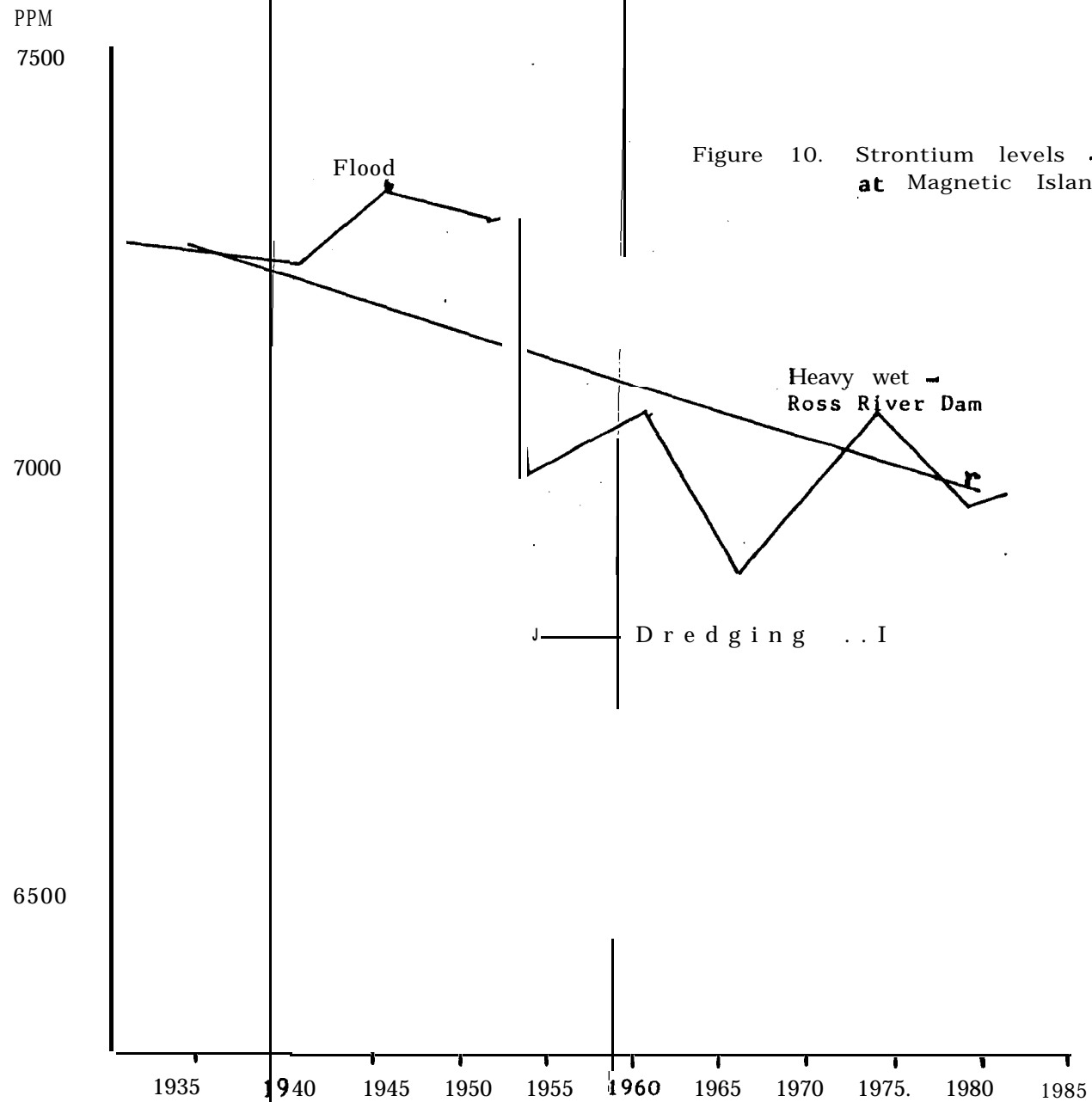
Figure 10. **Strontium levels — Porites spp at Magnetic Island**

Figure 11. Strontium levels – _Porites_ spp at Lou Isles
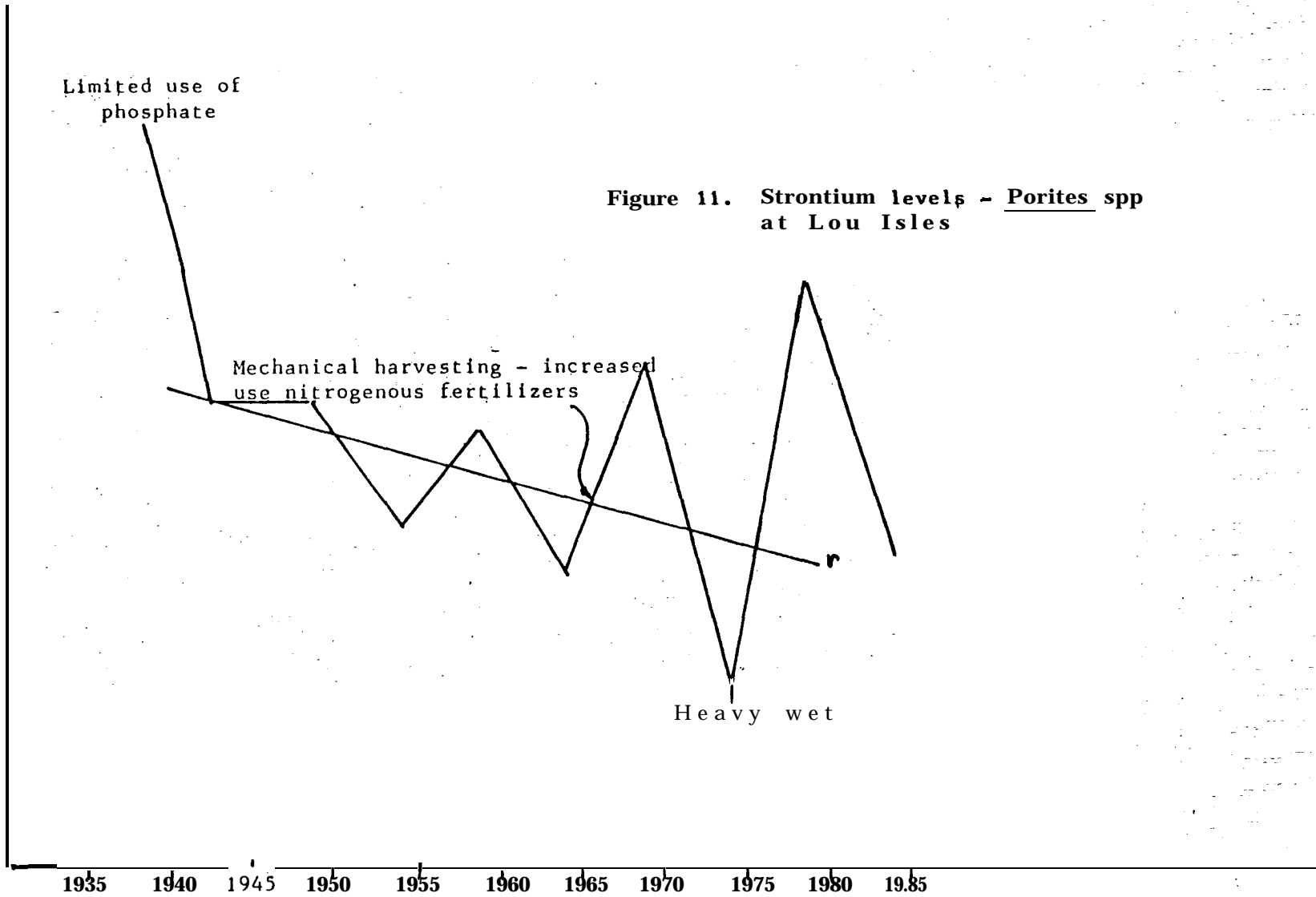
It would appear that strontium levels (interpreted here as the result of anthropdgenically introduced PO4 into the marine environment) provide an accurate interpretation of past environmental changes. From an examination of the Low Isles cores and the known history of sugarcane farming in the nearby terrestrial hinterland, it is possible to correlate the environmental history of the area with variations in the coral cores. The limited use of phosphatic type fertilizers prior to 1939 corresponds to the anticipated levels' of strontium expected in Porites species of corals as interpreted by Frazer Muir (1984). However, strontium levels drop with the introduction of phosphatic type fertilizers. At present *it* has only been possible to examine. the Low Isles core at selected temporal intervals. It is considered that examination on an annual basis will indicate a break in the regression line shown in Figure 11, corresponding to the introduction of mechanical harvesting and the subsequent ability to substitute phosphatic-type fertilizers with increasing amounts of the nitrogen enhancing fertilizers, subsequently leading to a decrease in PO4 entering the marine environment and a relative increase of strontium precipitated into the coral skeleton. Continued and expanding useage of phosphatic type fertilizers for other agricultural purposes on the Atherton Tablelands will tend to mar this upward trend, a point which is emphasised by the effects of the 1974 and 1979 wet seasons on the strontium values of the corals.

The drop in Strontium content in 1985 from the Magnetic Island coral colony is presently unaccountable. However; this was the outer limit of the sample and it may be a peculiarity of the corals. This peculiarity has also been noted in the Acropora formosa samples grown experimentally at Orpheus Island, but no explanation is presently possible.

CONCLUSIONS

1) From the results to hand a direct correlation exists between enhanced levels of PO4 in the marine environment and strontium concentrations precipitated into the coral skeleton.

2) Increased nutrient levels in streams of the Barron River catchment are closely linked to precipitation, landuse and land management practices.

3) A link, therefore, is suggested between land. management, **practices,** enhanced levels. of nutrients transported via mainland runoff into the marine environment, and strontium levels precipitated into the coral skeleton.

4) Experiments conducted on <u>Acropora formosa</u> at Orpheus Island indicate phosphatic **type** fertilizers have a deleterious effect on the skeletal deposition of the coral colony. At high levels, calcificat- ion is hindered, altering both the internal and external morphology of the coral structure. Thinning of the skeletal walls occurs, theoretically leading to increased fragility of the coral colony.

5) Data extrapolated from the coral cores suggsts the use of strontium levels precipitated into the corals. to (a) indicate historical anthropogenic influences, and **(b)** as a monitor of the present health and condition of the reef for future management planning.

6) The combined results from the above **studies** should ultimately provide an accurate spatial and temporal record of anthropogenically altered environments within the Great Barrier Reef. This will subsequently provide a scale against which <u>Acanthaster planci</u> data may be plotted.

OTHER VARIABLES

It is possible there are other sources of nutrient enhancement not being examined in this study, eg nutrient upwelling from oceanic currents; sewerage discharge into the marine environment. However it is **antici- pated** that examination of coral cores from a variety of environments will eliminate many of the confounding variables.

PROPOSED FUTURE RESEARCH

1) <u>Acropora formosa</u> samples removed from the experimental tanks on Orpheus Island during the period of coral spawning are presently being examined by Dr B Willis to assess the effects of increased levels of PO4 on the reproductive cycle of coral colonies.

2) <u>Acropora formosa</u> samples collected from various cross-shelf locat-
ions, . northern Great Barrier Reef, have been obtained from Dr
J Oliver.   These corals will be analysed to determine the relation-
ship between coral fragility and proximity to the mainland.

3) Experimental   corals will again be grown on Orpheus Island.   Rates
of PO4 injection will be altered to   include 1.0, 0.6 and 0.4
ugA/L   PO4.   Intermittent injection at spasmodic controlled
level5 will   also be   included in   the   experimental   programme.
Availability of previous research on <u>Porites</u> species of corals
dictate the suitability of using this species of coral for experi-
mental   research.   Thus,   for comparative purposes,   every effort
will be made to grow <u>Porites</u> species of corals under experimental
conditions.   Should this prove possible, <u>Porites</u> and <u>Acropora</u>
species will share experimental tanks.

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NUTRIENT HISTORY OF THE GREAT BARRIER REEF AQUARIUM

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INTRODUCTION

The Coral Reef Tank at the Great Barrier Reef Aquarium which opened in Townsville in June 1987, provides an ideal system in which to study nutrient cycling on a coral reef. This paper describes the nutrient history of the Coral Reef Tank, highlighting aspects which may be relevant to the management of nutrient discharge in the Great Barrier Reef Marine Park.

A coral reef has been constructed in a rectangular tank, 38m long by 17m wide, with a water volume of $2500m^3$. The tank is illuminated by sunlight and subject to waves, currents and potentially tides. The empty tank floor **was** covered with sand before addition of carbonate rock to create the reef framework. After the tank was filled with water, biological stocking began with representatives of the lowest trophic level and subsequently organisms from higher trophic levels were added. Currently, the tank supports a wide range of reef dwellers typical of the central Great Barrier Reef region.

The Coral Reef Tank is a closed system in which water quality is controlled by algal turf scrubbers (Adey, 1983). The tank is supported by $80m^2$ of algal turf scrubbers which process the entire water volume daily. The recently observed spawning of several tank inhabitants, including some scleractinian corals, suggests that the scrubbers are successful in maintaining acceptable water quality for a coral reef.

METHODS

Nitrate is regarded as an important dissolved nutrient in the Coral Reef Tank. It is the principal form of inorganic nitrogen in the tank, because the ammonia resulting from biological activity undergoes rapid bacterial conversion via nitrite to nitrate. Build up of nitrogenous compounds is a common phenomenon in closed circulation aquaria, and routine monitoring of nitrate concentration is a prerequisite for maintaining optimum water quality. Nitrate has been selected to provide a nutrient history of the Reef Tank.

Nitrate analyses were performed by standard automated techniques, following the methods of Ryle et al. (1981). Samples were , collected at a frequency of no less than three per week. W a t e r was filtered through 20um plankton mesh into: polyethylene bottles and stored frozen until analysis.

RESULTS.

Nitrate concentration varied widely with time since the tank was filled with water (Fig. 1). Levels ,in the incoming seawater were <0.05uM. The very high initial nitrate concentration (15.9uM) was the result of nutrient release from the sand and coral rock in the tank', and unconditioned algal scrubbers which were unable to cope with the sudden nutrient rise. The rapid fall in nitrate coincided with a phytoplankton bloom, after which the water was' discarded removing the excess nutrients from the system in the form of phytoplankton.
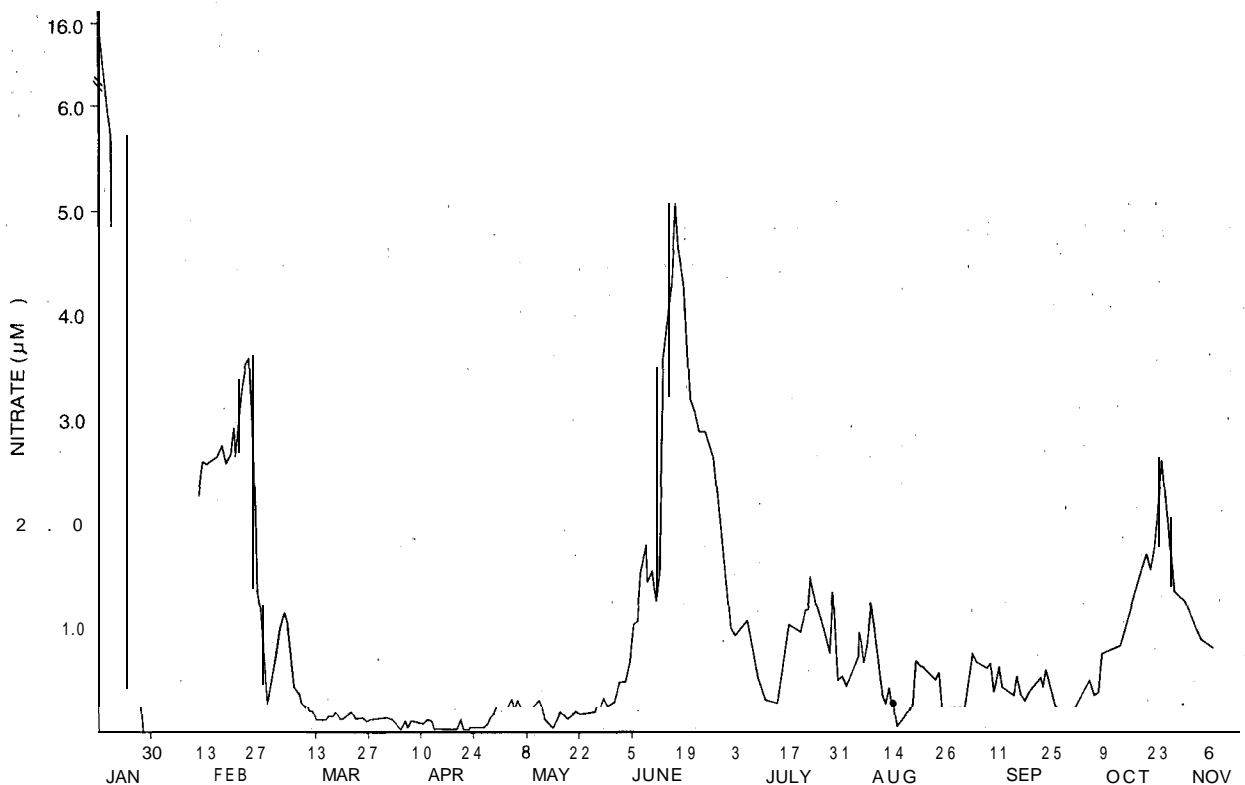
Figure 1. Variation of nitrate concentration in the Coral Reef Tank between January and November 1987.

A similar but lower magnitude nutrient peak (3.6uM) occurred after the second tank fill in mid-February. Residual nutrients from the substrata were again the source of nitrate. A phyptoplankton bloom similar to the first was prevented by excluding 90% of incident sunlight from the tank and the algal scrubbers responded to the elevated nitrate levels by an increase in productivity. Subsequently, there was a decrease in nitrate to levels below 0.3uM in a month.

Nitrate concentration remained low as stocking proceeded until early June when it rose to peak at 5.1uM. This spike was attributed to the intense removal of tank algae which were acting as nutrient cyclers. These tank algae were growing abundantly over the rock surfaces and were removed because of the negative influence on tank aesthetics and the damaging effects of detached algae on the reef benthos. The rapid addition of several field collections at this time may have also contributed to the nutrient problem. These events increased the nutrient loading of the tank at a rate faster than the algal scrubbers could respond, resulting in a rapid rise of nitrate.

Following this June peak, the operating levels of nitrate were more temporally variable as the standing stock in the tank increased. In late October, there was another nutrient spike which, although smaller in magnitude, is clearly discernable as a period of elevated nitrate (2.6uM) compared to the preceding and following periods. This rise in nutrients was associated with tank construction activity. Installation of a water cooling system necessitated isolation of 400m^3 of Reef Tank water for several days in a holdinq tank, allowing nutrients to accumulate. In addition the accompanying modified circulation resulted in scouring of sand in the tank releasing interstitial nutrients into the water.

Coral mortality in the Coral Reef Tank has occurred in two major episodes. Approximately 20% of the scleractinian corals in the tank died in June-July. This period corresponded most notably to a time of elevated nitrate levels and the dying corals were almost exclusively pocilloporids and species of Acropora. Many of the corals which died had been in the tank for several months and had previously looked healthy. The second episode occurred in late October-early November when 16% of the corals died. Individuals from all of the major coral groups were affected, including some which had survived in the tank for six months. This October-November period was characterized initially by high water temperature (>30°C) and subsequently by elevated nitrate levels.

DISCUSSION

Highest rates of coral mortality in the tank occurred at **times** of elevated nitrate levels. For the June-July episode of coral death, nutrients were the only water quality parameters which were abnormal, and mortality is directly connected with high nutrients. 'In October-November, both, temperature and nutrients were above acceptable levels. High temperature is lethal to corals' (Jokiel & Coles, 1977; Glynn, 1984), and corals' at their temperature tolerance limits are more susceptible to stress by other environmental factors (Coles & Jokiel, 1978). Elevated seawater temperatures in conjunction with high nutrients are identified as the cause of the second mortality event.

The nitrate concentrations at which widespread coral death occurred in the tank were above 2.5uM. This value is a marked increase over general levels on a coral reef (<1uM; Crossland,: 1983), but is low compared to concentrations that may be expected within the vicinity of a waste water discharge (Bell et al., 1987). Further., the nitrate spikes associated with coral death in the tank were short-term events and higher coral mortality would ensue if elevated nutrients persisted. The tank nitrate problems caused by the release of nutrients from disturbed sediment highlight the importance of the sedimentary nutrient pool and the danger of suspending sediment in a confined or restricted circulation area.

The scleractinian genus Acropora appears to be particularly sensitive to high nitrate levels in the tank. Adey (1983) also reported that Caribbean Acropora in a coral reef aquarium were more susceptible to disease at high (>5uM) nutrient levels. This result is significant because Acropora is a very important component of many coral communities on the Great Barrier Reef.

It is not possible to attribute the observed coral mortality specifically to nitrate, because elevated nitrate levels in the tank were accompanied by above normal concentrations of phosphate. Kinsey & Davies (1979) suggested that high phosphorus rather than nitrogen would be more detrimental to coral calcification, although the physiological basis of the relationship between nutrients and coral growth remains' uncertain.

Nevertheless, it is clear from our experiences in the Coral Reef Tank that the tolerance levels of corals to nitrogen and phosphorus are relatively low; and that enhanced nutrient levels in reef waters would have damaging effects on coral communities.

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TOLERANCE OF CORALS TO NUTRIENTS AND RELATED WATER QUALITY CHARACTERISTICS

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SUMMARY

The nature of eutrophication in aquatic areas is reviewed and the principle physicochemical and biological factors involved identified. In broad terms' the effects of nutrient enrichment in coral systems are similar to those in other aquatic areas with some specific unique features which apply to coral systems. Utilising the limited information available on local waters and coral systems elsewhere a preliminary set of tolerance levels in ambient waters have been developed.

INTRODUCTION

The addition of nutrients and associated substances to freshwater areas has been the subject of intensive investigations over the last 50 years. In Australia, Wood (1975) carried out an overall evaluation of the nature and extent of nutrient enrichment, often referred to as eutrophication, in Australian inland waters. Marine and estuarine areas in Australia and overseas are also subject to nutrient enrichment but have not been as intensively investigated as inland and freshwater bodies. However in many cases these 'water bodies have been seriously affected. For example in Australia many of the estuaries along the 'east coast are adversely affected and overseas the continental shelf off the north east coast of the United States, the Baltic Sea and the Black Sea are seriously enriched with nutrients.

With coral ecosystems only a limited range of data is available. However the value of this data can be extended by utilising the basic principles established on the nature of nutrient enrichment in inland waters. In this paper we will examine the principal features resulting from nutrient enrichment, collate the existing information available on the interactions with corals and finally suggest some tolerance levels for the relationship between nutrients and related water quality characteristics and corals.

DISCHARGES   CAUSING   **NUTRIENT   ENRICHMENT**

A variety of discharges to aquatic areas result in nutrient enrichment, together with associated water quality problems.   These discharges can be categorized broadly as

1.   sewage discharges

2.   water run-off

3.   industrial discharges

Most information is available on sewage discharges since this type of discharge is more consistent in composition than water run-off and industrial discharges. These latter two tend to vary in nature with the different situations involved but often have a lot of similarities to sewage discharges.   Table 1, from Arthington et al (1982), illustrates the water quality characteristics of wastewater from secondary sewage treatment plants.

Table 1 - Typical Composition of Secondarily-Treated Sewage Effluent'

Component	Concentration (mg/1) reported for plants throughout various countries	Concentration (mg/1) for plants in south-east Queensland
Suspended solids	20	18 - 23
BOD	12	12 - 21
Dissolved oxygen	7.1	
Temperature	15"	
Chloride	62	56 - 85
pH	7.5	7.5 - 7.8
Total nitrogen forms	18 - 28	8.3 - 37
Total phosphorus forms	3.5 - 9.0	5.1 - 7.6
Cu		0.029 - 0.040
Cd		0.003 - 0.007
Cr	0.05	
Hg	0.0013	0.0003 - 0.0007
Zn		0.17 - 0.90

*   It should be noted that there can be substantial variations from these values depending on such factors as loading on the plant, type of plant, wastewaters received and so on.

From considerations of the literature on water quality effects on aquatic ecosystems it can be suggested that suspended solids, BOD, chloride, total nitrogen forms and total phosphorus forms are' the most likely substances likely to adversely affect water quality and corals. Except in special circumstances these same parameters would be expected to be important in industrial discharges and water run-off. Chloride is different to the other parameters, here in that the salinity or chloride content, of a discharge may adversely alter the salinity in a coral reef area.

GENERAL BIOLOGICAL EFFECTS OF NUTRIENT ENRICHMENT

As nutrients are added to an aquatic area over time a gradual "ageing" of the body can be expected as illustrated in Figure 1. While this is more typical of freshwater lakes a somewhat similar process can be expected in coral reef lagoons and similar semi-enclosed areas. The classes oligotrophic, mesotrophic and eutrophic have been developed from freshwater lakes and have a related set of physicochemical and biological characteristics (Connell and Miller, 1984). However these terms are often used to describe oceanic and estuarine waters as well. In these situations different criteria would be expected to be applicable but the exact nature of those has not been' developed at present.
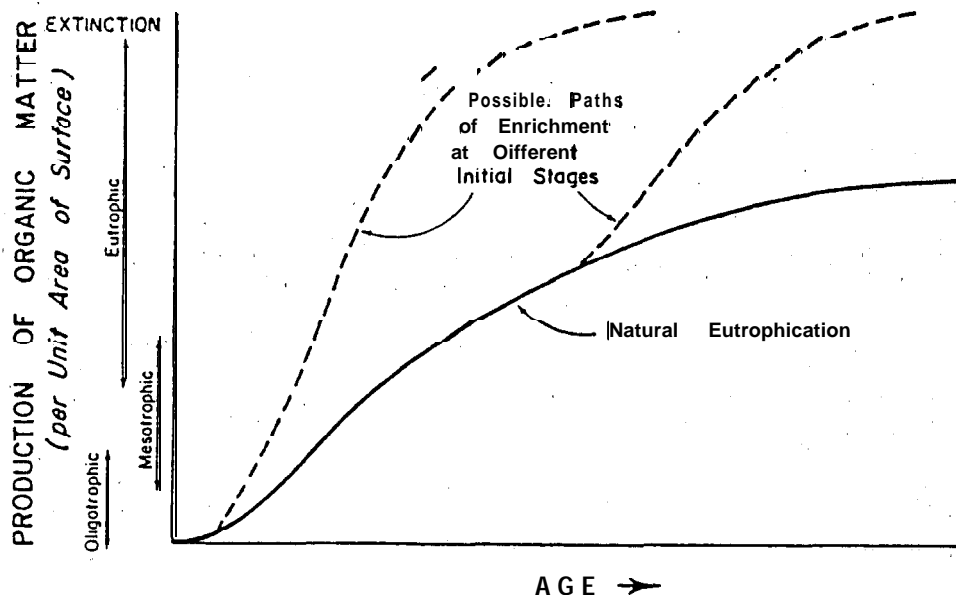
Figure. 1 . Hypothetical curve of the course of eutrophication in a water body. The broken lines show the possible course of accelerated eutrophication when enrichment from pollution occurs.

Table 2. Measure of eutrophication in a water body

1. **Nutrient and associated ion concentrations in the water.**

2. **Total dissolved solids (specific conductance).**

3. **Dissolved oxygen status.**

4. **Standing crop (biomass).**

5. **Primary production.**

6. **Production/biomass ratio.**

7. **Transparency of the water.**

a. **Species diversity and types present.**

9. **Lake morphometry.**

10. **Sediment core analysis.**

11. **Algal bioassays.**

Some of the characteristics used to measure eutrophication in aquatic areas are shown in Table 2 (Connell 1981). Many of these are applicable **to coral reef systems. Some of the biological and physicochemical changes resulting from nutrient enrichment are shown in Table 3. It should be kept in mind that many of these features often exhibit seasonal patterns of variation which must be considered in making evaluations.**

Table 3. Some biological and physicochemical changes which would be expected to result from nutrient enrichment of an aquatic area

Characteristic	Low Enrichment	High Enrichment
Total biomass	**low**	**high**
Number of species	**high**	**low**
Turbidity	**low**	**high**
Bottom sediments	**coarse**	**fine**
Primary production	**low**	**high**
Chlorophyll-a	**low**	**high**
Nutrient salts	**low**	**high**

EFFECTS OF WASTE. WATER DISCHARGE IN CORAL REEF ECOSYSTEMS

The 'harmful, effects of sewage are related to the capacity of the receiving waters to accept,; dilute and disperse the effluent: To some extent, its noxious. quality depends on the degree and extent of prior treatment, but treatment can give rise to sewage' sludge, which presents disposal problems of its own. Possibly the most well-known study on the effect of sewage on a'coral reef community is that of Kaneohe Bay, Hawaii. It is a partially enclosed embayment, 12.7 km long and 4.3 km broad, with an ocean frontage of 8.8 km on the north-eastern side of the island of Oahu. One portion of the bay was once known as the Coral Gardens, and before 1939, surrounding watersheds were dominated by rural and agricultural use. Since that time, however, the surrounding population has increased over tenfold, and sewage discharges into the bay increased, culminating in the construction of large sewage outfalls in the south-east sector of the bay in 1963 (Smith, 1977; Maragos, 1985; Banner; 1974). By 1977, the total sewage effluent volume totalled over 20 000 m^3 day^{-1}, with 95% being discharged into the southern section of the bay.'

Just after the Second World War, the most abundant coral species were reported to be Porites compressa and Mon'tipora verrucosa. Other corals of lesser importance included Pocillopora damicornis, Fungia scutaria, Cyphastrea ocellina, Leptastrea bottae, Pavona varians, and the ahermatypic Tubastrea aurea. Most, if not all, of the above genera are represented in the waters of the Great Barrier Reef. Available information, for Kaneohe Bay suggests that the most conspicuous effects of the sewage were in, terms of increased biomass and productivity, together with altered community structure (Smith, 1981). The sewage discharge was reported not to have markedly affected the pH, dissolved oxygen, or BOD in the bay away from the immediate areas of discharge. The most obvious changes to the once-living reef areas were the Toss of almost all living corals from the south-east sector of the bay, and the replacement of living corals by the alga Dictyosphaeria cavernosa in the central section. The' benthic fauna of the south-east section of the bay saw a dominance of filter and detrital feeders such as sponges, sea cucumbers, oysters and clams depending upon suspended organic material in the water. In addition, the bottom sediments were fine and black, with indications of anaerobic decomposition taking place near the surface. The reef flats had massive growths of algae, such

as <u>Acanthophora</u>, <u>Graciliara</u> and <u>Hydroclathrus</u> (but no <u>D. cavernosa</u>). In many' places, the old dead heads of <u>Porites compressa</u> were still present, though covered with fine sediment, together with sponges and sea cucumbers. Some coelenterate corals (e.g. <u>Porites compressa</u>) had been found extremely susceptible to increased phosphate concentrations so it is probable that the detergent phosphates in sewage effluent played an important role in reducing coral populations.

Sporadic outbreaks of phytoplankton concentrations known as "red tides" also became a feature of the bay. Average standing phytoplankton crops, as measured by chlorophyll a concentrations, increased by a factor of 1.56 in the south-east section, the site of the sewage outfalls, 0.38 in the middle bay, and 0.07 in the northern sector.

In 1977, 95% of the sewage that had previously been discharged into the poorly flushed south-east sector (residence time of the order of weeks (Maragos, 1985)), was diverted to an ocean outfall. This event presented investigators with the opportunity to confirm that the coral mortality evident was due primarily to the effects of sewage., and observe the recovery of the marine ecosystem Recent surveys have revealed a remarkable recovery of corals, especially <u>Porites compressa</u> and <u>Montipora verrucosa</u> . In contrast, the alga <u>Dictyosphaeria</u> declined greatly, with decreases in deeper water appearing to be larger than decreases in shallow water. With sewage diversion, the biomass of both plankton and benthos decreased rapidly, although benthic biological composition has not yet returned to pre-sewage conditions, partly because some key organisms are relatively long-lived and partly because the bay substratum has been perturbed by sewage input, and acts as a reservoir of nutrients and organic detritus (Smith, 1981).

Localized pollution of coral reef areas at Aqaba on the Red Sea, as a result of sewage discharge and spillage of phosphate dust during loading of phosphate mineral onto ships, has also been reported (Walker, 1982). Effects were studied by comparison of an area nearby a sewage outfall with a control area some distance away. The region around the outfall had reduced water visibility, increased algal cover (mainly <u>Ulva lactua</u> and <u>Enteromorpha clathrata</u>), a corresponding increase in small, grazing

gastropod mollusca and the sea-hare _Aphysia,_ and a decrease in coral diversity., _Stylophora pistillata,_ was found to be 'the only remaining coral species. In the control area of: reef flat, approximately 50% of the surface was covered with living coral colonies. These were mainly _Favia_ spp., _Favites_ spp., _Pocillopora danae,_ _Seriatopora hystrix_ and some' _Stylophora pistillata._ There was only a limited algal, presence observed. Table 4'provides a summary of a comparison between the sewage - influenced and control area.

Table 4 - Levels of increase of related parameters from the sewage-influenced area compared to those from the control area, Gulf of Aquaba (a)

Factor	Level in sewage-influenced area / Level in control area
Rate of coral death	4.7
Density of sea urchins	3.1
Algal biomass	2.2
% Suspended sediment	4.3
Phosphate concentration	3.3

(a) **From Walker and Ormond, 1982**

Investigations in an adjacent area of the Red Sea by Fishelson (1973); affected by oil spills and phosphate dust spillages,, 'resulting in eutrophication of shallow lagoon waters of the coral region, revealed much the same trends. Between 1966 and 1972, the average number of total living coral colonies along a series of 10 m transects fell, from 541 to 195. Fishelson also found that the bush-like micropolypal branching forms, such as species of the genera _Acropora,_ _Stylophora_ and _Seriatopora,_ are much more sensitive to severe ecological conditions than the brain-like macropolypal' species, such as those from 'the genera _Platygyra,_ _Favia,,,_ _Favites_ and _Lobophyllia._

Nutrient content is a significantfactor in the response of corals to seawater containing variable dilutions of treated sewage. In experiments involving a

treatment plant utilizing raw sewage from metropolitan Miami, Florida, effluents were produced over a wide range of qualities using primary (filtered raw sewage), secondary (activated sludge) and tertiary (alum precipitated) treatments. Corals and other reef biota were maintained in an array of 350 l seawater tanks, and exposed to a continuous flow of effluents at each of the treatment steps, with and without chlorination, at dilutions with seawater Of 1:30, 1:100 and 1:300. Preliminary results using the reef corals Montastrea cavernosa, Montastrea annularis and Dichocoenia stokesii as test specimens indicated that nutrient loading had the most pronounced effect on reef corals. Certain treatments and effluent concentrations greatly enhanced the growth of algae at the expense of coral. Coral morbidity and, mortality under those experimental conditions were thought not to be directly related to effluent toxicity, but the result of competition with algae for space, and especially light (Marszalek, 1981(a)).

Table 5. Summary of physicochemical and biological effects of sewage wastewater on coral systems

Characteristic	Change with increasing enrichment
biomass	increase
primary production	increase
coral numbers	decrease with Porites compressa among the most sensitive; numbers effective zero, in extreme situations
chlorophyll-a	large increase
filter and detritus feeders	large increase
benthic algae	large increase
sediments	medium size low in organic matter to fine and high in organic matter
sediment redox potential	high, with high dissolved oxygen in the interstital water, to patches with low oxygen arid some anaerobic areas
water characteristics	pH, DO, BOD, little affected
turbidity	increase
occurrence of blooms	large increase

Overall, the immediate effect of sewage input into coral reef systems would appear to be 'enhanced, nutrient levels and sedimentation rates. Subsequent effects include increased, primary, production and possibly decreased oxygen levels; , Because of' narrow environmenta. 'tolerances and immobility, corals are generally the most sensitive organisms in coral reef ecosystems to pollution including sewage. Table 5 presents, a summary of the physicochemical and biological effects of nutrient enrichment on coral systems.

WATER QUALITY ASPECTS OF NUTRIENT ENRICHMENT

Investigations concerning response of nutrient levels to sewage diversion in Kaneohe Bay , are useful in assessing effects on reef systems. Pre- and post-diversion levels for various forms of nitrogen and phosphorous are in Table 6. Results show decreases in nitrate plus nitrite, phosphorous and ammonium concentrations, but an increase in dissolved organic nitrogen.

Table 6 - Pre- and post-sewage diversion nutrient levels In Kaneohe Bay
$(\mu g$ at $1^{-1})^{(a)}$

Sector		North-west	Central	South-east	Ocean
Dissolved inorganic nitrogen					
Nitrate and nitrite	Pre Post	0.53 0.66	0.33 0.27	0.38 0.27	0.14
Ammonium	Pre Post	0.57 0.43	0.60 0.38	0.77 0.51	0.47
Dissolved organic nitrogen	Pre Post	4.4 5.1	4.50 5.7	5.4 6.2	4.5
Particulate nitrogen	Pre Post	2.04 1.55	2.28 1.81	4.04 2.86	0.44
Total nitrogen	Pre Post	7.5 7.7	7.7 8.2	10.6 9.8	5.6
Dissolved inorganic phosphorous	Pre Post	0.23 0.11	0.26 0.09	0.48 0.15	0.13
Dissolved organic phosphorous	Pre Post	0.27 0.15	0.30 0.19	0.33 0.24	0.30
Particulate phosphorous	Pre Post	0.08 0.05	0.09 0.06	0.20 0.13	0.01
Total phosphorous	Pre Post	0.58 0.31	0.65 0.34	1.01 0.52	0.44

(a) From Smith et al., 1981

Past-diversion dissolved organic nitrogen levels are Only slightly elevated over quoted oceanic' values, while the reverse is' true for dissolved organic phosphorous levels. On the basis of Table 6, it would seem that total phosphorous and nitrogen levels about twice background levels can cause phytoplankton growth and coral death. Levels, greater than this result in massive coral mortality (Smith, et al 1981).

A study of the phytoplankton community and water column chemistry in the bay, before and after sewage diversion, has shown that changes in total nutrient concentrations in the water cannot be accurately predicted without taking into account water-benthos interactions. The return towards oligotrophy of the system is relatively slow because of nutrient cycling between the sediments, benthic organisms and the overlying water.

The principal stresses on a reef community as a result of sewage discharges appear to result from elevated concentrations of plankton in the water. Thus various measures of plankton concentration such as chlorophyll a or adenosine triphosphate (ATP) levels may be more relevant towards judging the ecological impact of sewage than are inorganic nutrient concentrations.

In areas of the Red Sea near Aqaba where coral mortality due to the effects of sewage and phosphate pollution have been recorded, and phosphate levels (0. 96 µg at 1^{-1}) were found to be over three times greater than in control levels (0.26 µg at 1^{-1}). Increases of nutrient concentrations, particularly phosphate, in this case by a factor of 3 over background levels, result in severe coral mortality (Walker, 1982).

Thus it can be suggested that nutrient enrichment of coral reef communities produces a variety of direct and indirect effects. At lower nutrient levels, say up to twice background levels, primary production of benthic algae is. enhanced.

Extremely high nutrient inputs causing levels three or more times normal. exert additional stress on reef-building organisms by promoting sedimentation and toxicity. High nutrient loading enhances planktonic primary production and leads to increased sedimentation of organic material.

The process of sedimentation also constitutes a significant stress on coral reef ecosystems. Sediment can arise from sources such as terrestrial runoff, dredging and sewage; Suspended solids in receiving waters for sewage discharges originate 'from three sources: particles contained in, 'effluents, particulate organic matter produced by nutrient enrichment, and natural seston. The relative importance of these depends on wastewater treatment levels. This paper will not address this aspect, since it will be covered in other papers.

TOLERANCE OF CORALS TO NUTRIENT ENRICHMENT AND RELATED WATER QUALITY CHARACTERISTICS

Based on the work described previously it seems likely that nutrient levels (particularly total phosphorous) elevated to two or three times the normal ambient levels can cause increased primary production and biomass in both phytoplankton and benthic algal populations, affecting coral nutrition, growth and, ultimately, survival. Enhancement of nutrient levels by sewage discharges by a factor of 3 or more would appear to constitute a significant anthropogenic stress on coral reef communities. Therefore, enhanced nurient (nitrogen and phosphorous) concentrations can be used as an indication of detrimental effects of discharge, and as a preliminary estimate, levels should not exceed three times the normal (pre-discharge) levels.

Domestic sewage waste usually contains degradable organic materials derived from faecal and food wastes which require dissolved oxygen for efficient biological degradation. Receiving waters can therefore be severely depleted in oxygen, causing mortality to many sessile marine organims. Biochemical oxygen demand (BOD) is a commonly used criterion of effluent quality, and also suggests itself as a parameter which may be useful in assessing tolerances to sewage effluent. Although, in some instances, increasing BOD levels can be correlated with increasing stress symptons on coral reef communities often there is no relationship. For example, studies in Kaneohe Bay showed that sewage discharge had not markedly affected dissolved oxygen or BOD outside the immediate areas of discharge, yet there was significant coral mortality away from the outfall (Banner, 1974).

The principal stresses on a coral reef community as a direct result of sewage discharge result largely from increased attached algal growth, localized dissolved oxygen depletion and in some cases elevated concentrations of plankton in the water. Where the latter factor is important varous measures of seston concentration may be the most ecologically appropriate and significant indicators of sewage impact, rather than inorganic nutrient levels. Based on investigations in Kaneohe Bay, Hawaii, Laws and Redalje (1979) ranked water quality parameters according to sensitivity toward eutrophication is shown in Table 7. The most sensitive indicator was chlorophyll a concentration, followed

Table 7. Relative sensitivity of water quality parameters as indicators of eutrophication in Kaneohe Bay[a]

Most sensitive:	Chlorophyll a
Sensitive:	Inorganic phosphorous
	Particulate nitrogen
	Adenosine triphosphate
Insensitive:	Secchi disc depth
	Particulate organic carbon
Very insensitive:	Particulate inorganic carbon
	Ammonium
	Inorganic nitrogen
	Nitrate and nitrite

[a] From Laws and Redalje, 1979

by inorganic phosphorous, particulate nitrogen and adenosine triphosphate (ATP) levels

To assess the effects of eutrophication from sewage waste on hermatypic reef-building corals, 14 environmental variables were monitored along a transect of seven locations off the west coast of Barbados. The physicochemical and biological data indicate that an environmental gradient away from the primary

sources exists as a result of eutrophication of coastal waters. Growth rates of _Montastrea annularis_, a principal reef-builder measured along this' gradient, exhibited high correlation. with a number of water, quality variables. Mean suspended particulate matter and volatile particulate, matter concentrations were the strongest estimators of growth rates, followed by chlorophyll a and BOD. The highest chlorophyll a concentrations occurred at stations off Bridgetown (which is served by activated sludge treatment plants) and tourist resorts, with a gradual decrease away from these sites. Volatile particulate matter concentrations and BOD levels showed a similar trend. However, dissolved oxygen levels were relatively constant, possibly due to efficient flushing and circulation.

Table 8. Regression equations for predicting coral growth rates (Y in cm yr^{-1}) from water quality variables[a] using transformed ($\log (X + 1)$) data.

Suspended particulate matter ($mg\ 1^{-1}$)	$\log Y = - 0.638 \log SPM + 0.760$	$r^2 = 0.79$
Volatile particulate matter (m g 1^{-1})	$\log Y = \cdot 0.340 \log VPM + 1.670$	$r^2 = 0.79$
Chlorophyll a ($mg\ m^{-3}$)	$\log Y = - 0.863 \log CHL + 0.452$	$r^2 = 0.75$
BOD ($mg\ 1^{-1}$)	$\log Y = - 1.368 \log BOD + 0.611$	$r^2 = 0.72$
Sediment organic content (%)	$\log Y = - 0.169 \log ORG + 0.367$	$r^2 = 0.63$
Surface illumination (%)	$\log Y = 0.619 \log ILL - 0.701$	$r^2 = 0.56$
Inorganic phosphate	$\log Y = \cdot 1.940 \log PO_4 + 0.335$	$r^2 = 0.51$

Ammonium, Nitrate and Nitrite, Temperature, Salinity and Current Velocity all had $r^2 < 0.48$

[a] Tomascik and Sander, 1985.

Among the 'inorganic nutrients,. phosphate showed the strongest negative relationship with growth, followed by ammonium and nitrate plus nitrite concentrations. Table 8 presents linear regressions between transformed average

coral growth rates and environment variables, where the raw data is transformed
by log (X +1).

The applicability of these equations to other coral reef areas and the
sensitivity of coral to the more important of the parameters was assessed. The
factor increase in concentration for 90%, 50% and 10% decreases in growth was
calculated as in Table 9. Coral is clearly most sensitive to phosphorous and a
90% decrease in growth, probably effective death, is caused by an approximately
three fold increase in concentration in accord with previous investigations.

Table 9. Factor increases over ambient for various proportions of growth
inhibition with some water quality parameters[(a)]

Water Quality Parameter	% Growth Decrease		
	90	50	10
suspended particular matter	X 4.23	x 1.94	x 1.13
chlorophyll a	X 4.88	X 2.48	x 1.22
inorganic phosphate concentration	X 2.25	X 1.61	x -1.11

[(a)] derived from the equations in Table 8

It is arbitrary as to what decrease in growth rate constitutes an unacceptable
stress but a 20% decrease is 'sometimes taken as a threshold level. Using this a
set of tolerance levels for various water quality parameters is set out in Table
10. In deriving these, some knowledge of the appropriate water quality
parameters is required. Wolanski (1981) has 'found that total suspended
particulate concentration along a cross-shelf transect from Cape Ferguson to
Keeper Reef varied from 15 mg 1^{-1} inshore to 3 mg 1^{-1} at the mid-shelf Keeper
Reef, assuming a particulate density of 1.5 g cm^{-3}. These levels were
determined in mid-July, however, and it is likely that there is considerable
variability during the year, with large increases inshore during the rainy
season. The coral communities that exist across the shelf (i.e. outer shelf,

mid-shelf, fringing and inner shelf reefs) are all adapted to existence in environments of differing water qualities. For example, inner shelf reefs would be dominated by species capable of survival in turbid waters and efficient at sediment removal (Done, 1982). Based on this and Wolanski's data, it is suggested that suspended matter concentrations not to be exceeded for any extended-periods on mid-shelf and outer shelf locations be 3 x 1.28 or 3.85 mg l^{-1} (3.85 ppm). It should be noted that these values are based on limited data, and do not take into account natural temporal variation. More appropriate levels might be set by consideration of mean annual suspended solids concentration;

Chlorophyll a 'surface concentrations in local waters seem to be about 0.4 mg m^{-3}, compared to 0.13 mg m^{-3} in the Coral Sea (Andrews, 1982 and 1983; Ikeda, 1979). Again, values vary throughout the year, with a minimum in winter, and generally higher concentrations inshore, (Wolanski, 1981). Assuming a mean level of 0.4 mg m^{-3}, the maximum tolerable long-term concentration would be 1.48 x 0.4 or 0.59 mg m^{-3} It is stressed however, that local variations of chlorophyll need to be determined before this parameter can be used, and that it may not be appropriate in all cases. There is little information available on background BOD levels in waters surrounding tourist facilities,' since it is a parameter primarily associated with sewage effluent and is often only measured, after discharge has commenced. Based on Barbadian water, the threshold for BOD levels is 1.19 x 0.71 or 0.84 mg l^{-1}. Both chlorophyll a and BOD would appear to be sensitive indications of eutrophication, particularly where receiving waters are partially enclosed, and ciruclation relatively poor.

For inorganic nutrients, average phosphate concentrations in local reef areas appear to be approximately 0.2 μg at l^{-1} (Kinsey, 1979; Andrews, 1983, while NH_4^+ and $NO_3^- + NO_2^-$ concentrations average 0.17 and 0.34 μg at l^{-1} respectively. Tolerance limits then are 0.25, 0.65 and 1.31 μg at l^{-1}. From this data, nitrogen levels are relatively poor indicators of eutrophication, as also found by Laws (1979).

As a caveat, it should be remembered that these calculated tolerance limits are derived using data from one Barbadian coral genus (also present on the Great Barrier Reef), an arbitrary. stress limit, and limited local water quality information. Iniproved limit definition could be obtained by more extensive biological, chemical and physical investigations of local waters.

CONCLUSIONS

The derived long-term tolerance levels in ambient water below which minimal disruption to coral communities should occur are summarized in Table 10. The waste discharges considered are those effluents consisting principally of sewage although the ambient levels are probably applicable irrespective of source. These levels are conservative ones, since synergistic or additive deleterious effects are possible, but difficult to quantitate. It is also difficult to gauge the effects of natural stresses such as turbidity, temperature, salinity, borers and <u>Acanthaster</u> <u>planci</u> to coral ecosystems already stressed by waste discharges.

Table 10. Summary of derived coral maximum tolerance levels in ambient water[a]

Water Quality Characteristic	% increase over ambient levels	Quantitative estimate of tolerance levels
Suspended material	28	3.85 mg l^{-1}
Sedimentation rate		30 mg cm^{-2} day^{-1}
800	19	0.84 mg l^{-1}
Chlorophyll a	48	0.59 mg m^{-3}
PO_4^{3-}	23	0.25 µg at l^{-1}
NH_4^+	285	0.65 µg at l^{-1}
NO_2^- and NO_3^-	285	1.31 µg at l^{-1}

[a] derived on the basis of a tolerance of 20% growth decrease

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MONITORING TREATMENT AND MANAGEMENT OF NUTRIENTS IN WASTEWATER DISCHARGES TO THE GBRMP

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SUMMARY

Runoff and sewage discharges from tourist resorts can cause serious adverse impacts on coral reef communities. These impacts result from both the contaminants contained in the discharges and from the freshwater carrier, itself. Of the many components of sewage, the nutrients nitrogen and phosphorus appear to cause the most severe adverse impacts.' The main effects of nutrients on corals appear to be indirect. The higher nutrient levels result in increased algal growth which can ultimately lead to complete destruction of the delicately balanced coral reef ecosystem, The available evidence implies that denitrification and phosphorus removal are necessary treatment requirements if acceptable levels (after dilution) of these components are to be achieved in the different microenvironments within the discharge region. A significant effort is required to gather the relevant evidence on both the microscale and macroscale effects of nutrients in the GBRMP.

INTRODUCTION

Corals have the ability to thrive in nutrient-poor conditions; Salin (1983) notes they are like oases in the desert. Biologically, coral reefs'. are among the most diverse and most productive of all natural ecosystems. Johannes (1972) notes that these reef communities not only provide a vital source of protein for man but also are a source for a wide range of pharmacologically active compounds. Coral fringing-reefs, atolls and barrier-reefs provide protection from the seas for tropical islands and some continental coastlines and are a valuable tourist resource.

Runoff, groundwater and sewage discharges from tourist developments can adversely impact on coral reef communities. In order to predict the impact of such discharges, one needs to be able to define the tolerance levels of the various contaminants in the discharges. Once derived, these tolerance levels can be used to evaluate various waste-management options. This paper summarises such tolerance level data as derived for the Great Barrier, Reef (GBR) Australia (see Bell et al. 1987 for details). Some available options for the treatment/disposal of waste water discharges are also discussed.'

WASTE DISCHARGE SOURCES AND THEIR IMPACT

The main contaminants in sewage and run-off are listed in Table 1. Typical concentrations for many of these are given in Tables 2 and 5.

It is noted that in regions with significant rainfall the total annual contaminant loads from run-off can greatly exceed those from the discharge of sewage effluent. In this respect it is important to note that the freshwater itself needs to be considered'& a contaminant, because corals have a limited tolerance to hyposalaine conditions. The intensity of run-off events needs also to be considered; one high intensity storm could effectively destroy a nearby fringing reef.

The detrimental effects of sewage, run-off, and even groundwater discharges have been recognised for sometime (eg. see Pastorok and Bilyard, 1985; Tomascik and Sander, 1985). Pastorok and Bilyard (1985) note that coral-reef ecosystems are extrenely sensitive to environmental perturbations and that this high sensitivity is linked to three factors:

(i) corals have narrow physiological tolerance ranges for environmental conditions

(ii) the interactions of key reef species eg. algal-coral competition are susceptible to pollutant stresses

(iii) the effects of toxic substances may be enhanced by the high water temperatures common in coral reef environments.

The impacts result not only from the contaminants contained in the discharges but also from the freshwater carrier itself. The effects may be localised as is usually the case for BOD and freshwater or may be of a regional nature, as can be the case for nutrients such as nitrogen and phosphorus. Nutrients can affect corals directly through toxic effects or indirectly by promoting a eutrophic environment. Available evidence indicates that many of the impacts associated with waste discharges are synergistic in nature and it appears that the coral ecosystems are relatively intolerant to such disturbances. For example the detrimental impact of a sedimentation load would be magnified if at the same time there is a significant change in the salinity. Another important point to note is that not all impacts will be immediately observable. For example phosphorus levels could be such that deoreased calcification rates are occurring whereby the coral becomes less structurally sound. A single storm event following a prolonged elevation of phosphorus could destroy a reef. Also a combination of increased nutrient levels from continuous waste discharges with a storm run-off event (with the associated freshwater, turbidity, BOD and nutrient loads) could have disastrous effects. In such cases the sudden salinity drop and turbidity increase can cause widespread damage and even mass mortality of existing corals. The main effect of the nutrients is manifested after the event by promoting the growth of opportunistic algae. The algae would prevent the otherwise natural re-establishment of the corals. It is to such a sequence of events that Smith et al. (1981) attribute much of the destruction in Kaneohe Bay. In choosing tolerance levels, therefore, it is advisable to take a conservative approach.

TOLERANCE LEVELS

Tolerance levels for the various contaminants contained in sewage and run-off have been derived (see Bell et al. 1987 for details). These levels are given in Table 5. The derivation of these levels was based mainly on data collected from coral reef-regions around the world and by the use of procedures recommended by the USEPA for marine waters (Water Quality Criteria, 1972). It is stressed that these levels should be used with extreme caution, they are guidelines only.

NUTRIENTS (N and P)

At high levels nutrients such as phosphorus have been noted to have a direct toxic effect on corals (Pastorok and Bilyard, 1985). Kinsey and Davies (1979) conclude from results at Canton Atoll that $P-PO_4$ levels as low as 0.6 µM can cause significant (>50%) reduction in the calcification

rate (and hence growth rate). On the basis of calcification rates alone it would seem that any significant increase in the average background level -0.2 µM · 0.3 µM in regions of the GBR such as Lizard Island (see Table 3) would lead to significant decreases in calcification rates.',,

TABLE 1 Direct Discharge Sources,

Source	Main Contaminants
Sewage (including laundry and kitchen waste)	Biological Waste (BOD) Nutrients (eg. N and P) Surfactants, dispersants Suspended Solids Fresh Water (hyposaline)
*Swimming Pools	Chlorine, algicides, freshwater
*Airconditioning Units Power Houses	Freshwater Heated water Algicides, antifouling agents, hydrocarbons
*Desalination Plants	Hypersaline water Heated Water
*Industrial Plant	Various (eg. hydrodarbons, heavy metals)
*Laboratories	Chemicals
Run-off	Fresh water Suspended solids Nutrients (eg. N and P) Herbicides from gardens Pesticides Biological Wastes (BOD) Hydrocarbons · from roads

* Note all of these wastes are usually disposed of with sewage

TABLE 2 Typical Average composition of. Urban Run-off

Component'	Concentration
BOD_5	30 mg/l
Total · P	0.5 mg/l
Total · N·	2 mg/l
Suspended Solids	'100 mg/l

TABLE 3 Characteristics of Great Barrier Reef Waters

	North Shelf[2]		Lizard Island[3]		Outer	Central(')	Davies Reef[4]		One Tree[5]	
	Central	Edge	Across Reef	Offshore	Lagoon	Coral Sea	Inside Reef	Outside	Reef	Off Reef
Suspended Particle Matter (mgl^{-1})					$3.0^{(6)}$					
PO_4-P (μM)			0.22	0.26	0.13	0.13	0.105	0.105		
'Total Inorganic-N $(NO_x+NH_4)(\mu M)$	0.17*	0.15"	0.99	1.02	0.88**	0.07**	0.39""	0.05""	7.06	0.31
C:N:P atomic ratio in macro-algae (Aug)							485:45.5:1			
Chlorophyll-a (μgl^{-1})					0.13	0.39				

NOTES:

* $NO_3^- + NO_2^-$ Aug

** $NO_3^- + NO_2^-$

(1) Andrews (1983)
(2) Cresswell and Greig (1978)
(3) Crossland and Barnes (1983)
(4) Entch et al. (1983)
(5) Hatcher and Hatcher (1981)
(6) Wolanski et al. (1981)

Also, as noted above, corals have,the ability to thrive in nutrient poor conditions. The long-term addition of relatively small amounts of nutrients can cause major imbalances in existing coral reef, systems by promoting the growth of attached and planktonic algae; Attached,algae affect 'the coral by interfering with the complex life processes which normally occur at the coral surface (eg. by competition for light and nutrients). Planktonic algae also competes for light and nutrients. An additional problem with the planktonic algae is that they add to the sedimentation load • this causes additional stress to some coral species and encourages the growth of benthic filter feeders, which will directly compete with the corals for space.

It is interesting to note that whereas large outfalls in well flushed (ie. turbulent) open-coast regions appear to have minimal (at least in the short term) impact on coral reefs (Pastorok and Bilyard, 1985) small scale discharges if not effectively flushed can cause severe problems eg. Johannes (1972) has reported that seepage from a single cesspool serving a public restroom in Honaunau Bay has brought about the localized degeneration of the nearby coral community. Benthic (attached) algal populations were found to be larger than normal in this area, with much of the coral dead and encrusted. <u>Porites compressa</u> was the coral species found to be most susceptible to the effects of sewage effluent. The <u>Porites</u> genus is the major reef-building coral in Hawaii, and is also very common on the Great Barrier Reef (Domm, 1976).

At this stage the extent of the control that is required for the GBR is unclear but it is recommended that because the background levels are high and are in fact at or around levels that would be considered "polluted" in Barbados or Kaneohe Bay that only small increased in the background levels be accepted. Hence levels corresponding to 10% increases in background P-PO$_4$ and inorganic-N are taken as the required <u>tolerance levels.</u> These levels would need to be achieved within the initial dilution zone of a submarine outfall if it is located in the vicinity of coral reefs.

Increased phytoplankton growth in turn leads to an increase in the suspended solids concentration and, hence, an increase in the sedimentation load. Sewage and run-off themselves can both contain a significant load of suspended materials. The resultant increase in suspended solids can have a devastating effect on corals. In general the growth of coral is inversely proportional to the turbidity which is related to the suspended solids concentration. This due to the light requirements of the zooxanthellae within the tissue of the reef-building corals. The sediment can indirectly cause stress in corals by reducing light intensity. Sedimentation also affects corals directly by deposition on exposed coral tissue. This sediment must be removed to prevent suffocation , and the effort required by the coral to remove the sediment expends energy. If this is' excessive the coral is stressed.

DISPOSAL OF SEWAGE DISCHARGES

Table 4 summarises the options available to limit the concentrations of nutrients entering the GBRMP from tourist developments.

TABLE 4 Options for Controlling Concentrations of Nutrients in
            Wastewater   Discharges

DILUTION

TREATMENT   · Physical
                                   · Biological
                                   · Biological/Chemical
                                   · Chemical

CONTROL AT SOURCE (ie. reduce nutrient entry to waste disposal
                        system by use of phosphorus free detergents
                        for   example)

Marine   Disposal

Sewage from coastal tourist areas is usually disposed of via submarine
outfalls.   These outfalls are designed to use the natural processes of the
receiving water to dilute and disperse wastes so that the discharge is
assimilated by the marine ecosystem without significant adverse
environmental 'effects.   This method often incorporates the use of a
diffuser to achieve a localised dilution factor required by the discharge
licence. High capacity ocean outfalls can achieve initial dilutions in the
range 50 · 200. Subsequent dispersion and decay of wastes occur as the
effluent field is transported from the initial discharge zone by the
prevailing currents.   The dilution rate available in this secondary
dispersion zone is usually much less than that in the initial dispersion
zone, hence, it is important to achieve as high a dilution as is
practicable in the initial dilution zone.

Required Dilution for Coral Reefs

The required dilution ratio (F) for the various contaminants is readily
calculated from the discharge concentration data, if the background levels
and the tolerance levels are available:

$$F = \frac{C_{discharge} \cdot c_{tolerance}}{C_{tolerance} \cdot C_{background}}$$

The required dilution factors for a number of the components of primary
(1°), secondary (2°) and tertiary (3°) treated domestic sewage are given in
Table 5.   It can readily be seen that of the major components BOD_5 and the
nutrients N and P require by far the highest dilutions ($10^3 \cdot 10^5$). The
levels of dilution required for phosphorus and nitrogen are particularly
high.   It is clear that if the dilution criteria for the nutrients are met
then the criteria for all other components, both major and minor, should
easily be met.   However, it is stressed here that such high dilutions are
not normally achieved with conventional outfall systems;   an initial
dilution of the order of 10^2 is generally considered as being good.

Theoretically high dilutions of the required orders ($10^3 \cdot 10^5$) could be
achieved with correct (non-conventional) diffuser design if suitable
locations for discharge were available. Basically what is required is that
a diffuser of sufficient length, located at sufficient depth be used.
Typically, diffusers of lengths 10 · 100 m set at depths of 10 m or more

3

TABLE 5 Required Dilution Ratios for 1°, 2°, and 3" Treated Sewage for Waters of the Great Barrier Reef, Australia

Contaminant	$C_{discharge}$ Concentration in Sewage			$C_{tolerance}$ (%Increase over back ground) Tolerance Level	$C_{background}$ Background Level	F Required Dilution Ratios		
	1"	2°	3 "			1"	2°	3'
$BOD_5 (mgl^{-1})$	300	20	10	0.78 (10%)	0.71^+	4300	270	1 3 0
$NFR (mgl^{-1})$	300	30	10	3.3 (10%)	3.0^{++}	1000	90	20
Inorganic-N (μgl^{-1})	50000	20000	2000	15.4 (10%)	14^{**}	36000	14000	1400
$P-PO_4$ (μgl^{-1})	10000	10000	1000	7.5 (10%)	6.8^{**}	14000	14000	1400
Chlorine (μgl^{-1})	700	<700	<700	50	0.0	13	<13	<13
Salinity (ppt)	1	1	1	30	35	6	6	6
Pesticides (μgl^{-1})	1	<1	<1	10	0.0	0	0	0
Heavy Metals (μgl^{-1})								
Hg	3	<3	<3	0.1	0.0	30	<30	<30
Pb	70	<70	<70	10	<0.06	6	<6	<6
Zn	70	<70	<70	20	0.13	2.5	<2.5	<2.5
Cu	150	<150	<150	1	0.22	190	<190	<190
Ni	50	<50	<50	2	0.11	25	<25	<25

*   Total oxidiseable nitrogen
**   Values for Lizard Island (see Table 3)
\+   Barbados value
-t+   Estimated from Wolanski (1981)

may be required to achieve adequate initial dilution. The long diffusion lengths imply the use of additional pumping energy to distribute the discharge stream uniformly along the diffuser.

Control of Phosphorus in Effluent Discharges

The sensitivity of coral ecosystems to increased phosphorus levels requires extremely large dilution factors for effluents from both primary (1°) and secondary (2°) treated sewage (see Table 5). Even the required dilution factor for tertiary treated (3°) sewage is an order of magnitude greater than what is normally achieved with conventional marine outfall systems. To a large extent the phosphorus concentration in the sewage will determine the cost of the treatment/disposal system. Hence, it is worth considering the control of phosphorus at source. It is noted that usually one half the phosphorus in sewage results from the use of detergents and shampoos. Considerable cost savings in the disposal of sewage effluent would be achieved if this source were eliminated by substitution with phosphorus-free washing materials.

Sewage Sludge Disposal

Due to the fact that sewage sludge tends to concentrate many harmful constituents (eg. heavy metals, toxic organics, nutrients), discharge of sludge to the marine environment should never be considered as a disposal option. Land disposal of sludge on island resorts is currently practised. However, this disposal option needs to be looked at carefully as there is potential for this sludge to be a significant source of pollution of the groundwater, surface water and ultimately marine water.

Reuse/Recycle of Treated Effluent

Most of the tourist islands in Australia now experience some difficulty in obtaining adequate quantities of good quality water. As the population increases, possibly by more than 400 per cent over the next 25 years, the demand for water will similarly increase to more than 1 000 megalitres per year (Smith, 1985). This growth factor is very much dependent on future commercial decisions affecting tourist development. With the current rate of development of resort islands, the need for increased 'fresh water' supplies is expanding which in turn is increasing the production of hypersaline effluents from desalination plants. There is some potential for re-use of waste water on the islands. Techniques and processes are available to treat waste water to standards which would allow its use for non-domestic purposes such as garden and lawn watering. However, tne impact of such waters on the groundwater system and consequently the marine water system needs to be evaluated.

Run off

Run-off from developed areas and construction areas 'can contribute large loads of suspended solids, nutrients, BOD_5 and toxic organics (eg. pesticides and herbicides) in addition to the extremely large fresh-water load itself. Development per se not only tends to increase the quantity of run-off but also tends to reduce its quality.

Run-off from island resorts is particularly important due to the potential impact of the fresh-water itself on the fringing coral reefs. As mentioned earlier, many coral species are particularly sensitive to low salinity.

Run-off is not easily controlled, especially after the development is complete. Possible strategies to minimise the impact of run-off depend on whether, the situation represents an existing or a new development.

Existing Developments,

Run-off from,existing developments is an extremely serious problem as most developments are located in front of fringing reefs. This run-off needs to be diverted to some type of storage area. The water could then be used on the island or discharged in a controlled manner via submarine outfall so that sufficient dilution could be achieved. Nutrient removal prior to discharge may be required.

It is noted that a principal source of nutrients in run-off is fertilizers. The use of fertilizers should be discouraged.

Future Developments

All future developments should be designed to minimise the impact of run-off on the fringing reefs. One way to ensure this would be to forbid any development near to the fringing reefs. Other factors to be considered are:,

   the minimization of disturbances to the existing landscape
   the minimization of sealed areas such'as roads and parking areas
   the use of Australian native shrubs and trees in preference to exotic
   plants and lawns · such native plants normally require little or no
   fertilizer; lawns increase run-off and require fertilizer
   the use of contouring to divert run-off to storage areas. The storage
   areas could be either of a permanent type (eg. dams) or a temporary
   nature eg. large low lying land areas from which evaporation would be
   enhanced

MANAGEMENT STRATEGY

In proposing a management strategy from nutrient control in the Great Barrier Reef Marine Park, the following premises are assumed:

*   Phosphorus and nitrogen are limiting nutrients in GBRMP for corals.,

*   Circumstantial evidence implies elevated N and P levels lead to deleterious effects in reef environment

                   chronic
     (a). direct'
                'synergistic

     (b) indirect · algal growth

*   Uncertainty exists as to critical levels of N and P. These levels will be known more exactly in future (ca 0.22 μM PO_4-P)

*   Costs of removing N and P from all wastes are high, especially if very low levels of P must be achieved.

*   A management strategy is needed in the short term.

*   Enforceable management strategies must include measurable water quality and waste discharge variables.

* The GBRMP can be considered as a series of macro regions (eg. Whitsunday Passage) and micro regions (eg. Hamilton Island and surrounding reef areas)

The major current needs are as follows

* Collection of more data and greater interpretation of existing data

    • Gather, coordinate
    • Extend
    • Standardise

* Development of a flexible Management Strategy

    • Existing discharge limitations, use of dilution, proper location of discharge points; probably acceptable in short term but highest risk.

    • Addition of nutrient limitations to discharge streams; more costly, lower risk.

    • Addition of water quality criteria to permits; more difficult (Political, Legislative) but lowest risk.

* Increased educational activity

    • Existing and new developers

    • Visitors

For macroscale regions (ie GBRMP as a whole or for large regions within), the current evidence of nutrient induced problems is insufficient for widespread changes. in legislation. There is a need for a Total P budget over the Marine Park and over specific regions. In addition, there is a need to bring together and extend existing data to establish background levels throughout the GBRMP and specific regions. This will require more sampling and fewer analyses for fewer components.

At the microscale (ie. individual resort or development), a number of specific recommendations can be made:

* For a limited number of existing developments, establish links between specific water quality parameters and reef condition.

* Establish relevant water quality variables in the region of development relative to background levels away from the development.

* Require water quality within a defined region near a development to be maintained at some level relative to the background levels. This can be done by controlling point discharges and controlling run off.

* Establish the importance of runoff and groundwater in affecting fringing reefs.

The management options are summarised in Table 6.

TABLE 6 Management of Nutrients

Macrosys tern:	(1) Control Quantities Entering GBRMP
	(2) 'Control Total Quantities Discharged Within GBRMP
Microsystem:	(1) Control of Specific Point Discharges
	(2) Control of Non-point Discharges
	(3) Control of Water Quality Near Development Relative to Background Levels away from Development.

CONCLUSIONS

Run-off and sewage discharges from tourist resorts have the potential to cause serious adverse impacts on coral-reef communities. The components of most concern are the nutrients nitrogen (N) and phosphorus (P). The available evidence implies that coral reef environments are particularly sensitive to small increases in the background phosphorus level. This means that reefs in the vicinity of small discharges and reefs at some distance from larger discharges can be seriously affected. The available evidence also implies that denitrification and phosphorus removal are necessary treatment requirements if acceptable levels (after dilution) of these components are to be achieved

In regions with significant rainfall, efforts need to be made to ensure that run-off is not discharged in the vicinity of fringing reefs. Run-off should preferably be stored and reused, or discharged through a submarine diffuser. Treatment prior to discharge for the removal of nutrients may be necessary.

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ALGAL OVERGROWTH- DOES **IT** RELATE TO NUTRIENTS FROM TOUR VESSELS AND PONTOONS.

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INTRODUCTION.

'At the Agincourt Reef complex, **40 miles** northeast of Port **Douglas,** the two **large,** fast catamarans, **Quicksilver 1** and **Quicksilver 2, visit two** permanently moored pontoons situated at Agincourt 16013-d and at Agincourt 3, **bringing with** them up to 290 passengers **daily.**

Biologists from Reef **Biosearch visit** the **same snorkelling sites on** these reefs **daily.** **In** December 1986, **it was noticed** by Dr A. **Ayling** and **ourselves** that a mustard coloured **algae** was appearing **in** one area and was apparently causing **mortality in** some **corals.**

It was thought that **this could** be a summer phenomenon **which would die** out over **winter.** However the **algae continued to** expand over the **cooler** months. **In July 1987 it** was **decided to** study the **alga in** more **detail** and **to examine its distribution in** the **Agincourt complex.**

METHODS OF STUDY.

1. bverall distribution.

All backreef areas of the Agincourt **complex** have been surveyed **using two snorkellers swimming 10** to 20 metres apart to 'detect presence'or absence of the **algae.** The **total** distance covered **using this** method **is approximately 8 miles.'**

At **sites** where the **algae is** present **its distribution'has** been mapped,. **With** the use of **aerial** photographs taken at 5,500' and 2,500',known features on the reef could be **plotted** and **baselines established so** the geographical **distibution** of the **algae could** be mapped.

Within areas of **algal** presence, a **series** of 4 adjacent 0.25m by 0.25m quadrats were permanently marked and % cover of the **algae was estimated.** These quadrat **sites** were scattered **at** strategic known **positions** on the distribution map.

2. Benthic Line Transects.

A series of permanent 20m variable **direction benthic line intercept** transects have been **established at** the two reefs **with** moored pontoons. At each, **3 localities** each **with 5** transects have been **set** up **using fishing line and flagging** tape to mark the exact course of the transect. A total o f 600m of transect has been **established. Intercepts** of **all** benthos >1cm **is** recorded. **Corals** are **identified to species** where **possible. Data is collected bimonthly at** pontoon **sites** and quarterly at the **remaining sites**

RESULTS.

The **Alga- Identification** ∧ Methods of **Reproduction** and Attachment.

The **alga has** been **tentatively identified** by Dr **I. Price as** Chrysophaeum taylori **with affinities** to the Chrysophyta. The only record the author has found on **the alga was** when **it was first described in 1941 in the Carribean (Lewis et al, 1941). It is a unicellular alga which** forms **colonies 1-6cm in height** of a tubular shape. **Its colour is** a mustard **yellow.** The **cell is** pear shaped **with a** base at the neck **to which is attached a** group of **fine** threads. One'of the **field characteristics of** the **alga is its** extreme **fragility-** the mere waft of a hand **is sufficient to** break **it into tiny pieces. It is** probable that the threads are an important attachment mechanism at the **cellular level** and **its fragility merely** enhances **its distribution.** The **alga** reproduces **asexually** by zoospores but **its sexual** reproduction has not been recorded.

Microhabitat Preferences.

The **algae preferentially attaches to unconsolidated coral rubble, usually** from **branching corals.** However, when space **is limited** by **its** own **high** cover **it will attach to live branching corals.** The **corals** that appear **to** be most **readily** affected include-

Por. i tes cylindr ica
Por i tes nigrescens
Echinopora horrida
Hydnophora rigida
Paraclavarina triangularis
However Seritopora hystrix and some corymbose **Acroporiids** may also be affected (eg: A. cerealis, A. nana, A. nasuta). I n November 1987, the first evidence of **algal** growth on **massive corals was** observed on Lobophyllia ,Symphyllia and Platygyra.

When the algae is rubbed away from the live coral, the t issue often appears **healthy** beneath (no signs of stress or **bleaching). At** other **times the** coral **is obviously recently**

dead beneath and around where the **algae** grows.

Geographical Distribution.

There are many' **algae** that attach to the dead bases of **coral colonies** and some that even grow over **live corals,** however,' Chrysophaeum taylori has **only** been found **at two localities on,** Agincourt 16013d, where the **original** pontoon has been **established** for **nearly 4** years. These **localities** are the Eastern and Western points of the reef. The **algae is virtually** absent from the **central backreef** area where the pontoon **i's sited. It** has **only** been recorded at depths greater than 3.5m, **probably** because of **its fragility** and **susceptibility to wave action. Its** presence has been **confirmed** at15m but the maximum depth for growth has not been **estabished.**

The areas of **algal** presence expanded **considerably** from August to October 1987, **beginning as isolated** pockets **which** both spread outwards at the rate of about 4cm/ month, and disseminated to form new **clumps** nearby. One **clump** 8cm across was found in November 1987 adjacent **to** the **central** pontoon **in** an **otherwise algal** free' area,.

In the areas of **heaviest algal** growth, cover of up to 65% has been recorded **using the** quadrat method. The second set of data from the permanent benthic **line** transects **is now** due for **collection** and **will** be very **useful in determining temporal** change in **algal cover.**

Predators.

There are **large** numbers of roving herbivores **in the** area **i n c l u d i n g** Scarids (S. rivulatus, S. altipinnus, S. sordidus) and Acanthurids (A. xanthopterus). Most **observations have** shown fish to **select algae** other than C. taylori. An **exeption is** Zebrasoma **velliferum which** has been seen on occasion to eat **this species.**

DISCUSSION

Possible Causes of Algal Overgrowth.

At present **we** have **insufficient information to determine** whether **this particular alga is expanding** because of some **"natural"** cause, or whether **its** growth can be related to human use of the reef.

Natural perturbations **which could contribute to its expansion**

include cyclical phenomena, **El Nino** or more **likely a** combination of **several** factors. **If** the **previous distribution** of the **al-ga was** not **cosmopolitan,** perhaps the **increase in international diving tourism** has brought **algal** spores to **Barrier** Reef waters and **we are seeing** the **initial stages** of what **could** be an increasing problem.

If human use of **this** reef by the pontoon **and tour vessels is a catalyst'for this algal** overgrowth, it seems **likely that** nutrient **input** may be a key factor. **Because** of **this possibility,** Quicksilver now records **daily information regarding** the **different categories of nutrient input. This includes;**

1. Food scraps. (Number of buckets of meat scraps **entering** the water)

2 . Seabird faeces.**(Total** numbers of **birds** present on the pontoons and moored **vessels** are recorded **as** the Qucksilver approaches.)

3. Algal growth on **vessel hulls. (This is** scrubbed off about once a week- **estimates** of dry **weight** per square meter **will** be measured.)

4. "Island effect." The pontoon creates an **artificial** substrate for **algae** and other benthos which **helps maintain a large population of** browsers **(especially** Siganus spp and Xyphosus sp.**) This probably helps** to concentrate and **recycle nutrients in the pontoon vicinity.** Measurement of faecal **fallout at** the pontoon **could** be used to compare **with** control sites.

5. Sullage. This is not discharged at the reef, but is pumped out **in** the **shipping channel 15m SE** of the reef **site. Occasionally** there **is** a malfuntion **in a** rubber **seal** producing **a continuous drip so** the **outflow pipes are** checked **twice daily.**

If **it is** nutrients from the pontoon **causing algal overgrowth, an explanation as to** why **it is** densest away from the pontoon needs to be put forward. One **possiblity could** be current regimes. Because the reef faces SE, **during** the SE trades **it** has been noticed that eddy systems **develop** at the East and West **point of the reef. Possibly these eddies** draw water from the **central-section** and trap **it** and any nutrients **it holds, in** these areas. Further **investigation with** the use of drogues or dyes may be useful **in answering this question.**

Different species of **algae** may cause **overgrowth on nutrient rich** reefs. The **physiological adaptations** of the species, **its ability to vegetatively** reproduce and **its** dominance amongst other **species** at the commencement of **nutrient input may** determine which species **will predominate. For example Norman Reef,** where the **Hayles** catamarans **visit, have experienced comparable algal overgrowth of a different species,** however **this** may be a short term summer phenomenon.

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R.E.F.E.R.E.N.C E S

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A CASE HISTORY FROM TONGA: THE DEGRADATION OF FANGA'UTA LAGOON, TONGATA

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INTRODUCTION

The effects of urbanization, changing land use, pollution and overfishing are most apparent on coral reefs of the Third World nations of the South Pacific and South-East Asia. Australia, the only developed nation with significant areas of coral reefs, can learn much about anthropogenic effects on reefs from the misfortunes of others.

Fanga'uta Lagoon is a shallow, almost enclosed embayment in the northern coastline of Tongatapu Island, the main island of the Kingdom of Tonga in the South Pacific (Fig 1.). It was once the focus of the island; the ancient capital of M'ua lay on its western shore, and its waters provided shellfish and fish, particularly mullet.

The pressures on the island's meagre resources have intensified this century. During the past 80 years Tongatapu's population has grown eight fold, to about 60,000. Urbanization has been rapid; Nuku'alofa, the modern capital, has grown from 3,000 to 30,000 in 50 years (Crane, 1979).

Added pressure was placed on the lagoon's fisheries to 'meet the new urban demand for fresh fish. Traditional subsistence fishing techniques were replaced by more efficient monofilament gillnets, arrowhead fish fences, and a trawl fishery for penaeid prawns, and the use of explosives was common. The cichlid Tilapia has also been introduced, possibly competing with native species. The results of the increased fishing pressure has been dramatic; the lagoon fisheries virtually collapsed in the mid-1970s (W. Wilkinson, pers comm.).

Although commercial fishing was banned within the lagoon in 1975 the prohibition has never been strictly enforced. While the fish fences were removed from the lagoon, they were placed immediately outside the entrance where they continued to catch grey mullet migrating to and from the lagoon.

The general ecology was also greatly disturbed. Much of the lagoon has shoaled and the cover of mangroves, seagrasses and algae has increased. Water quality has declined; storm water drains and untreated sewage now discharge directly and indirectly into the lagoon. E. coli levels are high and typhus and other gastro-intestinal diseases are a major health problem in villages around the lagoon (Ludwig, 1979).

The following **briefly** summarizes the major findings of a joint
study of the ecology, hydrography and fisheries of Fanga'uta
Lagoon by the University of the South Pacific and the University
of Hawaii, under the International Sea Grant Program, in 1981
(Zann, Kimmerer and Brock, 1982).
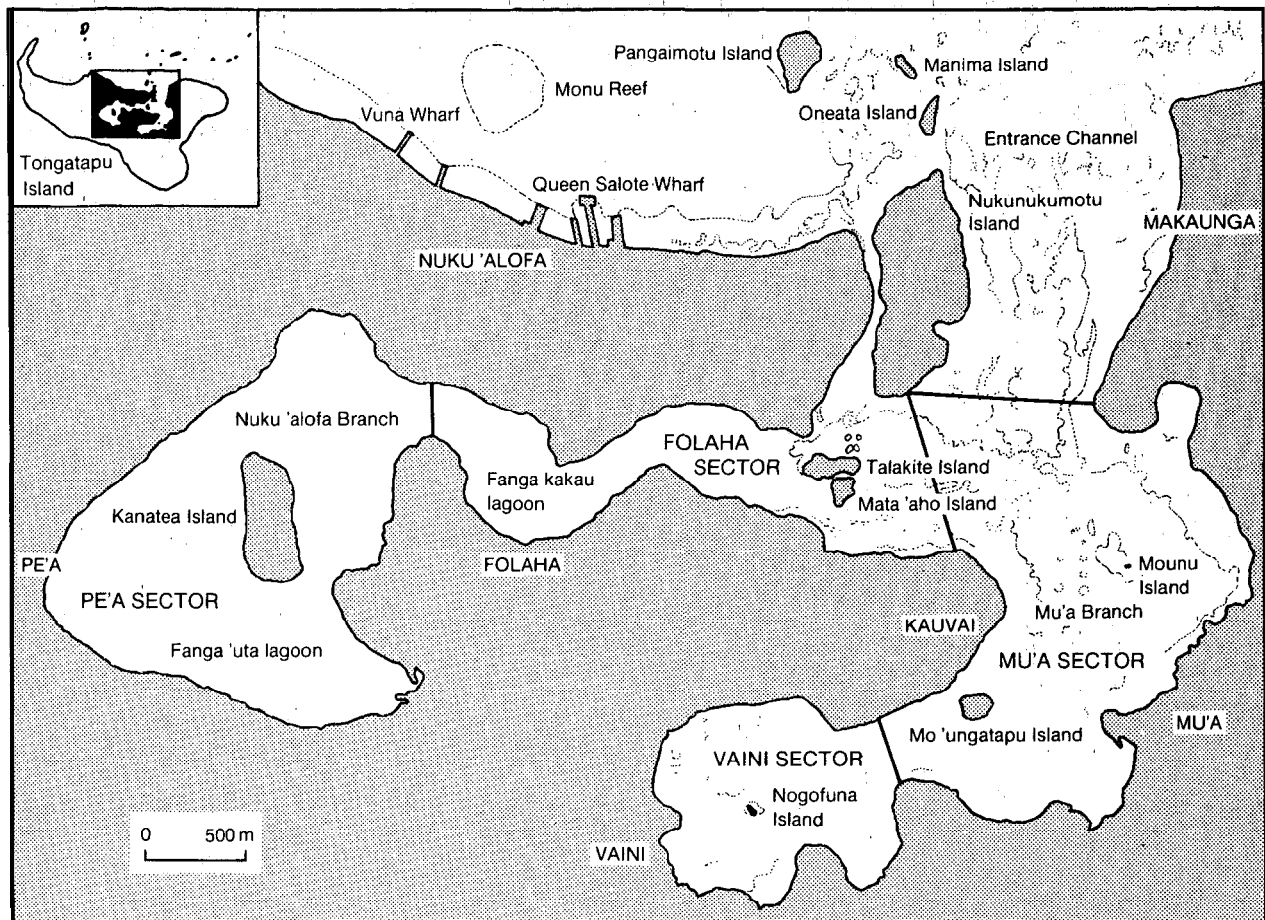
Figure 1. **Fanga'uta** Lagoon, Tongatapu

GEOMORPHOLOGY AND GEOGRAPHY

Tongatapu is an uplifted Pliocene/Quaternary coral reef. It lies
on a geologically active zone along the edge of the Fijian and
Pacific plates and has been progressively uplifted and tilted in
very recent geologic time.

About 40km in length, the island is surrounded by fringing coral
reefs. Platform reefs, some with sand cays, lie offshore on a
submerged shelf on the northern side. The lagoon fills a bi-lobed
depression in the centre of the island.

Fanga'uta Lagoon is about 27 sq.km in area, with a mean depth of
1.4m and a maximum of 6m. The two lobes (Nuku'alofa and Mu'a) are
naturally divided into four sectors (Fig. 1), of which the Pe'a
sector is the shallowest (mean depth 0.8m). The shallow areas are
extremely turbid, as fine bottom sediments are resuspended in
moderate winds.

The main opening consists of a wide intertidal reef flat (+0.2m to -1.0m datum), bissected by a channel (5.6m deep). The southern end of this subdivides into several channels which feed the two major branches.

The lagoon's watershed of 80 sq. km supports a human population of about 40,000. In Nuku'alofa which lies along the low northern and western shores of the lagoon urban planning has been minimal. Most. sewage discharges into the ocean although the hospital discharges untreated sewage directly into the shallow Pe'a sector of Fanga'uta lagoon. Dissolved wastes from domestic septic pits enter the lagoon via groundwater, or directly during floods. Wastes from an industrial estate (warehouses, paint factory, light manufacturing etc.) and the island's diesel power station, which has a cooling main to the lagoon, are potential sources of pollution. Some leakage of fuel oil from the power station was seen during this study.

About 99% of Tongatapu has been cleared for cultivation, mainly of copra, taro 'and bananas and about 40% of farmers regularly use chemical fertilizers, 23% use insecticides and 26% use fungicides (Crane, 1979). Although the island lacks streams, agricultural chemicals may also enter the lagoon via the groundwater..

Although commercial fishing is prohibited in the 'lagoon, subsistence fisheries are still permitted. Major techniques include gillnetting, line and spearfishing, fish drives, crab trapping, and gleaning and wading for invertebrates. About 90 outrigger canoes (paopoa) and 40 punts and skiffs were based in the lagoon in 1981 (Zann, 1982).

ECOLOGY

Coral dominates the benthos of the ocean (northern) entrance to the lagoon but rapidly declines in diversity and abundance along the channel (Zann, 1982). Only one species (Porites sp.) persists into the relatively well flushed Mu'a sector and none are found in the other sectors (Fig.2). Large areas of dead Acropora, some partially standing, and extensive rubble banks at the subtidal lagoon (southern) end of the entrance indicates that a large scale, and relatively recent disturbance has occurred. Because there has been little or no subsequent recolonization of Acropora in this area the problem appears to be a chronic one.
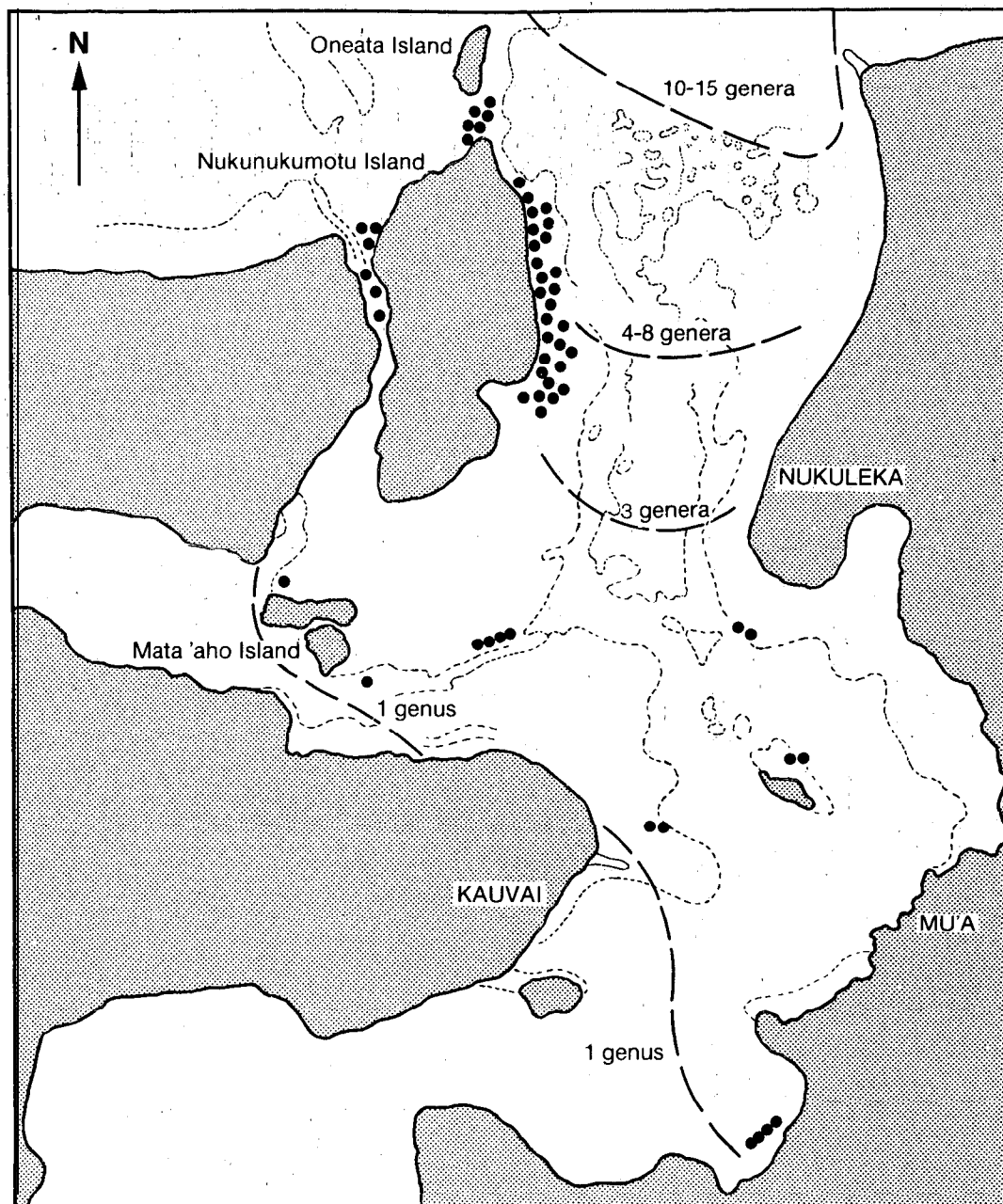
Figure 2. Genera of stony coral at dive sites, **Fanga'uta Lagoon**

The coral mortality has extended intertidally. Hundreds of large (2-3m diameter) Porites and faviid microatolls are, present on the reef flat surrounding Nukunukumoto Islet at the ocean entrance to the lagoon. Their general state of preservation also suggests a relatively recent time of death (decades or 'centuries ago), while their higher elevation (30-40cm) than living Porites microatolls in the vicinity indicates a sea level change was the cause of **death**. A major earthquake earlier this century is known to have caused some uplifting in **Nuku'alofa** (**S**. Tonganilava, pers. **comm.**).

The calcareous alga <u>Halimeda discoidea</u> dominates intertidal **reef** flats at the southern entrance. The seagrasses **Halophilia ovalis** and <u>Halodule pinifoliosa</u> are abundant on the **reef flats and extend** into the lagoon, particularly into the Vaini sector. Algae, dominated **by** <u>Caulerpa</u> **spp.**, extend subtidally, but decrease with depth. **Brock (1982)** estimated the average wet biomass of seagrasses and algae in the lagoon was 562 g/m2 (wet weight) (Table 1). The total benthic **production** of seagrasses and algae was estimated to be 2,723 tonnes C/year.

The fauna of **Fanga'uta** is relatively diverse: 32 species of cnidarians, over 40 species of **molluscs**, 14 species of crustaceans, 18 species of echinoderms (Zann, 1982) and 96 species for fish **(Brock,** 1982).

HYDROGRAPHY AND CIRCULATION

The **lagoonal** circulation is driven predominantly by tides (Kimmerer, 1982). The ocean tidal range of about 1m drives a current of up to 2.6 knots in the main channel and because the channel is constricted and shallow, the **lagoonal** tides lag behind the ocean and are of lower amplitude (eg. **Nuku'alofa** branch **0.13m** range, lagging 3-4 hrs).

As there are no rivers or streams on the island, freshwater input into the lagoon occurs from the **groundwater** lens, and direct rainfall. An average input is ca. 2.6×10^3 m^3/day, of which 85% enters through diffuse 'subsurface springs and 15% from solution channels on the shore.

From models of the freshwater input and tides, the residence time of water in the lagoon was estimated to be 23 days. Mixing on each tidal excursion is only about 12%; most of the water entering on the flood tide leaves on the following ebb tide without mixing.

WATER CHEMISTRY

Kimmerer (1982) found that nutrient levels in the surrounding ocean were low while those in the groundwater were high (Table 2). Nitrate and silica levels were much higher than normal but phosphate was not abnormally high. Nutrient levels in the lagoon were much lower (Table 3) indicating that it is very rapidly taken up by plants.

Kimmerer's mass balance model of total nitrogen and dissolved silica fluxes indicates that the biological processes dominating the four sectors are quite distinctive. The **deep,** clear, but relatively poorly flushed **Vaini** sector is largely dominated by benthic processes as illustrated by algae and seagrasses; the very shallow and very poorly flushed **Pe'a** sector is dominated by both plankton and detrital processes; and the better flushed Folaha and **Mu'a** sectors closer to the entrance are more dominated by planktonic processes (table 4).

DISCUSSION

Because Fanga'uta Lagoon is a complex semi-estuarine system with a constricted entrance to the sea and consequent long residence times, it has been particularly prone to natural and human 'disturbances. The combination, of the changes in' depth and circulation following the geological uplift of the northern coastline of Tongatapu Island, the introduction of new fishing technologies and high urban demand for fish, and the high input of nutrients from urban and rural developments has seriously disturbed the ecology of the lagoon.

Increased nutrient levels have probably had a significant effect. Some nutrients enter the lagoon directly from the hospital sewage outfall, storm drains from Nuku'alofa, and from surface runoff during heavy rain, but the majority probably enter via the groundwater. Nitrate levels in the groundwater are extremely high; although phosphates are relatively low. Benthic algae, seagrass and mangroves have therefore proliferated in the clearer areas of the lagoon although in the turbid Pe'a sector the system is 'dominated by decomposers and plankton.

The shallow entrance of the lagoon has shifted from being a coral-dominated system to an algal/seagrass dominated system. The shift is at least partially natural. The death of intertidal microatolls at the entrance to the lagoon is attributed to recent, geological uplift, while the virtual extinction of Acropora in subtidal areas may be due to changes in the lagoon's hydrography, and possibly the effects of increased nutrient levels on an already stressed system.

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TABLE **1**
Wet we-ight in grams of the most common **seagrass** and **algal** species collected from $150cm^2$ random grab samples from each of the **major** sectors of **Fanga'uta** Lagoon (all depths, combined) (from Zann, Kimmerer and Brock, 1982)

Species	Wet Weight (g/m^2)		
	Nuku'alofa Sector	Folaha Sector	Mu'a **Sector**
Seagrasses			
Halophilia ovalis	113	33	13
Halodule pinifoliosa	113	140	193
Algae			
Caulerpa serrulata		293	
C. ramosa	80		240
C. ashmeadii	0.7		320
Cladophora sp.			53
Chlorodesmis spp.	93		
Halimeda discoidea		207	147
Gracilaria sp.			7

TABLE 2
Nutrient concentrations in groundwater
(from Zann, Kimmerer and Brock,, 1982)

Nutrient	Concentration, g-at 1^{-1}	
	Mean	95% **C.L.**
Nitrate	78	57-99
Ammonium	<0.5	--
Phosphate	0.6	0.25-0.95
Silica	310	240-380

NOTE: **Means** and 95% confidence limits of the mean, (N-16)

TABLE 3
Summary statistics for water chemistry variables in **Fanga'uta** Lagoon sectors (from Zann, Kimmerer and **Brock,** 1982)

Variable	Sector			
	Pe'a	Folaha	**Vaini**	Mu'a
Nitrate	0.11±0.06(6)	0.11±0.08(3)	0.97±0.5(3)	0.4±0.3(5)
Ammonium	0.7±0.4(6)	0.5±0.01(3)	0.05±0.07(3)	0.7±0.3(5)
Phosphate	0.08±0.04(6)	0.5±0.004(3)	0.04±0.01(3)	0.09±0.08(5)
Silica	91±19(6)	48±3(3)	39±11(3)	17±4(5)
Dissolved organic nitrogen	23±3(5)	16±0.5(3)	11±3(3)	10±2(5)
Particulate nitrogen	10±1(3)	6±1(2)	4±3(3)	3.0±0.2(2)
Total nitrogen	34±4(3)	21±4(2)	17±4(3)	13±2(3)
Particulate inorganic c-a-r-bon	3.3±1.7(3)	6.5±2(2)	5±2.5(3)	4.5±1.3(3)
Organic C:N ratio	12±1(3)	7±0.3(2)	9.2±0.8(3)	13±2(3)
Chlorophyll mg m^{-3}	1.8±0.9(6)	1.7±0.3(2)	1.9±1.6(3)	1.2±0.6(5)
%plant carbon	11±6(3)	17±(1)	26±5(3)	18±5(3)

NOTE: Mean + standard deviation **(N)**. All values in g-at 1^{-1} unless otherwise noted.

T A B L E   4
Material flux model for total nitrogen and dissolved silica (from Zann, Kimmerer and Brock, 1982).

	Pe'a Sector	Folaha Sector	Vaini Sector	Mu'a Sector
		Total	Nitrogen	
Input in groundwater	8.0	1.3	6.6	4.7
Flux with adjacent sector	-6.0	6.0	-1.9	1.9
Flux to ocean	0	-6.2	0	-5.9
Uptake (net loss to benthos)	-2.0	-1.1	-4.7	-0.4
Sector area (km^2)	8.8	4.9	3.8	9.7,
Uptake per unit area (mmoles $m^{-2}d^{-1}$)	0.2	0.2	1.2	0.1
		Dissolved	Silica	
Input in groundwater	31.0	6.0	26.0	18.0
Flux with adjacent sector	-20.0	20.0	-11.0	11.0
Flux to ocean	0.0	-22.0	0.0	-18.0
Uptake (net loss to benthos)	-11.0	-4.0	-15.0	-11.0
Sector area (km^2)	8.8	4.9	3.8	9.7
Uptake per unit area (mmoles $M^{-2}d^{-1}$)	1.3	0.8	3.9	1.1

N O T E :Fluxes are in Kmoles d^{-1} and are positive for flux into the sector.

PRELIMINARY REPORT OF A TERRESTRIAL COMPONENT IN THE DIETS OF
BARRIER REEF CORALS: IMPLICATIONS FOR REEF DESTRUCTION AND REEF
MANAGEMENT

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    Biochemistry, James Cook University, Townsville, Australia.

INTRODUCTION

The authors are involved in a variety of research projects, some of
which bear on the ecology of coral reefs. Some of the preliminary
results are very intriguing, and seem to point the way to new
techniques and principles that may be applied to long-standing
questions of reef metabolism and stability. We have presented these
results here in the hope that they might contribute to the larger
purposes of the Workshop, but we do so with the admonition that the
trends we herein describe are based on preliminary data only.

The use of stable isotopes to decipher diets and paleodiets of
vertebrates is an active field of research at McMaster (Lovell et al.,
1986; Schwarcz et al., 1985; Chisholm et al., 1982). The general
principle is that the isotopic signature of the food source will be
reflected in the tissue of the consumer, particularly in the
structural proteins. Much of our modern and archaeological research
has involved measurement of isotopic ratios of C, H and N in the
collagen of humans and their prey, and in their vegetable food
sources. Recently, this research has been applied to marine
invertebrates. We have been able to relate the isotopic signature
of the flesh of bivalves to their major food sources in Arctic
(Magwood et al. , 1985) and temperate-(Leblanc and Risk, 1985)
estuaries. In addition, the organic matrix in bivalve shells may
be extracted by dialyzing in EDTA (Leblanc et al., 1985). This
matrix also reflects the diet, and leads to the possibility of
reconstructing fossil food webs. Coral skeletons also contain
organic matter, although there is some question whether this is a
true "organic matrix". It is therefore possible to analyze the
change in coral diet through time (Risk and Tomascik, research in
progress). We have recently begun a program designed to ascertain
the possible terrestrial contribution to the diet of corals.
Collaborative research between two of us (MJR and PWS) has
sulted in a series of papers on bioerosion of corals. Risk and
Sammarco, 1982; Sammarco et al. , 1986, and Sammarco et al. , in
press. We were able to show that grazing affects the rate of
internal bioerosion and the makeup of the bioeroding community,
and that grazing itself removes significant amounts of dead coral
substrate. We have recently extended this work to a major study
of cross-shelf trends in bioerosion. These research projects were
initiated independently, and some preliminary and very interesting
results are available. It now seems likely that, as often happens,
these processes are interrelated. This paper will briefly describe
results to date, discuss the interrelationships, and draw possible
conclusions re. management of reef ecosystems.

MATERIALS   AND   METHODS

Samples were taken in November, 1986. Several **reefs were** visited, along an **onshore-offshore** gradient in the Central Region,' from Magnetic Island to **Myrmidon** Reef. At each **reef,** about **6 colonies** each of **Acropora formosa** and **Porites lobata were** collected **within** as small an area **as possible** (generally a radius of a few **tens of metres).**

For the bioerosion study, heads were slabbed in the laboratory, **photographed,** and the amount of material removed by the various bioeroding groups digitized from the photographs, as in other studies (**Hein** & Risk, 1975; Risk & Sammarco, 1982).

Samples for isotopic analysis were frozen immediately after collection, and transported to James Cook University, where the coral tissue was separated from **the** zooxanthellae. Freeze-dried residues were sent to **McMaster** University. Samples were combusted with cupric oxide in evacuated tubes in a muffle furnace at **550°C,** and the CO2 and N2 liberated **were** analyzed with a Micromass 602D mass spectrometer. Carbon isotope ratios are reported relative to the Chicago **PDB** carbonate standard. Nitrogen isotope ratios are reported relative to atmospheric nitrogen. Only a few $0^{15}N$ values are reported here. '

RESULTS   AND   DISCUSSION

1.   Bioerosion

At present, only the <u>Porites</u> results are available. The data show that there is a pronounced shift in makeup of the bioeroder community with distance from shore. Nearshore sites are dominated by the boring bivalve, <u>Lithophaga</u> (some coral heads **are completely** riddled) with lesser amounts of boring sponge. Bioerosion on **midshelf** reefs is mostly by boring sponges, particularly <u>Clithosa hancocki</u> and <u>Cliona viridis.</u> Overall, there is a striking increase in bioerosion on nearshore reefs (Fig. 1). An avera'ge of 11% of the total volume of <u>Porites</u> heads on nearshore reefs has been'removed by bioecosion, whereas on Myrmidon Reef the figure is only 1%.

Bioerosion is one of the major processes by which corals are weakened and killed (Hein & Risk, 1977, Tunnicliffe, 1982). Boring by Lithophaga makes the already-weak <u>Porites</u> skeleton more susceptible: to biological disturbance, such as predation by triggerfish (Guzman, 1986). These fish bite off large chunks of <u>Porites</u> in order to feed on the Lithophaga.

Some of the boring sponges occurring here are capable of 'overgrowing and killing corals in a short time (**Acker** & Risk, 1985). High bioerosion rates on ins'hore reefs are believed to be due to increased productivity, as the major bioeroders are filter feeders. **Any** increase in nutrient loading or, productivity in coastal waters will result in an increase in rate of coral destruction by bio-eroders, as predicted by Risk & M Geachy (1978) and verified by Rose & Risk (1985).
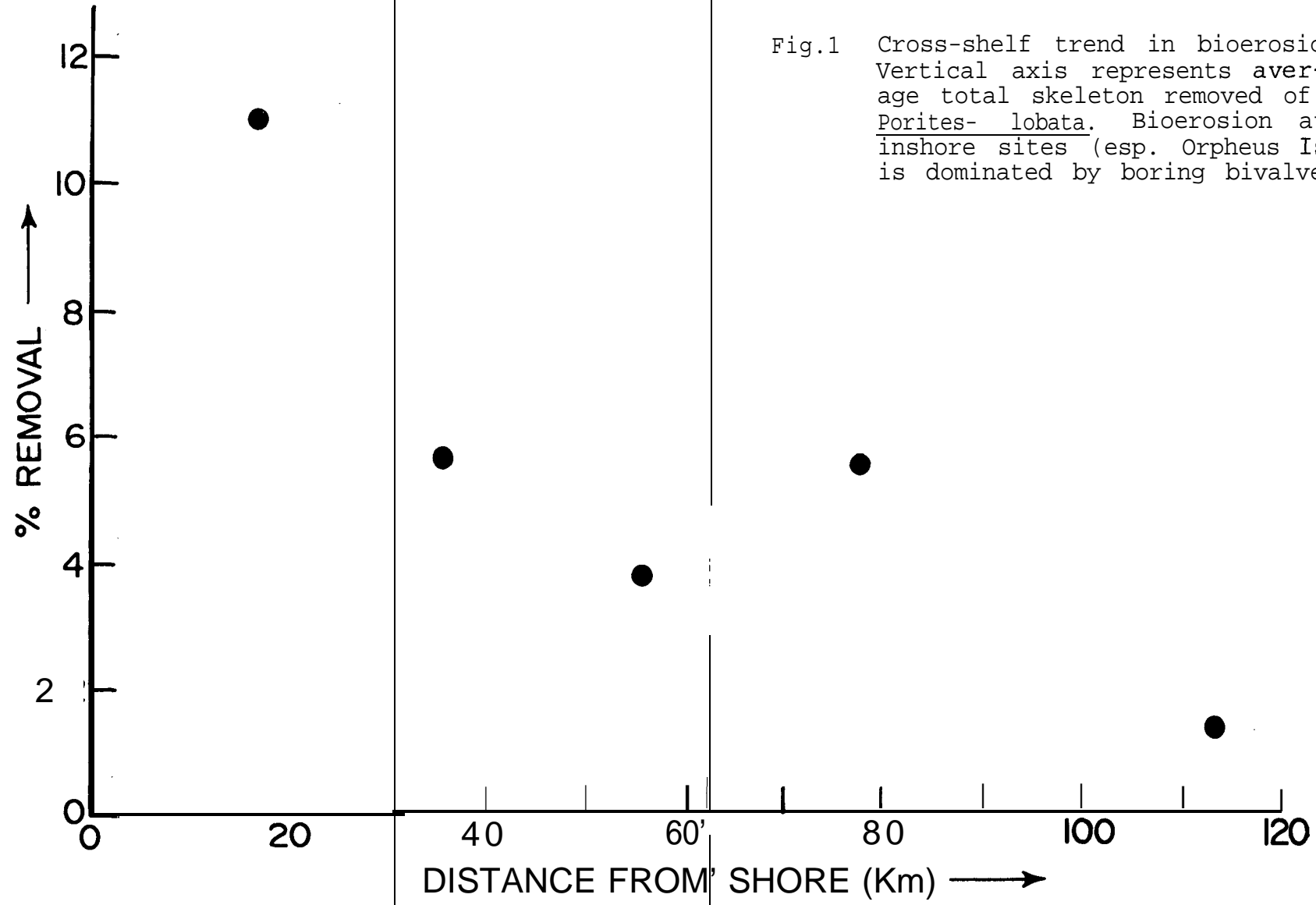
Fig.1 Cross-shelf trend in bioerosion. Vertical axis represents average total skeleton removed of Porites- lobata. Bioerosion at inshore sites (esp. Orpheus Is.) is dominated by boring bivalves.
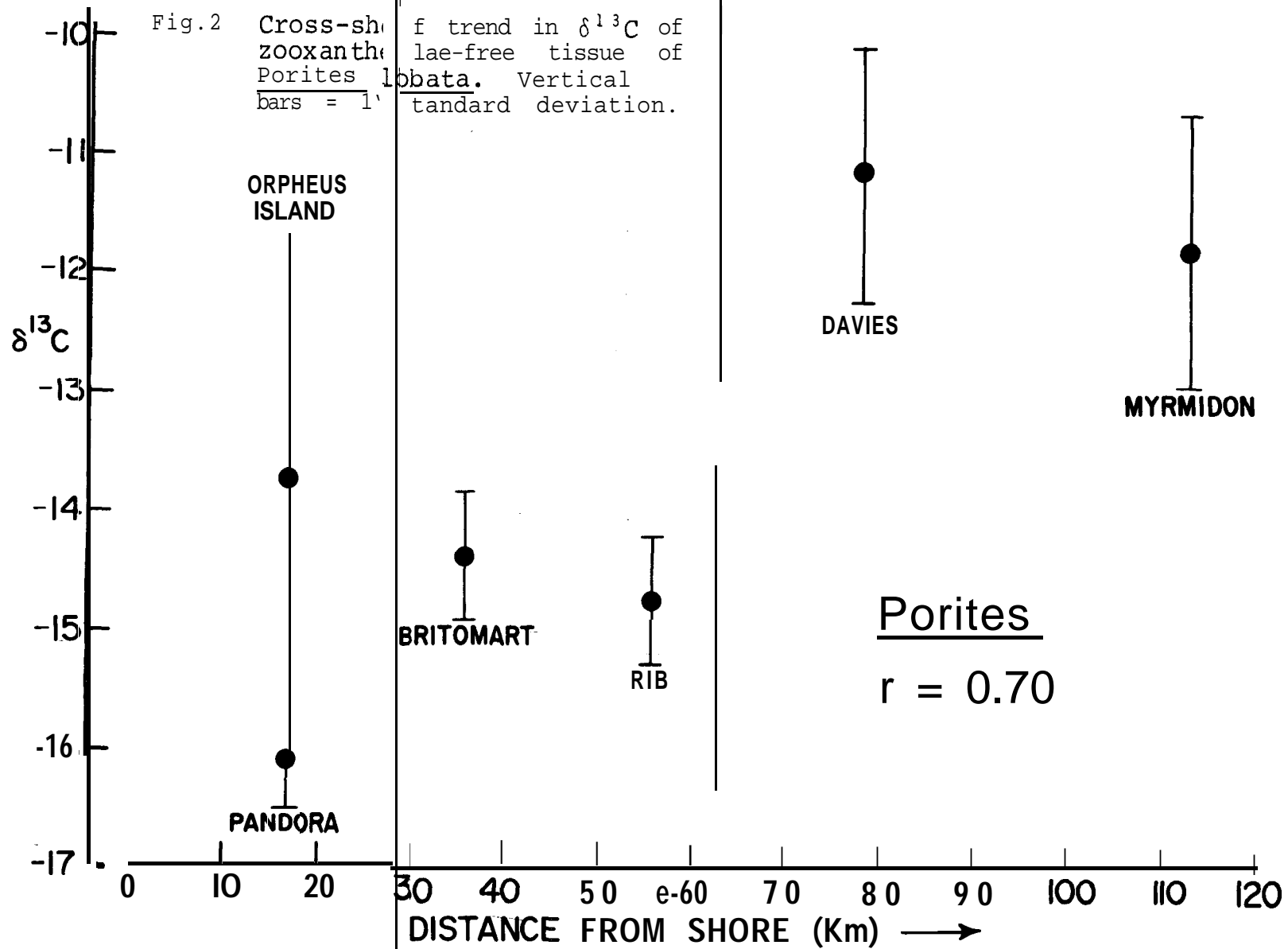
2. Stable isotopes

The results to date are presented in Table 1. Most of the tissue analyses for $\delta^{13}C$ have been completed for both species of corals at each site. Some $\delta^{15}N$ analyses have also been done for coral flesh. Zooxanthellae pre'parations will be analyzed in the near future.

Several interesting trends may be observed in 'the data in Table 1. First, there is a significant trend, in both corals, 'towards ^{13}C enrichment offshore (Figs'. 2, 3). The trend is stronger, and the slope of the line steeper, in Porites. Evidently, Porites is more dependent on terrestrial carbon, at 'least on inshore reefs, than is Acropora.

The terrestrial carbon pool in this region of the Barrier Reef Lagoon has a $\delta^{13}C$ value of about -27‰ (Chivas et al., 198.3; MJR, research in progress) while the oceanic carbon reservoir is - 19‰ (Torgersen et al., 1983). Our results show significant uptake of terrestrial carbon by corals in nearshore 'environments, with a large ^{13}C enrichment relative to the terrestrial carbon pool. The cause of this enrichment is unknown, and intriguing. Somehow, large amounts of the light isotope, ^{12}C, have been lost. In dietary studies using isotopes, the fractionation between food source and animal flesh is generally less than or equal to 2‰ₒₒ, and is attributed to respiratory loss of ^{12}C. This enrichment may be due to fractionation in a partially-closed system, accompanied by rpeated recycling of respiratory CO2 between the coral host and the zooxanthellae. T h e ' degree of fractionation could be used to measure the extent to which the coral-zooxanthellae system is closed in any given coral species.

Some of the light CO2 produced is used in building the coral skeleton, which is depleted in ^{13}C relative to normal marine carbonates (Weber and Woodhead, 1970). Such closed-system carbon re-cycling could explain δ^{13} values of -10‰, rising well above those of any known food source.

Another intriguing aspect of these data is the high intra-site variance. In studies of the' diet of bivalves, one normally encounters values at a site that differ, at most, by about 0.5‰. In this case, for example, Acropora values at Davies 'Reef differ by almost 4‰. Most of these values have been replicated, so there is little possihility they simply represent poor analytical precision. It is possible that this variance, in fact, is recording the degree of autotrophy, or the dependence on carnivory, of individual coral 'heads. Values of $\delta^{13}C$ are sensitive to trophic shifts, and generally become enriched in ^{13}C at higher trophic levels (as shown by Rodelli et al., 1984, for a mangrove-dominated Malaysian ecosystem). Values of $\delta^{15}N$ are even more sensitive to trophic level shifts, and although few data are yet available it seems that values of $\delta^{13}C$ and $\delta^{15}N$ for individual corals are correlated (Fig. 4). That is, individual coral heads from the same area of a reef are capable of having quite differen't meta-bolic strategies,, with differing degrees of dependence on their tooxanthellae.

Fig.2 Cross-shelf trend in $\delta^{13}C$ of zooxanthellae-free tissue of Porites lobata. Vertical bars = 1 standard deviation.

Ficf.3 Cross-shelf trend in $\delta^{13}C$ of zooxanthellae-free tissue of Acropora formosa. Vertical bars = 1 standard deviation.

MAGNETIC ISLANDS

PANDORA

ORPHEUS ISLAND

BRITOMART

RIB

DAVIES

MYRMIDON

Acropora

r = 0.51

$\delta^{13}C$

DISTANCE FROM SHORE (Km) ⟶
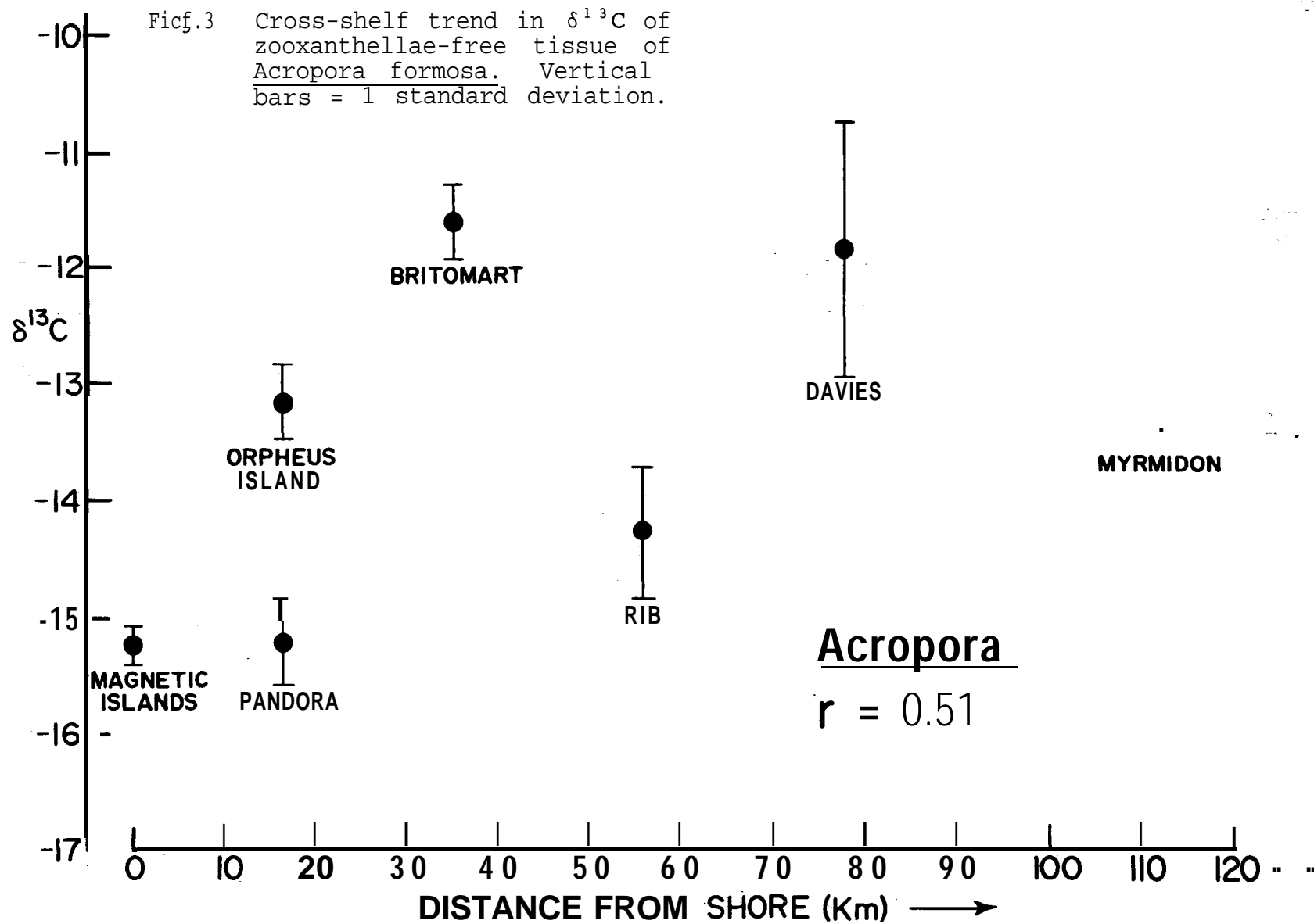
Fig.4   Relationship between δ^{13}C
and δ^{15}N for <u>Acropora</u>
<u>formosa</u> at Davies Reef.

Acropora ,
Davies Reef
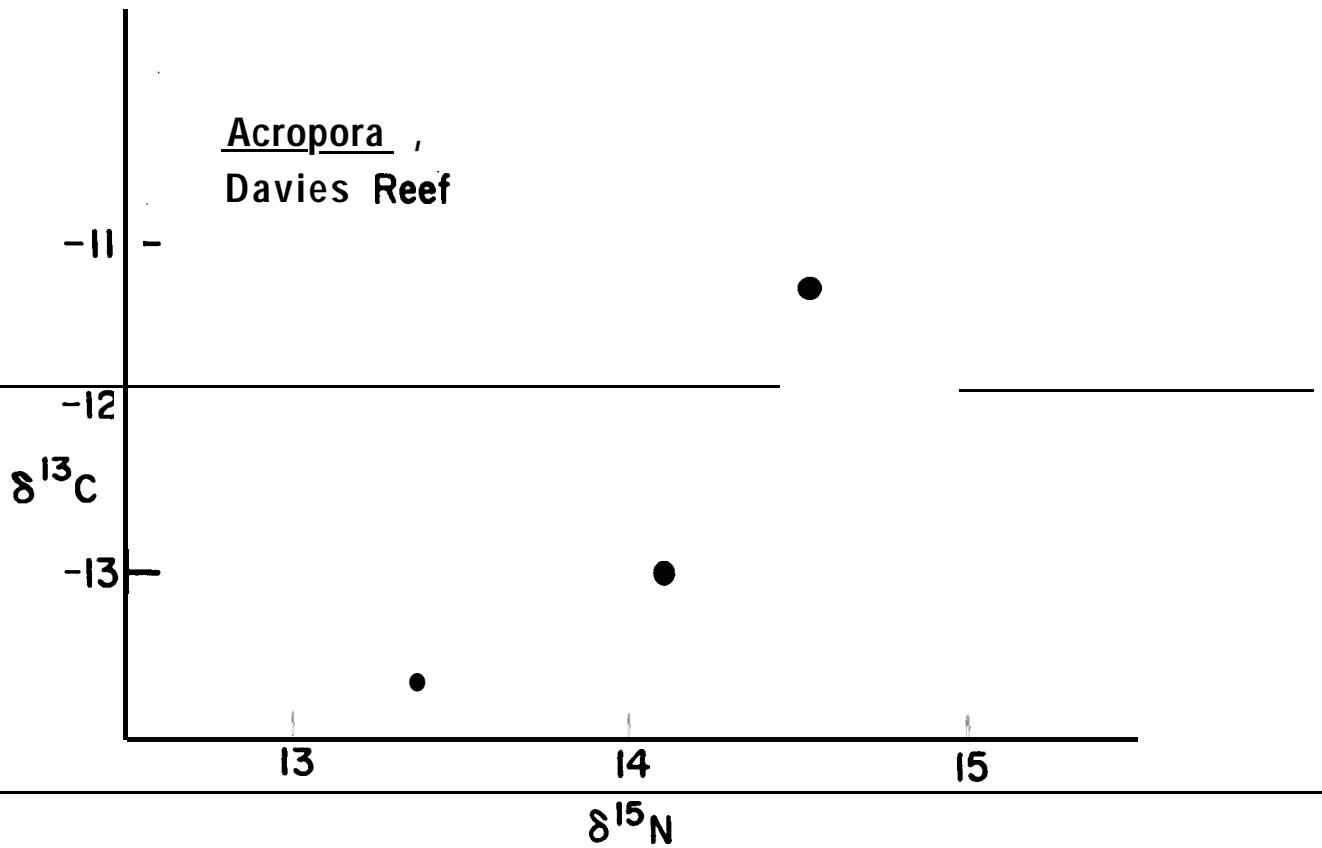
3. Synergistic effects.

The results of the bioerosion study suggest that nearshore reefs are very vulnerable to accelerated bioerosion caused by increased nutrient input, leading to higher productivity in coastal, waters. The results would be increased sediment production, coral weakening and coral death. Inshore reefs would become much more susceptible to cyclone damage, because of the weakening and undermining that takes place between cyclones.

The main thrust of the initial isotope study was to determine whether there was any uptake of terrestrial carbon by reef corals. The results show that there is a clear link between terrestrial runoff and the diet of corals, and that the degree of linkage is quantifiable. The extent to which accelerated bioerosion may threaten inshore corals may be monitored using isotopic tracers.

Bioerosion is e major ordering process on coral reefs, especially in nearshore environments. The principle bioeroders, Lithophaga and the sponges, are filter feeders, and their destructive capabilities will be enhanced by any increase in coastal productivity. the link between the two studies is the unique potential of stable isotopic analyses to assess the importance of terrestrial input to the diets of both the. corals end the bioeroding organisms.

OVERVIEW: IMPLICATIONS FOR REEF MANAGEMENT

1) The process of bioerosion has now been identified as a significant factor in the state of nearshore reefs. Changes in the rate of bioerosion can be detected via a program in which coral heads are censussed at regular intervals, the growth of boring sponge colonies is monitored, and the population dynamics of Lithophaga studied. It is important that, as soon as possible, baseline values of terrestrial contribution to the diets of Lithophage and the boring sponges be assessed.

2) Input of terrigenous material may be es clastic sediments (siltation) and dissolved and particulate organic matter. The effect of siltation on reefs is well known, and a technique is available to monitor these effects throughout the life of an individual coral head (Cortes and Risk, 1985). Increased nutrient input may result in accelerated growth of algae, which can out--compete corals for space, and may also cause increased rates of biological (and hence physical) destruction of reefs. Uptake of terrestrial organic matter by marine organisms can be monitored using stable isotope tracers. In addition, by analyzing the organic matrix of coral skeletons, we can detect historical changes in the rate of input of terrestrial material.

3. Agricultural activities may result in increased runoff of nitrogen--rich organic matter. Uptake of this anthropogenic nitrogen may be monitored using $O^{15}N$ ratios (Sweeney and Kaplan, 1980). Living organisms may be sampled, and also the progress of entrophication through time, via coral skeleton studies.

4.   Isotopic tracer methods appear to be very powerful tools in
the study of coral metabolism, allowing us to evaluate the degree
of **carnivory** of an individual coral head, and the relative
dependence on terrestrial **organic** matter.

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TABLE 1. Stable carbon isotope ratios for <u>Acropora formosa</u> and <u>Porites labata</u> from reefs of the <u>Central Region, Great Barrier Reef.</u>

$\delta^{13}C$

Location	Acropora	Porites
Magnetic Island	-15.09 -15.36	not obtained
Pandora Reef	-14.91 -15.53:	-16.42 -15.87
Orpheus Island	-12.94 -13.43	-12.27 -15.24
Britomart Reef	-11.92 -11.32	-14.62 -14.13
Rib Reef	-13.58 -14.11	-14.29 -15.23
Davies Reef	-12.97 -10.71 -11.23 -13.66	-10.22 -12.06 -10.77
Myrmidon Reef	-13.44	-10.84 -12.80

NUTRIENT INPUT IN CLEVELAND BAY

Graham Jones
Townsville/Thuringowa Water 'Authority:

INTRODUCTION:

Case studies of severe eutrophication problems throughout Austra-lia (AEC Report No. 19, 1987) clearly implicate blue-green algae. Proliferation o f these algae in water can cause nuisance odours, toxins in the water, f i sh kills (Putnam a n d Hain, 1980), alterations t o the planktonic community (Murphy et al. 1976), and more recently mobilisation of toxic metal ions in i nstiore waters of the Great Barrier Reef Lagoon (GBRL) (Jones et al, 1982; Jones et al. 1986; Jones, 1986; Jones, 1987a, b; Jones and Thomas, i n press). Overseas t he increased occurrence of phytoplanktonic blooms in Hong Kong has reached a l a r m i n g propor t i on5 recently, such that the Environmental Protection Department i s convinced that pollution is the cause, and legislation to improve water qual ity is underway. Extensive red tides of plankton in 'the Seto Inland Sea in Japan are attributed to' sewage input (Okaichi, 1987).

My interest in nutrient inputs in Cleveland Bay stems from my earlier PhD stud i es involving the effects of *Trichodesmium* blooms on toxic metal ions in the bay and my present, position with the Townsvi 1 le City Council. blooms of this blue-green a l g a e are so prolific in certain regions of the reef, and effect inshore water5 for many months that in my view a potentially s e r i o u s environmental threat exists from the interaction of these b l o o m s and pollutant input (Jones, 1987b). This potential t h r e a t is inextricably 1 inked with organ i c mat ter exud i ng from inshore *Trichodesmium* f ilaments. This organic matter binds the element iron extremely efficently (Jones and Thomas, 1988a, b). The extent of. these blooms in the GBRL is slowly being reali'sed (Kuchler 'and Arnold, 1986). Of thirty one retrospective Landsat images taken during November and December 1980-84 and 1972, thirteen had captured massive surf ace blooms. This represented a temporal occurrence of 41.93% of the total sample. Spatial ly each bloom (with one exception covered more than 5% of the 34,225 sq.km of 'area' sampled (171 lsq. km) . Four processes are high1 ighted, which in conjunction with *Trichodesmium* blooms could cause s e r i o u s environmental damage to the reef (Jones, 1987b) . These are;

(1) Input o f sediment f r o m t h e erosian o f s o i l or sandmining. Such processes, i n conjunction with *Trichodesmium* blooms a r e potential ly capable of mobi 1 ising metal ions.

(2) The interaction of sewage and *Trichodesmium* bl'ooms will mobi 1 ise metal ions.

(3) The effects of dredging and *Trichodesmium* b l o o m s is potentially capable of mobilising metal ions.

(4) The input of metal wastes into, the GBRL could havg far greater impact in those regions where *Trichodesmium* blooms occur.

Al though 1 i tt le work has been carried out on the charactrrisation of this mar i tie humus We are able to say;

(1)   The bu 1 k of the mar i ne humus is produced f rom Irichodesmium inshore. The   process   seems to be predominantly   an   INSHORE PHENOMENON.

(2)   The marine humics frorn Irichodesmium are more soluble   than their   terrestrial   counterparts introduced into the sea in the monsoonal   season, and persist in coastal waters at Townsville for many months(Jones et a1.1982).

(3) The marine humus exuding from the filaments exhibits high UV absorption   and   fluorescence, and   chelates iron in   seawater to levels of   5%, an 'enrichment factor of 45 million over   seawater iron   levels. It is bel ieved that   this fact   has   considerable environmental   siqnif icance   in those regions of Australia where this   algae   accumulates, and in regions of Australia   where   this algae has accumulated in the past (McConchie, 1987).

(4)   Althouqh this marine humus causes marked enrichment in   the toxic   metal ions cadmium, nickel, and lead, it also mobilises these toxic   ions to more availible forms to marine life. This   material is   therefore capable of interfering with the natural   scavenging process that removes metal ions in the sea.

(5) This marine humus is taken up by the branching coral Acropora formosa   in the laboratory, prior to spawning. UnexposedA. formosa did not spawn.

Al thouqh   what   I   have described affects trace and   toxic metal   ions I believe this process will   also   affect   nutrients which   are   adsorbed to col loidal particles and   suspended sediments. An   interestinq paper, which illustrate5   how   effective organic material can be i-n causing serious environmental problems especially   eutrophication   is   the   work   of   Murphy et al (. 1976). 'During   an   invest iqat ion in   the Bay of Quinte, a eutrophic bay on the northern shore of Lake Ontario it was   found that   during 'blue-qreen algal blooms ofAnabaenaandScenedesmus other   algae can be completely suppressed. These workers concluded that the ability of blue-green algae to suppress other algae   can be determined by the availibility o f iron. Iron deprivation induced   the   production of hydroxamate chelators, which were   the agents   suppressing other algae. These authors concluded that   the availibility of iron may be an important factor in determininq the stabi 1 i ty and composition of acquatic ecosystems. A   diagram depicting   how excess P increases the nitrogen budget of natural waters from the activities of blue-qreen algae is shown in Fig 1. This   clearly   demonstrates how important it is to control P ernrn i ss i ons   to   our   environmen t (Water   Pollution   Control Federation, 1983).

PHOSPHORUS INPUT:

In assessing man-made P inputs to Cleveland Bay it is important to realise that natural inputs also occur.Natural inputs include; mangroves; anoxic sediments,freshwater runoff ,groundwater intrusions, Trichodesmium blooms,suspended sediments.Man-made inputs include sewage discharge, agricultural runoff, stowater runoff, animal husbandry (eg.acquaculture), tourist development. In my' work in Cleveland Bay I will be concentrating on' three areas. (1) Sewage,, Discharge.(2)Freshwater Runoff .(3)Trichodesmium input and trying to asses5 the significance of each.

SEWAGE DISCHARGE AND TREATMENT:

Treatment of Townsville and Thuringowa's waste water takes place at the Mt St John and Bohle sewage treament plants to the' west of the city.At present only 25% of our total wastewater is treated a t these plants.The remaining wastewater (75%) is discharged untreated into Cleveland Bay at Sandf ly Creek.
        The Bohle plant is quite small treating effluent from a population of about 1000 people and some industries in t tie area. Treatment of wastewater at 'Mt St John is by primary sedimentation,secondary treatment by biological filters,sediment-ation,sludge digestion and finally effluent discharge.The effluent from the plant is discharged by gravity to a perrnanen t channel cf the western boundary of the Town Common,which is connected directly to a tributary of the Bohle River.These plants have a l ice'nce to discharge effluent of a 20:30 quality(i.e. 20 BOD, 30 suspended solids) .Overall 85-90% of the BOD and 90% of the suspended sol ids are removed.At Magnetic Island sewage treatment is by an extended aeration plant at Nelly Bay. In Thuringowa City sewage wi 11 soon be treated at Condon by an extended aeration plant and wi 11 process effluent from 10,000 people.

Historically raw sewage ha5 been discharged into Cleveland Bay since 1940,primarily at the mouth of the Ross Estuary.This outlet was closed in 1986.From December 1963 raw effluent started to be d i schargedf rom Sandf ly Creek.In a few months the Cleveland Bay Pur if ication Plant (CBPP) wi 11 be commissioned to treat raw sewage' f rom the Western Suburb5 Scheme. This sewage scheme was constructed from the mid 1950's to the rnid 1970's,and services mainly residential suburbs.This effluent, will be, used, by Colinta Holdings Pty Ltd for irrigation and pasture improvement.Effluent from the Eastern Suburbs Scheme wi 11 not be treated for some years since more development is needed at the CBPP(McIntyre and Associates, 1987).

The overall treatment process at the CBPP is identified as the PASSAD Process. The process incorporates essentially two separate and independant treatment operations as follows.

PAS- Primary Activated Sludge, loaded with raw sewage in the high to very high biological loading range, to produce an effluent suitable for outfall discharge and a waste sludge requiring further treatment.

SAD-Secondary Anaerobic Digestion including pre-thickening and post dewatering, to stabilise the waste activated sludge from the PAS process, with final land disposal on site. At present treatment will only involve the provision of PAS facilities for flows from the Western Suburbs, and effluent quality will be 50/60 quality. When this plant is in operation the effluent characteristics will change with the volatile fatty acid fraction increasing.

Sewage Discharge:

The CBPP has the highest discharge(30 megalitres/day), followed by Mt St John(10.5) and a small discharge from the Bohle Plant (0.15). Total. daily discharge of wastewater to Cleveland Bay is therefore.- in excess of 40.65 megalitres/day. In order to get some idea of the quantities of orthophosphate discharged into Cleveland Bay I have decided to take the period 1974-86, since this shows a high and low freshwater input cycle.

Freshwater Runoff

Total freshwater runoff for the Ross River catchment from 1974-86 totals 1,103,192 megalitres(QWRC), whilst sewage discharge for the same period was 178,047 megalitres. Sewage discharge was therefore 16% of freshwater discharge during this 12 year period. From 1981-86 however sewage discharge comprised all of the discharge to Cleveland Bay. This alternating cycle of wet/drought can obviously affect the marine coastal regions to varying degrees.

Orthophosphate Input

Although P discharge at Mt St John is high this discharge is buffered from the marine environment by the Bohle Estuary and the surrounding lagoons which harbour prolific bird life. In this discussion I will concentrate on inputs at Sandfly Creek since flows are substantially higher than the other plants, and no buffering takes place. Based on a concentration of 6 mg/l of orthophosphate in raw sewage at Sandfly Creek total input of dissolved orthophosphate for the twelve year period totals 788.4

metric tons.Approximately 110 metric ton5 of dissolved orthophosphate is as been delivered to Cleveland Bay from freshwater discharge. This is based on a freshwater concentration of 100 ug/1 of dissolved orthophosphate.Man-made input of dissolved orthophosphate therefore exceeds natural inputs from freshwater discharge by a factor of well over 7 times, that of natural sources,since we have not considered inputs from diffuse sources, and the other two plants.Total P emissions: from wastewater are obviously much higher than these figures since, orthophosphate in wastewater is about 50% of the total P levels. Clearly with the commissioning of the CBPP P emissions will reduce to Cleveland Bay, and the overall quality of wastewater discharged into the bay will dramatically improve.

CORAL CORES AS GEOCHRONILOGICAL INDICATORS OF FRESHWATER RUNOFF AND POLLUTANT INPUT IN CLEVELAND BAY

In association with Dr Peter Isdale and Dr Kevan Boto(AIMS) I am working on the above project.This project is suported by the Australian Water Resources Advisory Council(AWRAC) and AIMS under the Partnership Programme of AWRAC. In addition to the valuable runoff data for the Ross Dam region the analysis of the chemical signatures laid down in the coral matrix should be of great value as indicators of past event5 in Cleveland Bay,especially events that relate to nutrient input.Core material from Geoffrey Bay is being processed at the moment for' P,but other poi lutant element' analysis are planned.This core will provide records going back to 1814.

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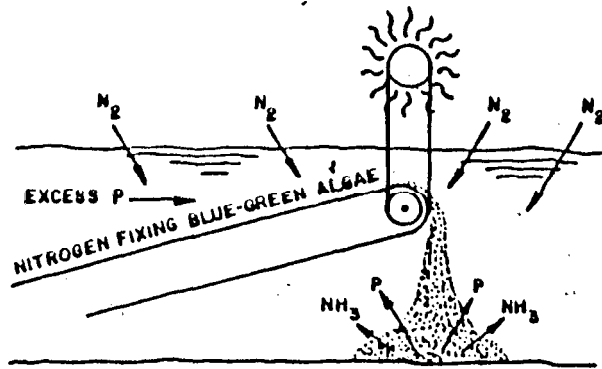
ROLE AND IMPACT OF NUTRIENTS

FIGURE 1. Diagram depicting h o w excess phosphorus increases nitrogen budget of natural waters and hastens eutrophication.

NUTRIENT TRANSPORT BY INORGANIC COLLOIDS

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ABSTRACT

The availability of nutrients and other trace elements in natural systems is strongly influenced by the manner in which they are transported within the system. One mode of transport which is important in many environments involves adsorption onto colloidal 'particles, and subsequent desorption in response to changes in environmental conditions. Environmentally significant aspects of the chemistry of natural inorganic colloids are summarised, and two examples of their impact on biogeochemical processes in a marginal marine setting are presented. In the first example, colloidal iron-oxides acting as a chemical conveyor belt give rise to anomalously high heavy metal concentrations in marine bivalves, while in the second example, they are responsible for localised increases in phosphate concentrations in surficial marine sediments.

INTRODUCTION

When examining the dynamics of nutrients and trace elements in natural systems, emphasis is commonly placed on input concentrations and supply rates for the components of interest (e.g., the composition and discharge volumes of an industrial effluent), and on the effect of these 'diluted' reagents on selected target organisms or sediments elsewhere in the system. However, although it is frequently overlooked, it is equally important to determine how these reagents are moved around within the system. The mode of transport of a nutrient or trace element within the system will influence whether it is diluted and widely dispersed (e.g., dissolved ions), or it is concentrated by sedimentological, chemical, and biological processes at particular sites in the system and released slowly at that site only (e.g., chemicals transported as a component of suspended organic matter or clastic detritus, or chemicals adsorbed onto fine organic or inorganic particles). Clearly, each chemical constituent will have a differing environmental impact depending on whether it is transported in a manner which leads to dilution and dispersion, or it is transported in a manner which leads to localised accumulation of high concentrations. In practice, very few chemical reagents (including toxic chemicals in polluted systems) in natural systems are likely to have a seriously damaging environmental impact unless they are concentrated by some process at particular points in the system; concentration could involve selective sedimentation or bioaccumulation and biomagnification.

This paper examines the role of inorganic colloids in natural systems as a nutrient and trace element transporting agent which commonly causes localised accumulation of the transported reagents. The colloids can also influence the rate of release of adsorbed chemicals to other parts of the system in response to changes in biogeochemical conditions. Colloidal organic matter can also play a significant role in chemical transport in natural environments, but discussion of this group of substances is beyond the scope of this paper.

COLLOIDS AND THEIR BEIIAVIOUR

In environmental analysis, particularly in relation to water samples, it is normal practice to filter samples through a glass fibre filter when determining total suspended solids, or a 0.45 pm filter as a preparation for water analysis; material passing through the filter is considered to be in solution while material retained by the filter is treated separately as suspended solids. However, this arbitary boundary may often lead to an important sub-group of particles (the colloidal particles) being completely overlooked. Colloidal particles are generally considered to range in size between 0.1 μm and 0.1 nm (Krauskopf, 1979), and would pass through the filter, but their chemical and physical properties are quite distinct from those of ions in true solution (Yariv and Cross, 1979). The distinctive physical and chemical properties of colloidal particles confer on them an important role in many natural processess (e.g., McConchie, 1984; Lawrance, 1985; Martin et al., 1986).

A substance is colloidal if it consists of very fine particles (solid, liquid, or gas) dispersed in another substance. In this paper the term colloidal is confined to solids dispersed in water. Compositionally, a large range of compounds can form colloidal particles, but in natural waters the most common ones are clays, iron-oxides / -hydroxides, aluminium-hydroxides, manganese-oxides / -hydroxides, silicon-hydroxides, a variety of sulphides (primarily the hydrated iron-monosulphides, melnikovite and hydrotroilite), carbonates, and a variety of organic and organometallic compounds. Of these compounds, the clays and the iron-oxides / -hydroxides are the most important; although studies of Pre-Cambrian sedimentation (e.g., Ewers and Morris, 1981; McConchie, 1984) indicate that colloidal silicon-hydroxide may have been environmentally important in the past, it is now only significant, in relation to hydrothermal exhalations.
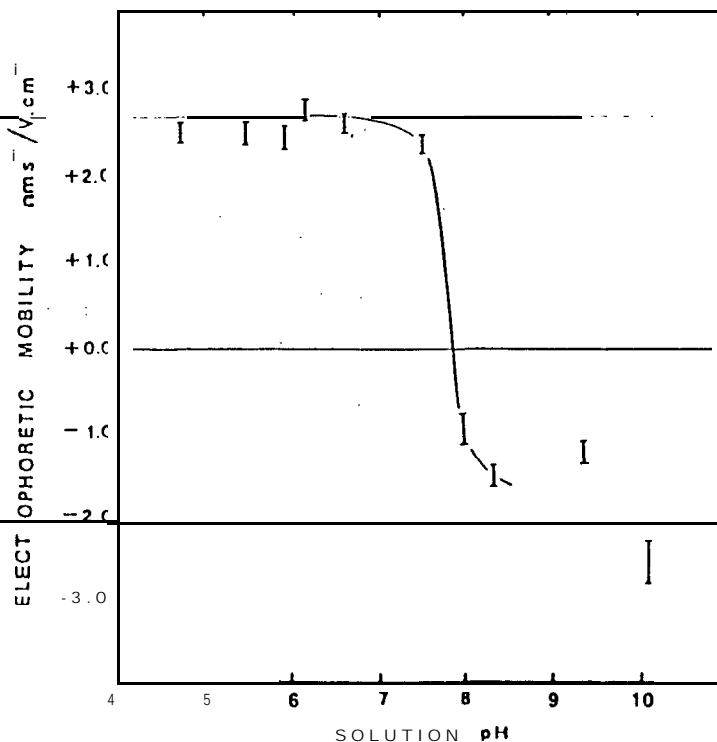

Figure 1. Plot of electrophoretic mobility against pH for colloidal hematite; note the isoelectric point at pH = **7.85,**

Two properties of colloids are particularly important in an environmental sense; firstly their'; high surface area to volume ratio, and secondly their high charge to mass ratio. As a result of their high surface area to volume ratio, and because chemical reactions involving solids take place on surfaces, colloidal particles are very surface active (e.g., 1 gm of colloidal iron-oxides with a mean particle diameter of 10^{-2} μm will have an effective surface area of about 10^6 cm^2. The evaluation of surface charge density and sign is more complex (e.g., Yariv and Cross, 1979). because the sign and magnitude of the charge will depend on the composition of the particle, the pH of the solution, and the type and concentration of other ions present. Exactly how the charge develops is not well understood, but it is known to be strongly pH dependant (e.g., Krauskopf, 1979), and to have a major influence on the' behaviour of colloids in natural environments. There are two ways in which the charge on colloidal particles is environmentally important a) it governs flocculation vs. dispersion processes, and b) it controls adsorption / desorption and ion exchange reactions.

Flocculation and dispersion

The dipolar water molecule orients itself in relation to the charges on colloidal particles to form a vicinal or oriented water layer (see Yariv and Cross, 1979) which prevents the colloidal particles from settling out unless the charge is cancelled. When the charge is cancelled by other ions in solution the colloidal particles may flocculate and settle out, but our knowlege of how the process works is very limited. Generally, if the colloidal particles are negatively charged, monovalent cations will tend to be dispersing agents while multivalent cations are flocculants; similarly monovalent anions will tend to be dispersants

TABLE 1
Isoelectric points for common colloidal materials

Compound	IEP
Al(OH)$_3$ [amorphous]	7.1-9.4
α-Al(OH)$_3$ [gibbsite]	5.0
γ-Al$_2$O$_3$	8.0-8.5
Fe(OH)$_3$ [amorphous]	7.1-8.5
a-FeO(OH) [goethite]	3.2-6.7
γ-FeO(OH) [lepidocrocite]	5.4-7.4
FeO(OH) [limonite]	3.6
α-Fe$_2$O$_3$ [Shark Bay hematite]	7.8
γ-Fe$_2$O$_3$ [maghemite]	6.7
MnO$_2$	4.0-4.5
Mn(OH)$_2$	7.0
SiO$_2$ [quartz]	2.2
SiO$_2$ [amorphous]	1.8
Sulphides	<6.0
CaCO$_3$ [calcite]	9.5

for positively charged colloids, while multivalent anions are flocculants. Furthermore, whereas dilute electrolytes may be dispersive, the same electrolyte at higher concentrations may promote flocculation. Hence, $Fe(OH)_3$ which is a common colloid in river systems, is virtually absent in normal seawater due to the higher electrolyte concentration; it is precipitated within estuaries as the electrolyte concentration rises. Colloid flocculation induced by a rise in electrolyte concentration is an important process in esturarine settings.

The charge on colloidal particles can also be neutralised by **a** small change in solution pH. The sign and magnitude of the charge may change significantly over a small pH range (Fig. 1) from strongly positive below the isoelectric point (IEP; the pH at which the charge on the particles is zero) to strongly negative above the IEP. The change in charge sign in natural environments is well illustrated by colloidal hematite which has an isoelectric point at pH 7.8 (Fig 1) such that it is negatively charged in normal marine waters where the prevailing pH is about 8.2 (Drever, 1982), but positively charged in non-marine systems where the pH tends to be < 7.5. The isoelectric points for a selection of common colloid forming compounds in natural environments are summarised in Table 1.

The flocculation and precipitation of colloids (particularly iron-oxides and -hydroxides in estuaries) may also result in the precipitation of other chemical species in the water body by the process of co-precipitation. This process is sufficiently efficient (e.g., Harder, 1965; Yariv and Cross, 1979, McConchie, 1984) that precipitation of iron-oxides/-hydroxides, due to a rise in Eh and/or pH, can result in the co-precipitation of a mass of silica equivalent to 40% of the mass of the ferruginous precipitate, even if the silica was only at 10% satuaration levels in the solution.

Adsorption / desorption, and ion exchange

Because colloidal particles carry an electrostatic charge under all pH conditions, except at the isoelectric point, positively charged colloids have a marked tendency to bind anions while negatively charged colloids bind cations. These adsorbed ions may be exchanged in response to changes in the activities of other ions in the solution, or they may be desorbed in response to a change in the solution pH; slow desorption during diagenesis will also accompany the ageing of any colloidal precipitate.

Clay minerals are a special case because they can carry both positive and negative charges simultaneously; the magnitude of the charge will depend on the type of clay mineral and the type and extent of isomorphous substitutions within the mineral lattice. Positive charges are centred on the crystal edges perpendicular to the '001' lattice plane and result from the isomorphous replacement of structural oxygen by hydroxyl groups leaving a negative charge deficiency. Residual positive charges are particularly noticable in kaolinites (Grim, 1968) and can bind phosphate ions rather well because not only is the charge suitable but the atomic geometry of the phosphate ion is a good match for the silica-tetrahedral layer of the clay. Negative charges are centered on the '001' lattice plane and are largely due to the isomorphous replacement of structural silicon by aluminium or ferric iron, or the replacement of structural aluminium by magnesium or ferrous iron. The negative charges on clays are usually much greater than the positive charges and cations are readily bound by electrostatic attraction into interlayer positions on the '001' surfaces.
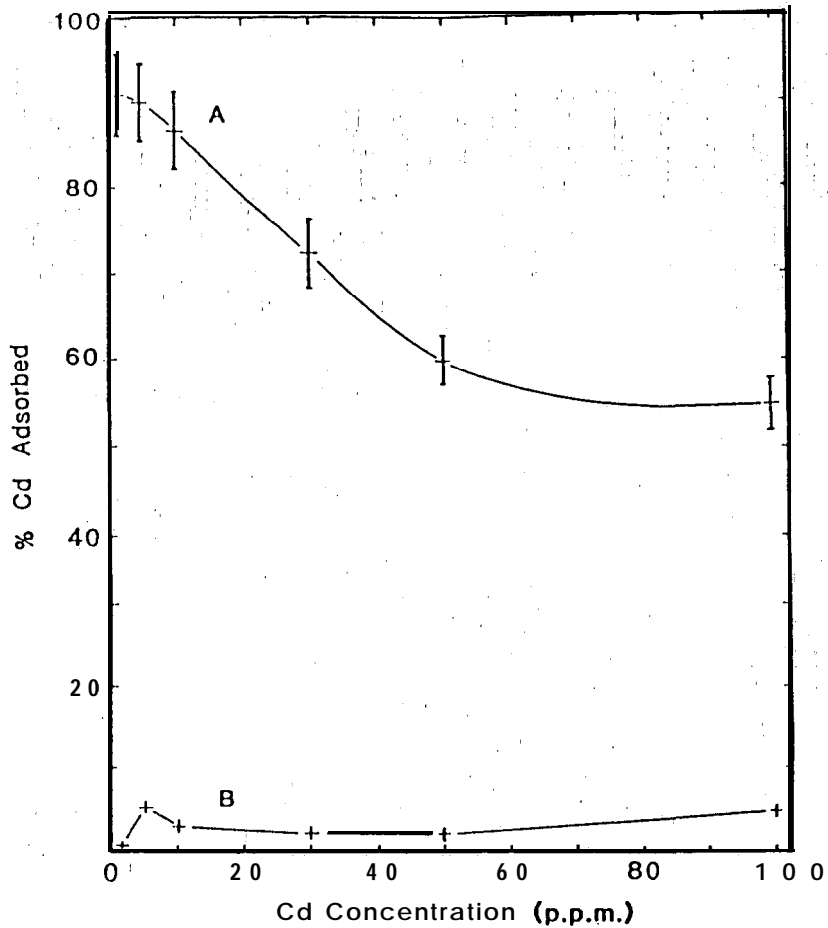
Figure 2. Plot of the percentage of cadmium adsorbed from spiked solutions of Shark Bay seawater by colloidal iron-oxides extracted from Shark Bay sediments. Curve A is the plot for tests involving the iron-oxides; plot B is for an identical experimental system in the absence of the iron-oxides.

Ions electrostatically bound to clay minerals and to other inorganic colloidal particles are not strongly fixed, and most can take part in ion exchange reactions in response to changes in the type and activity of ions in the associated solution. Thus, ions carried on colloidal particles can be released into the environment by a change in the ionic composition of the solution, and ions in the solution can be selectively bound to the colloidal particles. This process is environmentally important, particularly in estuaries where there are rapid changes in electrolyte concentrations; it is also important in the formation of many authigenic minerals (e.g., McConchie *et* al., 1979; McConchie, 1984). Each clay or colloid will have its own total ion exchange capacity, but different ions will have differing tendencies to be adsorbed depending on several factors including::
* The size and charge of the ion,
* The pH of the solution,
* The type and concentration of ions competing for the adsorption sites,
* The total ionic strength of the solution, and
* Temperature.

Because several of these factors vary widely within and between natural environments, it is not useful to generalise about preferential exchange sequences. However, it is significant to note that selective adsorption of ions can be extremely efficient, even at very low ionic strengths (e.g., the uptake of cadmium by colloidal iron-oxides in Shark Bay, Western Australia; Fig. 2).

There are several other properties of colloids (e.g., ageing, selective ion diffusion, crystal growth in gels, etc) which are environmentally significant, but discussion of these is beyond the scope of this paper; a good introduction to these aspects can be found in Yariv and Cross (1979).

ION TRANSPORT BY COLLOIDS IN NATURAL SYSTEMS

Substantial quantities of macronutrients including K^+, NO_3^-, and PO_4^{3-}, and a wide range of trace elements can be transported in natural environments as ions adsorbed onto colloids and clay minerals (e.g., Grim, 1968; Yariv and Cross, 1979; see also several papers in Lasserre and Martin, 1986). K^+ in particular is moved in large quantities in natural environments as an ion bound into the interlayer position in clay minerals; it is not commonly transported by other colloidal particles. Hence, an influx of clay minerals as a result of a flood for example can substantially raise the potash availability for benthic flora in an estuary. Phosphate and nitrate are transported in small quantities by clay minerals where they are bound to crystal edges perpendicular to the '001' plane; they are also transported by colloidal particles under conditions where the pH is below the IEP for the colloid. In many non-marine settings, colloidal iron-oxides or -hydroxides are very efficient in transporting phosphate and nitrate because the pH is usually below the IEP, but under marine conditions where the pH is above the IEP anions are desorbed. Hence, colloidal iron-oxides and -hydroxides (possibly with adsorbed phosphate and nitrate), transported by fluvial systems, will flocculate in estuaries and other marginal marine settings due to the rise in electrolyte concentration, and the adsorbed anions will be desorbed due to the rise in pH. Thus, where anionic nutrients (e.g., from agricultural runoff) are adsorbed onto ferruginous colloids and transported by rivers, nutrient concentrations may rise in estuaries and other near-shore environments, but increases are unlikely to be detectable more than a few kms offshore. The efficiency of colloidal iron-oxides in transporting ionic species in marginal marine environments is well illustrated by the following two examples from Shark Bay, Western-Australia.

Colloids as a chemical conveyor belt

Shark Bay, Western Australia (Fig. 3), is a shallow marine embayment of about $8,000km^2$ with an average water depth of 10m; over about $2,000km^2$ the water depth is less than 1m. The topographic relief of the surrounding landmass is low and the area is exposed to strong winds which are very effective at resuspending fine sediments in the extensive shallow water parts of the embayment. Shark Bay is geographically remote from all known industrial and geological sources of heavy metals, but several species of mollusc found there have cadmium contents which exceed both the usual limits of 2ppm wet weight for molluscs taken for human consumption, and levels found in molluscs from areas of recognised heavy metal pollution (McConchie et al., 1988). The cadmium content of several species of Shark Bay molluscs frequently exceeds 10ppm wet weight, locally exceeds 20ppm, and shows substantial regional variation within the embayment (Fig. 4). Some regionally variable factors which could influence the rate of cadmium uptake include, an anthropogenic source, species variation, salinity variation, local groundwater influx, and variation in the dissolved cadmium concentration, but none of these possibilities are supported by the data of Lawrance (1985) and McConchie et al. (1988).
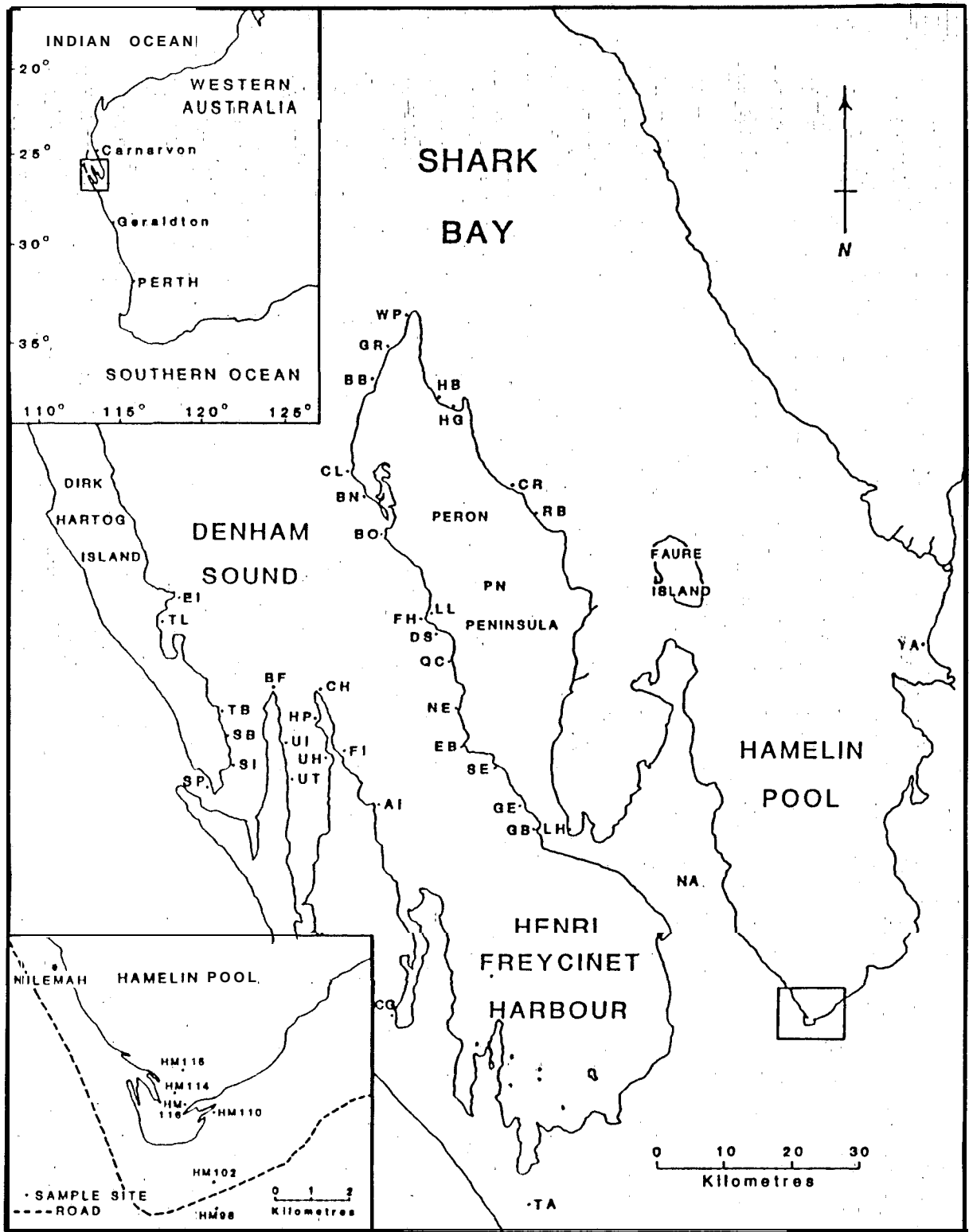
Figure 3. Map of the Shark Bay area showing sample sites examined during the 1984/5 phase of the project; after McConchie et *al.* (1988). Herald Bight is the embayment, toward the north of Peion Peninsula, which includes sites HB and HG

The concentration of dissolved cadmium in the waters of Shark Bay is not substantially different from that in normal oceanic water (0.06ppb), and the cadmium concentration in substrate sediment seldom exceeds 0.005ppm. Few viable explanations for the high cadmium concentrations in the Shark Bay molluscs were apparent until it was discovered that molluscs had their highest cadmium concentrations in areas of the bay where turbulance was high and the substrate sediment had a high iron-oxide content. The iron-oxides are derived from the ferruginous Peron Sandstone exposed in some coastal cliffs around the bay and constitute up to 2% of substrate sediments immediately offshore from these cliffs. It became clear, and was subsequently statistically confirmed, that cadmium in the water was adsorbing onto the surface of colloidal hematite, which was negatively charged at the prevailing pH of 8.15, and that these particles were suspended by turbulance and ingested by the organisms. The adsorption onto the iron-oxides is extremely efficient at low cadmium concentrations (e.g., Fig. 2). Once inside the organisms, lower pH conditions prevail, the iron-oxides become positively charged, and the cadmium is released in ionic form and accumulated within the organism. For areas with a similar turbulance the correlation between iron-oxides in the substrate sediment and cadmium in the molluscs is 0.87.

Further confirmation of the link between cadmium uptake and colloids can be found in the fact that bottom dwelling oysters have a substantially higher (up to 10 times) cadmium content than oysters grown in baskets suspended at the same site. The rate of cadmium uptake by oysters in an aquarium spiked with traces of cadmium was also found to be substantially enhanced by the addition of colloidal iron-oxide and sustained turbulance.

In this example, although the iron-oxides constitute only a small proportion of the substrate sediment, they carry most of the metal load, essentially they act as a chemical conveyor belt preconcentrating cadmium from the water, carrying it to the molluscs, *then* returning to the sediment as fecal matter to start the process again.

Phosphate transport in Herald Bight

The southern end of Herald Bight (sites HG and HB in Fig. 3) is unusual for Shark Bay because despite a very high iron-oxide concentration in the substrate sediment, molluscs in the area have relatively low cadmium concentrations by Shark Bay standards. The reason for this appears to be linked to the fact that seawater near the sediment/water interface has a pH of about 7.0 for much of the year (during and for several weeks after periods of high rainfall), which is below the IEP for the iron-oxides. The lower pH in this area of Herald Bight is due to a combination of the seepage into the bay of slightly acidic groundwater, bacterial decomposition of organic matter trapped by mangrove pneumatophores, and poor circulation.

The iron-oxides in sediments from the southern end of Herald Bight can be distinguished from those just 2km north and from those in all other sediments examined in Shark Bay by their high phosphate content. The phosphate content of these iron-oxides often exceeds 50ppm compared with concentrations of less than 1ppm further up the bight. The examination of a series of surface sediment samples taken at regular intervals along line transects perpendicular to the shore at the southern end of Herald Bight reveals a progressive northward decrease in the phosphate content of the iron-oxides. The decrease in the phosphate concentration correlates well with a progressive rise in the mean pH from 6.8 to 8.1 (r = 0.78 at the 95% confidence level); there is no matching shift in the dissolved phosphate concentration. It therefore appears likely that phosphate released during biotic decomposition in the mangrove zone is being adsorbed onto the colloidal iron-oxides, transported northward, and progressively desorbed as the pH rises and the charge on the oxides is reversed. It was also noted that benthic flora were more abundant and extended further seawards in this area of the bight than further north.
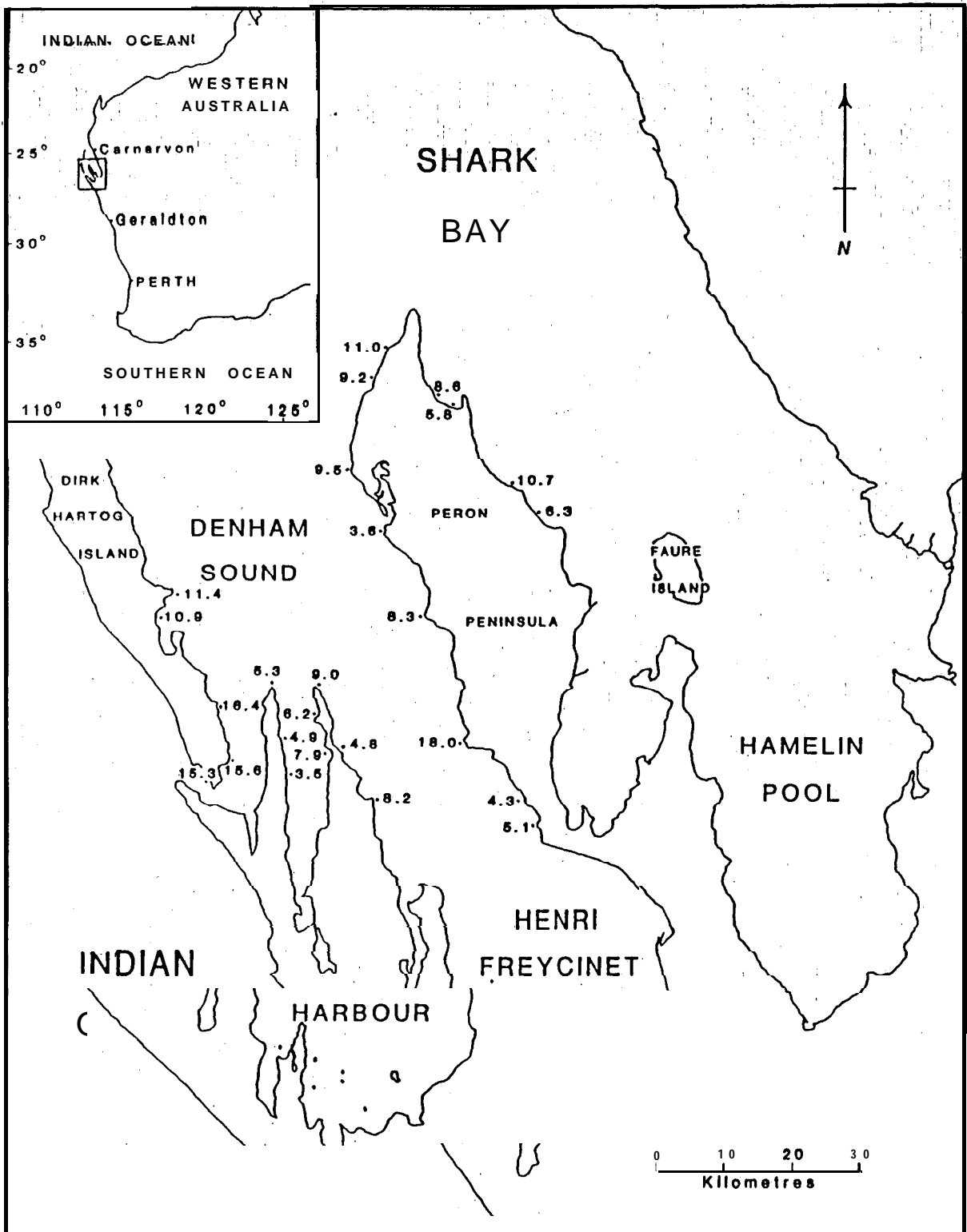
Figure 4. Map of Shark Bay showing regional variation in the geometric mean cadmium cancentration (in ppm) for pooled samples of **the** pearl oyster **Pinctada curchariarium;** after McConchie **et al.** (1988).

CONCLUSIONS AND IMPLICATIONS FOR THE GREAT BARRIER REEF REGION

This paper has outlined some of the ways in which inorganic colloids are very effective agents in the transport nutrients and other trace elements in aquatic environments, and some of the ways in which their chemical behaviour respohds to changes in environmental conditions. For Shark Bay it is clear that the ion transporting capacity of colloidal iron-oxides has a major influence on several biological processes in the embayment. Although colloids probably have their greatest impact in estuarine settings where changes in pH and electrolyte concentration are marked, the Shark Bay study indicates that they. may also be important in fully marine settings.

In the Great Barrier Reef region, nutrients and other trace elements, derived from agricultural run-off or sewage disposal operations on the mainland, and adsorbed onto colloidal particles, are very unlikely to be transported far offshore. Rises in electrolyte strength and pH in oceanic waters are likely to restrict the dispersion of colloidally transported ions to the nearshore zone, particularly to the major estuaries.

Although in offshore areas of the reef, colloidal material derived by continental runoff is not going to have a significant impact, any local accumulations of colloidal material on the reef may have an effect. A possible source of local accumulations of colloidal material on the reef involves the grounding and breakup of ships carrying iron- or aluminium-oxides. Both iron- and aluminium-oxides have IEPs in the pH range which would be expected in geochemical subenvironments on the reef. Hence, there may be a need for evaluation of the likely environmental impact of the accidental dumping of large quantities of these oxides on the reef, and some contingency planning to deal with such an eventuality. The hulks of wrecked ships may also constitute a source of colloidal iron-hydroxides during decomposition, and there is a tantalising link between this possibility and the commonly observed increase in algal growth around rusting ironware in marine environments (e.g., the wreck on Heron Island in the Capricomia section of the Great Barrier Reef). A further possible source of colloidal material which may affect nutrient cycling in the reef environment involves biogenic oxide or hydroxide production by the alga *Trichodesmium* (Jones *et al.,* 1986), and this possibility also warrants further investigation.

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SUMMARY OF FIRST DAY'S PROCEEDINGS

Dr D. Kinsey

I will attempt to .summarise what I believe to be the main thrust evident from the papers which were heard yesterday.

Firstly, nutrient input may come from general run-off, either natural, urban or agricultural, or from point sources such as rivers, streams and specific effluent outfalls. However, there are other sources which are easy to overlook. The first, and by far the greatest of all sources of nutrients for the continental shelf is the throughput of oceanic water. The levels are low but the volumes are extremely high. Added to this, there is the input occasionally or in some cases frequently, of nutrients brought to the surface in shelf edge intrusions of deep water or from direct upwellings.

It is clear that all biological processes proceed as a function of nutrient concentration. Concentration is a function of supply and recycling. Supply is a function of input, mixing and circulation. Recycling is a function of biological processes.

The following principles apply in consideration of the effects of nutrients on living ecosystems:

.   there is some evidence of local response to specific point source inputs in some but not all cases;

.   there is clear evidence of some deterioration in inshore reef systems. It is not clear whether this is man-induced;

.   there is general agreement that phosphate poses the most significant threat especially to corals and other calcifying organisms;

.   there is good general agreement on the phosphate levels above which some threat is posed;

.   the present inshore nutrient levels (particularly phosphate) are at or near threatening levels:

   ▪ it is not clear for how long they have been at that level
   ▪ it is not certain whether human influences are involved
   ▪ it is not clear how long we have before these levels reach hazardous limits.

These factors can be monitored and the outline of a management. strategy could be formulated on the basis of knowledge of the participants present at this workshop to determine:

   ▪ the level of risk
   ▪ the rate of change towards higher risk
   ▪ the need for further controls.

Such monitoring will certainly need to be applied to

- specific areas such as Green Island/Cairns, the Whitsuridays, arid Townsville
- Great Barrier Reef-wide

The methodology and cost-effectiveness of monitoring have been considered to some extent in the papers and it is clear that reasonable strategies can be discussed at this time.

WORKING GROUPS: GUIDELINES FOR DISCUSSION

1. THE NEED FOR CONCERN

    1.1   Identify types of discharge/activity
    1.2   Geographical areas of concern
    1.3   Any other aspects

2. MANAGEMENT RECOMMENDATIONS

    2.1   Objectives of management
    2.2   Overall management strategies
    2.3   Requirements for management
    2.4   Management actions needed
    2.5   Any other aspects
    2.6   Co-ordination

3. MONITORING STRATEGY

    3.1   Objectives of monitoring
    3.2   Monitoring strategy
    3.3   Monitoring methods

4. RESEARCH

    4.1   Gaps
    4.2   Priority studies

WORKING GROUP PARTICIPANTS

1. Great Barrier Reef Region Working Group
    Des Connell - Chairman
    Grahame Byron - Rapporteur
    Peter Ottesen
    Peter Bell
    Miles Furnas
    Graham Jones
    Alan Mitchell

2. Green Island Working Group

    Leon Zann - Chairman
    Jon Day - Rapporteur
    Eric Gustavson
    Ian Baxter
    Brian Prove
    Wendy Richards
    Cecily Rasmussen
    David Hopley
    David McConchie

3. Whitsunday Island Area Working Group
    Claudia Baldwin - Chairman
    Peter McGinnity - Rapporteur
    Paul Greenfield
    Phillip Cosser
    Dave Johnson
    Janice Morrissey

WORKING GROUP REPORT ON GREAT BARRIER **REEF** REGION
D. **Connell** and **G.** Byron

THE NEED FOR **CONCERN**

Sources external to-the Marine Park are believed to contribute a
significant volume of nutrient throughout the GBR. Anthropogenic inputs to
the reef through agriculture and sewage discharges were identified as being
a major concern in controlling nutrient enrichment in the GBR Region.

The group felt however that there was a need to establish the relative
importance of natural versus anthropogenic sources. The major natural
sources were considered to be the open ocean and runoff from natural
catchments.

In general, the group felt that inshore reefs close to the mainland sources
of discharges were in need of careful management when considering future
development proposals in the GBR. In particular the section of the reef
north of Cairns was felt to be vulnerable to nutrient discharges because of
its proximity to the shoreline end of the prevalent northerly flow of
seawater. This flow could transport nutrients from southern sources to
this area.

Existing developments in the Whitsunday area and Green Island have resulted
in the exposure of the adjacent reefs to increased levels of nutrients. In
addition, the large nutrient inputs from sewage in the Townsville area
raises questions as to its biological impact. The Trinity Inlet area near
Cairns is in a somewhat similar situation, and the many current and
proposed developments in the Cairns area generally were--of--con-c-erny

Specific parts of the reef adjacent to resorts, floating hotels, and reefs
used as tourist destinations in some cases may be exposed to detrimental
effects from nutrient containing discharges.

MANAGEMENT RECOMMENDATIONS

Management Strategies and Ambient Water Quality Standards

The group recommended that proponents should be requested to use the best
wastewater treatment technology which is economically feasible for their
project, and suggested that there would also be considerable advantage in
setting tolerance levels for nutrients in ambient waters. Whilst accepting
that there is currently insufficient information available to set ambient
water quality standards with a high level of confidence, the group agreed
that a set of criteria and standards can be developed which will provide
guidelines for protection. As further information becomes available, these
guidelines can be changed and improved.

The group agreed that a 20% decrease in the growth of corals can, be used as a reference for the development of these guidelines. However, it should be kept in mind that the guidelines should, be applied with caution to different sections of the reef due to their differing biological and physico-chemical nature.

'The following water quality parameters are suggested as most appropriate for monitoring nutrient enrichment in the GBR and where appropriate the suggested ambient water quality guideline, based' on information currently available, is noted after, the parameter.

Physico-Chemical

Transparency/NFR (Non Filterable Residue)
Salinity/Conductivity
Temperature
Dissolved Oxygen (in some situations)
Total P
Ortho P — based on a 20% decrease in growth. It is suggested that 10-20% (averaged over a large number of samples) over ambient levels could be tolerated.
Dissolved Inorganic Nitrogen $<0.2 \mu g/AL$
Chlorophyll a $<1 \mu g/L$

All these-levels need to be verified by further study.

Biological

% cover of macroalgae
nos. and species of corals
live + dead coral cover
filter feeders

Coordination

Consideration should be given by GBRMPA to request membership of the Queensland Water.Quality Council to enable it to coordinate its activities with other bodies such as the Qld DPI.

The Authority.should consider the possibility of establishing a Nutrient Advisory Committee.

The group felt that further workshops on nutrient management and research on the reef would also greatly assist in coordination of information and research effort relevant to nutrients.

MONITORING STRATEGY

The aims of the GBRMPA strategy for monitoring nutrients should be to:

> i) detect over time any changes in the reef resulting from nutrient containing discharges and using this information, in formulating and assessing the success of current waste water management strategies;

ii) establish existing ambient levels of nutrients and their relationship to biological factors;

iii) the provision of plans for water quality management relevant to development proposals; and

iv) request that nutrient monitoring be included in appropriate research projects.

The monitoring strategy should focus on identified problem areas together with appropriate control areas. It should also provide a database for the establishment of a mass balance of nutrient inputs and losses to the reef.

The development of remote sensing techniques for monitoring of nutrient input and distribution should be given careful consideration.

RESEARCH

The working group recommended that detailed studies of a number of discharges in different situations should be undertaken and related to the physico-chemical and biological characteristics of the location so that guidelines on tolerances can be developed. In carrying out this study there would be -an advantage in separating the effects of sewage discharges, water runoff and groundwater.

The group further recommended that there should be a continuation of investigations of mainland runoff paying'particular attention to flood events.

The group noted that a considerable volume of data on physico-chemical characteristics and related biological characteristics was available and should-be-evaluated.

The group supports the continuation of development of water exchange models on a range of scales across the GBR.

WORKING GROUP REPORT ON GREEN ISLAND
L. Zann and J. Day

BACKGROUND

Green Island, 27 kilometres north-east of Cairns, is a vegetated sandy cay of approximately 12 hectares. The cay (660m x 260m) lies roughly east-west, surrounded by a lagoonal platform reef of approximately 1200 hectares (4.6 km x 2.8 km).. The reef is regarded as a mid-shelf reef although it is situated relatively close to the mainland.

The cay has probably been the subject of intensive human use longer than anywhere else on the Great Barrier Reef. It has been a popular tourist destination since the 1890s, and the first regular tourist ferry service began in 1924. In 1987 approximately 190 000 people visited the cay.

The reef has been subjected to two major infestations'of crown of thorns starfish during the periods 1962-67 and 1979-81. Because it was the first reef on which infestations of the starfish were seen on both outbreaks of crown of thorns starfish on the Great Barrier Reef (1962-1974; 1979 - present), it has been suggested that Green Island was at or near the epicentre of A. planci outbreaks on both occasions.

Today the reef environment surrounding Green Island is generally considered to be severely degraded, and there is circumstantial evidence to relate this degradation with changes in nutrient levels.

MANAGEMENT CONCERNS RELATED TO NUTRIENTS

There are two levels of concern regarding changes in nutrients in relation to Green Island:

1. Local influences-From island based septic systems, existing and previous. For example, the Cairns City Council permit.to discharge septic waste
   - current permit requires only flow volumes to be recorded and typical analyses of effluent
   - Queensland Water Quality Council requirements do not'include nutrient analysis.

2. Broader area concerns - What are the external nutrient influences affecting Green Island? For example, many mainland/broader area influences, such as the effects of clearing, mining, canefield tillage, urbanization and/or trawling of adjacent seabeds, could be having an effect.

CURRENT STATUS OF KNOWLEDGE ABOUT GREEN ISLAND

While there are only a few scientific publications, there are many relevant past research studies; for example:

- Beach Protection Authority's beach profiles
- Geomorphological studies (Kuchler)
- COTS program (Pearson 1960s; Harriott and Fisk, 1980s)
- Flow modelling (Wolanski, Black)

Most of these have been summarised in the Review of Current Knowledge of Green Island (Ian Baxter, James Cook University).

Current research and monitoring studies include:

- Northern Fisheries Research Centre - studies of seagrass, barramundi and prawns
- James Cook University multi-disciplinary study
   a) sediment cores through seagrass
   b) coral cores to determine past levels of nutrients
   c) dye studies to determine the fate of sewage
- Crown of Thorns Starfish Program - studies of crown of thorns starfish recruitment (Fisk)
- Cairns City Council - water quality analysis
- Beach Protection Authority - monitoring and aerial photography of beach areas

RECOMMENDED MANAGEMENT STRATEGIES

1.   Ascertain the problem - Identify the causes and quantify the impact

   a) Determine the extent /nature of the local problem, conduct immediate research (over at least a one year period)
      - monthly analyses of wastes
      - dye studies to establish dispersion
      - establish baseline levels

   b) Establish fixed monitoring sites to be monitored regularly, at different tides and different seasons. It is recommended that Green Island should not be studied in isolation from the region.

   c) Search "back in time" using cores and sediment profiles to establish past trends. (Importance of Isdale/Rasmussen studies).

   d) Longer-term research (2-3 years)
      - Compare Green Island situation with other islands of similar proximity to the mainland (e.g. Low Isles and Three Isles).

2.   Rehabilitate from the present autotrophic to a heterotrophic, coral-dominated community

   The management actions required will depend on the extent of the problem. Examples from other areas (e.g. Kaneohe Bay, Hawaii) indicated that a disturbed reef may quickly recover when the disturbance is removed.

POSSIBLE **MANAGEMENT ACTIONS**

a). If a local point source is shown to be the main probldm, (i.e. if local sewage is the major concern), then the alternatives are:
- tertiary treatment on island
- 'ship waste water back to Cairns for treatment
- 'develop better bacteriological process for treatment. (e.g. new systems which work more effectively in salt water)

b) If mainland influences turn out to be the main problems; rather -than or in addition to local sources, then there'are major political and environmental implications.

RECOMMENDED **MONITORING** STRATEGY

The main objective should be to determine if changes are occurring, and their likely causes (e.g. anthropogenic influences)

It is important to have a structured monitoring program. Monitoring of the following key parameters for nutrients should be undertaken in the priority order indicated:

a) Water quality
1. - phosphates
2. - nitrogen compounds - nitrates
                          - nitrites
                          - ammonia
3. - chlorophyll a

b) Biological
4. - algal indicators
5. - state of the corals (especially the susceptible corals)
6. - crown of thorns starfish populations

FURTHER POINTS WHICH NEED TO BE CONSIDERED

Members of the working group also raised the following points in their discussions:

a) If desalination plants are to be widely used in the Great Barrier Reef Region, the use and effects of flocculants (e.g. Calgon) should be investigated.

b) High salinity levels (and variations in salinity) reduce the efficiency of septic systems.

c) The implications of fishfeeding affecting nutrient levels should 'not be overlooked.

d) Large dams (like Lake Tinaroo) act as nutrient storages which are often flushed out after a "big wet".

e) Need to collect and disseminate results of chemical analyses in a standardised way - it is suggested that GBRMPA should print cards/sheets for universal recording methods.

f) The importance of coral cores for past trends in nutrient levels should be emphasised.

g) The regional study undertaken on anthropogenic inputs by C. Rasmussen and D..Hopley (JCU) is important, as Green Island should not be studied in isolation.

h) The general productivity of the Cairns reefs is being investigated by remote sensing (Coastal Zone Colour Scanner for chlorophyll a),

i) There is a need for low-cost field equipment to **be** developed for in-situ monitoring. D. McConchie (NRCAE) is currently developing such a kit.

j) The subject of nutrient enrichment in the Great Barrier Reef Region should be considered as a Research and Monitoring priority area for the Great Barrier Reef Marine Park Authority.

WORKING GROUP REPORT ON WHITSUNDAY ISLANDS AREA
C. Baldwin and P. McGinnity

THE NEED FOR CONCERN

There are no real data to indicate the need for concern, however, the general feeling is that inputs of nutrients, from the Whitsundays area is trivial on a Regional scale. There are, however,, possible concerns for localised areas within the Whitsundays, particularly those fringing reefs subjected to heavy usage (i.e. combination of stresses as discussed by Dr Kinsey). The Whitsunday area is characterised by a high tidal range. As a result, it was suggested that nutrients may be distributed more widely and may not be pushed back onto the coast as occurs further north.

SOURCES OF NUTRIENTS

a)   <u>Island Resorts</u> - (8 resorts): Hook, Hayman, Hamilton, South Molle, Lindeman, Long (2), Daydream

- point source - untreated and secondary treated sewage
                        - fish feeding and dumping of garbage
- non point source - run-off (including effluent used for irrigation)
                        - seepage from septic systems

b)   <u>Vessels/Anchorages</u> - (100 plus bare boats, and cruising yachts, 30 plus medium size charter vessels, ocean liners)

- non point source - sewage
                        - garbage (food scraps)

c)   <u>M a i n l a n d</u>

- point source - sewage* (Airlie Beach, Shute Harbour, Proserpine)
- non point source - urban run off into rivers and creeks,
                        - agricultural run-off adjacent to cane areas (particularly Proserpine and Pioneer Rivers)

d)   <u>Hardy Reef Pontoons (2)/Fast Catamarans</u>

- point source - sewage from resident staff (3-4) at Hardy Reef pontoons considered insignificant
                        - fishfeeding
- non point source - sewage in holding tanks and discharged on return trip to mainland

* note: extent of discharge not known to participants

GEOGRAPHIC **AREAS** OF CONCERN

a)   Fringing reefs used for tourism at resort islands
          certain reefs were identified as having particular tourist
          significance;   some resorts with odour problems

b)   Well developed fringing reefs throughout the area (see sites zoned
          MNPA 'B', Central Section Zoning Plan)

          these reefs may already be stressed by use (e.g. anchor damage,
          damage by snorkellers and divers)

c)   Fringing reefs at heavily used anchorages where approximately 30
          vessels are often anchored, but depending on wind, could be many
          more than this.

          Butterfly Bay
          Windy Bay
          Nara Inlet
          Shute Harbour
          Gulnare Inlet
          Cid Harbour
          Whitehaven Beach

OBJECTIVES OF MANAGEMENT IN THE **WHITSUNDAY AREA**

·   maintenance of quality environment for conservational values
        and tourism, including, fringing reefs, national parks,
        unpopulated islands.

MANAGEMENT   STRATEGIES

a)   locate discharges to obtain good dilution and transport away from
          areas of concern (based on studies)

b)   encourage resorts to treat sewage to achieve cost efficient
          nutrient removal and in particular removal of solids and carbon
          (secondary treatment preferred)

c)   require tertiary treatment only if shown to be necessary

d)   encourage use of sea water for flushing of cisterns and mix low
          salinity effluent with brine from dedischiators prior to ' arge

e)   implement a monitoring program to investigate trends in both water
          quality and biota at geographic areas of concern, as above, (based
          on outcome of pilot study).

MONITORING

Initial   Studies

Priorities are,: a) resort discharge and run-off (local impacts)
                 b) anchorages
                 c) mainland (river and creek) run-off
                 d) mainland discharges
                 e) fish feeding (local impacts on' water'quality and
                    biota)

a)   to be investigated in a pilot study over the next   18 months at
         Hamilton Island, Daydream Island (to give range in size of
         discharges/run off and geographic locations) and then possibly
         expanded to all resort discharges.

b)   to be investigated at key sites beginning with a pilot study at
         Butterfly Bay (major anchorage, outstanding reef)

c)   add water quality to studies proposed by Dave Johnson (possible
         integration with work by Furnas and Mitchell)

d)   to be investigated in a similar manner to (a)

e)   a study at a selected site(s) to be incorporated in Region wide
         monitoring program.

Ongoing Studies

         Expansion of pilot study (a) above to cover all resorts and
         mainland discharges.

         Implementation of a key sites monitoring program to include water
         quality and biota and to include some control sites.

APPENDIX ONE: PROGRAM

THURSDAY NOVEMBER' 26

9.00   Opening —
Chairman of Workshop: Don Kinsey, Executive Officer,
                Great Barrier Reef Marine Park
                Authority (GBRMPA)

Time	Speaker	Topic
9.20	Claudia Baldwin, Peter McGinni ty, Grahame Byron, GBRMPA	Waste discharge in the Great Barrier Reef Marine Park
9.40	Ed Boggiano, Qld Water Quality Council	Waste discharge controls under the Clean Waters Act
10.00	Don Kinsey, GBRMPA	Responses of coral reef systems to elevated nutrient levels
10.20	David Hopley, Cecily Rasmussen Sir George Fisher Centre, James Cook University (JCU)	Effects of nutrients carried by mainland run-off on reefs of the Cairns area
10.40	MORNING TEA	
11.00	Alan Mitchell, Australian Institute of Marine Science (AIMS)	River inputs of nutrients
11.20	Mike Risk, McMaster University and Paul Sammarco, AIMS (presented by Dave Johnson)	Input of terrestrial organic matter to GBR corals as determined by stable isotopes and possible effects on bioerosion rates: A preliminary report
11.40	Brian Prove, Qld Department of Primary Industries	Soil erosion monitoring in cane fields on the wet tropical coast
11.50	Dave Johnson, Bob Carter, Geology Dept, JCU	Sedimentary evidence on the seaward limits of suspended materials from rivers
12.10	Kevin Boto, AIMS (presented by Alistar Robertson)	Nutrient cycling in mangrove systems

12.30	DISCUSSION	
12.45	LUNCH	
1.40	Des Connell, D. Hawker Griffith University	Effects of nutrients on corals
2.00	Janice Morrissey, GBR Aquarium	Nutrient cycling in the Great Barrier Reef Aquarium
2.20	Leon Zann, GBRMPA	A case history from Tonga
2.40	Wendy Richards, Reef Biosearch	Algal overgrowth: does it relate to nutrients from tour vessels and pontoons
3.00	Paul Greenfield, Peter Bell Dept of Chemical Engineering Queensland University	Monitoring and treatment of nutrients in wastewater discharges to the GBRMP
3.20	AFTERNOON TEA	
3.40	G B Jones, Townsville/Thuringowa Water Authority	Nutrient input in the tropics
4.00	Miles Furnas, AIMS	Nutrient uptake by phytoplankton/water column processes
4.20	D McConchie, Northern Rivers College of Advanced Education	Relationships between colloids and nutrient cycling
4.40	Eric Wolanski, AIMS	Predicting the movement of nutrients in the Great Barrier Reef
5.00	DISCUSSION	

FRIDAY NOVEMBER 27'

09.00   #Explanation of roles of concurrent working groups

       1. Great   Barrier   Reef Region:

           . to determine the need for concern about nutrients in the
              GBR Region
           . to make management recommendations
           . to develop monitoring strategy, if necessary

          Chairman: Des Connell
          Rapporteur: Grahame Byron

       2. Whitsunday Area:

           . to determine the need for concern about nutrients in
              localised areas such as Whitsundays
           . to make management recommendations
           . to develop monitoring strategy, if necessary

         Chairman: Claudia Baldwin
          Rapporteur: Peter McGinnity

       3. Green Island Area:

           . to determine the need for concern about nutrients in
              localised areas such as Green Island/Cairns
           . to make management recommendations
           . to develop monitoring strategy, if necessary

          Chairman: Leon Zann
          Rapporteur: Jon Day

          -help yourself to morning tea as need arises-

12.30   LUNCH

         . Chairman and rapporteurs will'write up discussion and
          recommendations from morning. These will be typed and
          distributed for discussion after lunch

1.00   . Optional technical tour of GBR Aquarium (approximately'
          $5 per person)

2.30   Presentation and discussion of working group papers,

        Chairman: Don Kinsey

APPENDIX TWO: PARTICIPANTS IN WORKSHOP

NAME (in alphabetical order)	AFFILIATION
Claudia Baldwin	Great Barrier Reef Marine Park Authority (GBRMPA)
Peter Bell	Department of Chemical Engineering University of Queensland
Ed Boggiano	Queensland Water Quality Council
Grahame Byron	GBRMPA
Des Connell	School of Australian Environmental Studies, Griffith University
Phillip Cosser	School of Australian Environmental Studies, Griffith University
Christine Dalliston	GBRMPA
Jon Day	GBRMPA
Miles Furnas	Australian Institute of Marine Science (AIMS)
Paul Greenfield	Department of Chemical Engineering University of Queensland
Eric Gustavson	Queensland Water Quality Council
David Hopley	Sir George Fisher Centre for Tropical Marine Studies, James Cook University (JCU)
Dave Johnson	Geology Department, JCU
G.B. Jones	Townsville/Thuringowa Water Authority
Graeme Kelleher	GBRMPA
Don Kinsey	GBRMPA
D. McConchie	Northern Rivers College of Advanced Education
Peter McGinnity	GBRMPA
Alan Mitchell	AIMS
Janice Morrissey	GBR Aquarium, GBRMPA

Peter Ottesen	GBRMPA
Brian Prove	Queensland Departmept of Primary Industries
Cecily Rasmussen	Sir George Fisher Centre, JCU
Wendy Richards	Reef' Biosearch
Alistar Robertson	AIMS
Eric Wolanski	AIMS
Leon Zann	GBRMPA