REGIONAL COORDINATING UNIT
EAST ASIAN SEAS ACTION PLAN

UNEP UNITED NATIONS ENVIRONMENT PROGRAMME

PROCEEDINGS OF THE WORKSHOP ON EUTROPHICATION IN TROPICAL MARINE SYSTEMS - THE IMPACTS AND MANAGEMENT OF NUTRIENT POLLUTION

Edited by Trevor J. Ward

RCU/EAS TECHNICAL REPORTS SERIES NO. 8

Prepared in cooperation with:

Great Barrier Reef
Marine Park Authority

UNEP
Bangkok, 1996

Note: This document is proceedings of the Townsville Workshop on Eutrophication in Tropical Marine Systems - The Impacts and Management of Nutrient Pollution. The workshop was held during 8-16 August 1995 at the Great Barrier Reef Marine Park Authority in Townsville, Australia as one of the activities under the EAS-33 project "FP/ES/9101-94-66: Training workshop on the biological effects of pollutants: East Asian Seas region". The project was funded by the UNEP Regional Office for Asia and the Pacific (UNEP/ROAP) as a contribution towards the development of the East Asian Seas Action Plan.

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PREFACE

This volume of the Regional Coordinating Unit for the East Asian Seas Action Plan (EAS/RCU) Technical Reports Series presents the proceedings of the Townsville Workshop on Eutrophication in Tropical Marine Systems — the Impacts and Management of Nutrient Pollution. The workshop was part of the EAS-33 (Biological Impacts of Pollutants) project, approved by the Coordinating Body on the Seas of East Asia (COBSEA), and held during 8 - 16 August, 1995, at the Great Barrier Reef Marine Park Authority in Townsville, Australia.

The EAS-33 project was funded by UNEP's Regional Office for Asia and the Pacific (UNEP/ROAP) as a contribution towards the development of the East Asian Seas Action Plan.

The Townsville Workshop, the third in the Biological Impacts of Pollution series, focuses on the effects of nutrient pollution in tropical systems and on key issues surrounding its management and amelioration. This issue was identified by the participants of the Singapore Workshop as a key problem of concern in many of the countries participating in the East Asian Seas Action Plan.

The main themes of the Townsville Workshop were nutrients in the water, their biological effects in the water column and on coral reefs and the practical issues associated with regards to managing the pollution in order to reduce impacts. The technical understanding of nutrient issues was linked to actions to reduce their impact by focusing on ways to use scientific data and information to establish practical and effective environmental management programmes.

The workshop was designed to achieve two major goals:

- to present a basic understanding of nutrient pollution issues in tropical systems, together with modern techniques and approaches to their management; and
- to establish a personal network of contacts so that technical issues facing COBSEA nations may be more easily resolved using networks of laboratories and experts operating in the region.

To achieve these goals a number of Australian resource persons presented material at the workshop. The presentations covered a variety of technical matters, all designed to assist with developing an improved capacity to identify, understand and ameliorate nutrient pollution problems in tropical marine systems.

The scientific programme for the Workshop was developed by the Great Barrier Reef Marine Park Authority (GBRMPA) and CSIRO in conjunction with EAS/RCU. The workshop was conducted by staff from GBRMPA, CSIRO, the Australian Institute of Marine Science, the CRC for Reef Research, and James Cook University.

The workshop proceedings were compiled and edited by Trevor J. Ward, in conjunction with the EAS/RCU. At the EAS/RCU, Mr. Steven Arquitt contributed substantially in the formatting and finalization of the camera-ready copy.

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Trevor J. Ward
Great Barrier Reef Marine Park Authority
and CSIRO Division of Fisheries
Perth, Western Australia

INTRODUCTION

Tropical countries, and particularly the countries of East Asia, are facing an unprecedented rate of economic growth. Their increased growth, and the quest for improvement in economic circumstances and quality of life for many people in the region, is accompanied by much coastal urbanisation and development. This is the result of the growth of new industries (such as tourism) and the expansion of existing ones (such as agriculture). Much of the growth is based on the use of "natural capital", and, if it is to be sustained growth, it will be heavily dependent on the maintenance of the quality of the natural resources. Coastal and marine resources are dependent on an ecological infrastructure: habitats such as seagrasses, coral reefs, mangroves, etc. Many of the natural resources used as the "natural capital" for the current surge of economic growth, and the habitats that support them, are potentially subject to the damaging effects of nutrient pollution.

The pressure of nutrients on coastal systems is largely due to the effects of nutrients and sediments eroded from river catchments, or to those discarded to rivers from industrial processes and sewage wastes. Whilst river catchments have always eroded, the magnitude and the time scales of this erosion are now being dramatically altered by increasing development of river catchments, shores and estuarine wetlands. Marine and estuarine systems are not necessarily able to withstand the often very large increases in nutrient and sediment loads, and so the "natural capital", particularly the sensitive species like coral reefs and seagrasses, becomes progressively degraded (see, for example, Hopkinson and Vallino, 1995).

In some countries the high and immediate cash returns being offered by the markets of advanced countries for agricultural/harvested products are increasing the pressure for use of land to maximise returns in the shortest possible time frame. These pressures can result in the use of highly non-sustainable practices (stripping of forest cover, intensive use of fertilisers, intensive fishing practices, etc.) over large areas. In coastal areas, in response to these market forces, the farming of shrimp has become a major industry, and is still growing. Others, like caged fish farming, are also developing.

The intensive use of shallow coastal systems, including wetlands, can lead to considerable degradation of coastal resources. Mangroves are used as the site for intensive mariculture operations, and the discarding of waste waters from the mariculture sites or processing factories. Together with the pressures arising from urban areas, from agricultural lands and from intensive fishing pressures, coastal marine systems are under intensive pressure in many tropical regions.

Probably the most widespread pollution pressure in tropical regions comes from nutrients and sediments. They alter coastal systems by simplification of the species composition, by altering light climate in the water column, by favouring the growth of opportunistic species like algae, and by reducing the aesthetic acceptability of coastal areas for tourism. Whilst there are many more toxic pollutants that can be found in some places, the changes in nutrient and sediment status of coastal marine systems are characteristic of increasing development of tropical areas. Nutrient and sediment pollution is a major class of pollution, because of its very wide spread occurrence, and it has significant effects in coastal marine systems, even in tropical areas where nutrients and sediments can be naturally high.

In this broad overview of nutrient pollution and management in the tropics, I identify the key issues, some of the responses we need to implement, some key research needs, and finally, a set of the challenges for our future.

THE MAIN ISSUES AND CONCERNS

Balancing production and conservation objectives

Is it possible to increase resource production in coastal systems (fishing, mariculture. tourism, etc.) but do so in harmony with conservation or sustainable management objectives for the natural marine resources?

It is well known that, in general terms, the fish production of coastal systems is related to the primary production, which in turn is related to gross inputs of nutrients (see, for example, Houde and Rutherford 1993). This production sustains the fisheries of coastal communities, provides a livelihood for towns and villages, and in many places is part of traditional cultures. Although pressures on this resource are increasing, because of increasing human population sizes, increasing market opportunities, etc., fishing is still a dominant industry in many tropical nations.

Given the relationship of nutrients to fish production, and experience in managed freshwater systems, we know that the input of nutrients to coastal waters is capable of enhancing the biomass of some species. Unfortunately, these may not be the species we favour for food, or be valuable for sale, and they may actually exclude the species of most value. We have little way of controlling which species respond to nutrient inputs (except in cage systems), and so permitting the increasing inputs of nutrients to coastal waterways is a high risk strategy. In fact, in many places, very undesirable species, such as toxic phytoplankton, may respond to enhanced nutrient conditions, thus dramatically reducing the value of the "natural capital".

So, increasing the nutrient loads to tropical marine waters may have very significant associated environment costs, and some of these may have direct commercial impacts on the "natural capital". These costs may include:

- altering coastal habitats (changing sand to mud, clear water to turbid water, etc.)

- modification of species diversity (altering the mix of species, replacing populations of valued species with species of lower value)

- blooms of species, causing nuisance and toxicity (for recreation and seafood industries)

- unbalancing of ecosystem services and processes (reducing the ability of estuaries and bays to absorb natural stresses such as floods or cyclones)

- a plethora of indirect costs (such reducing the availability of low-cost trash fish for mariculture operations)

Some of these environmental costs might be offset by complementary management strategies (such as use of protected areas to maintain genetic diversity, shifting of fishing activities to less polluted places, etc.), but it is probably more cost-effective to maintain control over the inputs of nutrients than to attempt to maintain the "natural capital" in the face of increasing pressures from degrading influences. Certainly, once an estuarine or marine system has been substantially degraded the cost to restore the original ecosystem values is probably prohibitive. As an example, in Australia's most famous nutrient polluted estuary (the Peel-Harvey, in the south-west of Western Australia), repeated blooms of toxic algae are a major problem for the tourism, recreation and fishing industries. In recent years remedial efforts have included the development of new agricultural practices in the catchment (tree-planting, fertiliser re-formulations, buffer zones, etc.) and a $50M channel designed to bring seawater into the estuary to prevent the development of anoxia and the seasonal release of sediment-bound nutrients into the water column. However, even here, under the weight of advanced technological innovation, the success of these efforts in returning the Peel-Harvey values and preventing algal blooms remains to be seen.

Nutrients are of course a natural part of all marine systems. Since the biological systems will have some ability to absorb nutrients without becoming radically unbalanced, they will have some capacity to assimilate additional (probably small) amounts of added nutrients. The major issue is knowing how much, and where and when, such nutrients can be permitted to enter the marine and estuarine environment without having unacceptable effects on the environment. Probably the key problem preventing broad acceptance of the fact that **some** nutrients can probably be discharged to tropical waters (i.e. they can assimilate some nutrients without detrimental effects on the natural values) is the lack of cases where this has been shown to be effective. In fact, there is a proliferation of cases demonstrating the opposite. Typically, conservation values for a marine systems are poorly known or expressed. Even where the values can be articulated as some form of ecological target (such as maintenance of a given population size of a valued species, water clarity of greater than a given value, maintenance of the existing spatial range of a habitat type, etc.) the process for monitoring and reporting on such indicators is not well established, or is too expensive to be properly implemented. This means that there are few cases where nutrient discharges have been demonstrated to be acceptable.

So, in terms of the usual range of values ascribed to tropical marine systems (harvesting of marine resources, recreation and tourism, nature conservation) no examples exist where the costs of pollution and the benefits of effective management have been well demonstrated. This means that there are no prior models that can be adopted for implementation in tropical marine systems to manage the inputs of nutrients consistent with the conservation and sustainable use of "natural capital". The most appealing current theories are those relating to the multiple-use of large marine ecosystems paradigm, because at least they offer a framework within which multiple stakeholders might be forced to address conflicting uses for the same resources, and do so within a long term context that promotes sustainable use.

Without doubt, the key environmental issue facing Asia over the next few decades will be the balancing of demands for increased natural resources with the conservation of the "natural capital", since much of the growth will be critically dependent on this capital. Developing sustainable uses, and identifying the extent to which pollutants such as nutrients can be assimilated in the environment without detrimental effects on the "natural capital", will be the central technical matters to be resolved.

Improved waste management

Since much of the nutrient reaching estuaries and the seas is derived from land-based sources, improved catchment management practices and industrial waste controls should result in decreased inputs of unwanted nutrients into coastal systems. Included in this is the need for management of sediments eroding from lands, because they carry large amounts of nutrients, and once deposited into coastal sediments these nutrients, under certain conditions, can be released to the water column. Of course, as well as being a nutrient source, sediments themselves can have major physical effects in coastal systems, for instance smothering reef systems and altering the nature of benthic sediment fauna.

Other sources of nutrients include urban areas, and particularly those more industrialised ones. Sewage and industrial wastes often are located in specific places, and there they can have very dramatic effects on the local marine ecosystems. Whilst marine environment managers are sometimes forced to accept major degradation of some areas, they try to trade this off against protection of other areas, according to the time-honoured principle of keeping all the "dirty" industries together. Although this does keep open the option to maintain some areas in an unpolluted condition, it is more likely to merely postpone the degradation to another time rather than fully protecting areas from pollution. This is because of the increasing demand for development of water-frontages and other coastal development sites, and the result of incremental decision making without a strategic planning framework (known as the "tyranny of small decisions").

The conflict between urbanisation and sustainable use of coastal resources is difficult to manage, but for pollution aspects, it probably is best managed by controls on inputs of nutrients to waterways (such as controlling the effluents from waste treatment works). Whilst such treatment options are apparently costly, the alternative (no treatment) is also costly, but in a different way — in environmental damage. Some of these costs are entrenched by trade and market schemes that do not include some explicit cost for environmental pollution or application of a trading penalty based on the environmental cost associated with the production of a commodity. Even so, environmental pollution is an economic cost that is displaced away from its source, and it commonly generates indirect costs to other sectors. For example, in Australia, in some places fish are known to have high levels of toxic chemicals, and fishing is banned. The environment was polluted by industries that have long since closed and abandoned their sites, but left large amounts of residues in the sediments of the adjacent bays. So, the bays were used as a free disposal site for wastes, and the cost of this has been borne by the ecosystem (which has been degraded), and by the commercial and recreational fishing industries (which now cannot take fish from this area). Had the true cost of disposal of wastes been accepted by the companies involved at the time, the wastes might have been properly treated, disposed of more safely, or perhaps recycled within the factories.

Improving waste management practices may not be as costly as they first appear. In Australia, research has discovered that the more efficient use of fertilisers could save farmers money as well as reduce nutrient-rich runoff to estuaries, and even offset the cost of development of new formulations of fertilisers that are less prone to leach nutrients into waterways.

Forgone opportunities and their costs

Permitting nutrients to continue to have impacts in coastal systems may lead to great loss of future opportunities. They may include:

- tourism – pristine marine environments are becoming increasingly rare; failing to maintain them is likely to incur a major forgone opportunity cost

- loss of genetic resources – bio-prospecting for valuable genetic resources is a growth industry, and the tropics of Asia are a major storehouse of species

- fisheries – loss of harvestable resources, particularly resources that have yet to be commercially exploited.

Whilst the future value of resources (such as a particular species) is always a matter of great speculation, it is clear that many major advances in science and technology are based on studies, and manipulation, of natural systems. Without this as the basis for inspiration, it has been argued that the future of civilisation is bleak, as we try to raise the quality of life for many of the tropical nations but without the lessons learned by their natural ecosystems and expressed in their existing ecological structure and functions (see for example, Norse 1993).

Meeting Global responsibilities

A number of countries are party to international conventions such as RAMSAR and the Biodiversity Convention. These agreements impose certain responsibilities on countries in respect to their management and maintenance of biodiversity. One of the major issues that can degrade biodiversity is nutrient pollution. The development of achievable national goals for these agreements and the monitoring of progress towards them in the face of threats from pollution is a key issue for national governments.

HOW CAN WE RESPOND?

Monitoring programs

To be able to detect and report on nutrient pollution and its effects we need monitoring programs designed to achieve specific goals. These monitoring programs need to be scientifically robust, but also cost-effective. In general, they should focus on two types of indicators: stress and response indicators. Stress indicators are those that measure the extent and type of stress being imposed on the natural resources (such as nutrient levels in water, biomass of opportunistic algae, etc.). Response indicators are those that are linked to the resources we value (such as fish catch and effort, area of coral reefs, etc.). Key steps in establishing a monitoring program are:

Prioritisation of resources and pollutants to be monitored.

To ensure that the most important issues are monitored, it is necessary to prioritise according to the following criteria:

- high value
- most vulnerable
- key habitats, ecological processes, or ecosystem services
- most toxic or wide spread of effects.

Rigorous design of monitoring program.

Poor monitoring designs can lead to a false sense of security, or can fail to detect key changes in resources/pollutants early enough to permit effective responses. It is therefore crucial that there is a significant investment in the initial design to make the monitoring fully operational and sensitive from its inception. Whilst a monitoring design may be complex, in technical terms, the measurements should be simple and capable of routine collection without highly sophisticated instruments/skills.

Balance between environmental health and resource-driven monitoring.

Because all "natural capital" is supported by ecological processes and structures, it is necessary to monitor not only utilised resources but also key indicators of overall environmental health. Environmental health monitoring may be less intensive and conducted over broader scales, but is an important safety net for detecting slow or un-predicted changes in marine ecosystems that could ultimately have a detrimental impact on the utilised resources.

Clear and explicit objectives.

The clarity of the objectives will determine the success of the monitoring program. These objectives need to be simple and accessible to all stakeholder groups.

Participation by user groups.

A monitoring program can only be successful if it is maintained in the long term. Therefore, a participatory approach involving the user groups needs to be adopted. Participation can consist of taking part in the design, data collection and management, decision making and reporting from the monitoring program.

Indicator selection.

The indicators should be chosen in conjunction with the resource users based upon criteria such as: feasibility; cost-effectiveness; ease of measurement; statistical power; sensitivity; ease of interpretation; and potential for feedback.

Organisation of monitoring personnel and logistics.

To facilitate common understanding of the monitoring objectives and outcomes it is important to encourage linkages between the user groups, national agencies and NGOs through the monitoring program. This should also be used to rationalise the use of human resources in conducting the monitoring.

Interpretation of monitoring data.

Interpretation of the monitoring data needs to be carried out according to the objectives of the monitoring program. To achieve this it is necessary to create a simple but robust method for analysis of the data to produce useful information in an accessible form.

Establishment of the reporting and feedback processes.

Resource users need free and open access to the information from the monitoring programme. To achieve this it is necessary to conduct, for example, regular workshops, have a community newsletter in the relevant languages, etc.

Pathways to management action.

Without a link to management responses or actions, monitoring data is of little value. Decision-makers at all levels need to be fully aware of the resource/pollutant status, and need to carefully manage resource use and pollutant inputs in response to information from the monitoring program. It is also important to consider different ways of managing the resource and the pollutants apart from any traditional mechanisms.

Integration of user objectives.

Different user groups may have conflicting objectives for the same resource or pollutant, and it is necessary to ensure consensus on different ways of maintaining the sustainable use of a resource or achieving ambient levels of a pollutant.

Validation processes.

Different users of the same resource or pollutant may have different perspectives of its value, its status, or the need for management action. Also, they may perceive the outcomes of management in different ways. It may therefore be important to conduct cross-checks of the various data and information, and protocols used.

Use of pilot studies.

Monitoring programs need to be carefully evaluated using a small subset of the resources and the pollutants to assess the feasibility of the full monitoring plan prior to its implementation.

Engineering solutions

Control of nutrient inputs to marine and coastal systems can be achieved using various mechanisms. Land-use planning is a popular form of control mechanism, so that industries that must release nutrients are grouped together, possibly enabling better management of their impacts. For agriculture, forms of fertiliser that are permitted for use are sometimes specified, and erosion control and land-care programs can be supported. However, the most common mechanism is control of point-source releases of nutrients — both rates of release and pollutant content. This can be achieved by licensing discharges, and by supporting improved treatment of waste discharges to reduce nutrient levels in liquid wastes. This might, for example, mean having waste treatment retention ponds incorporated into mariculture facilities, or advanced nutrient stripping of nutrients from sewage.

Whilst treatment at the point-source is the technologically preferred solution, it generally fails to deal effectively with the diffuse sources of nutrients. Introduction of high technology is often costly, and not practical by individual landowners or householders. Also, the end-of-pipe technologies and strategies are conceptually weak because they cannot, alone, correctly define the target concentrations or loads that they seek to achieve. Whilst it is technologically feasible and possible to strip **all** nutrients from all waste waters, the cost is prohibitive. Therefore, all resource users and industries seek targets for nutrient loads and concentrations that can be permitted to be discharged to waterways. In the absence of clear demonstration examples, where marine discharges of nutrients are shown to have no detrimental effects on "natural capital", such targets are often set somewhat haphazardly, and sometimes the level is chosen largely so that an industry will not suffer excessive financial costs in meeting the discharge targets. Thus, in the absence of supportable end-points based on impacts of nutrients on the "natural capital", discharge standards are only capable of effectively controlling impacts of nutrients by trial and error in each situation. Whilst this is not necessarily impossible to achieve, the usual situation is that effective monitoring programs are not put in place and so feedback about the "error" term is not appropriate or timely, and so major effects can pass unnoticed until they become catastrophic.

Overall, engineering solutions offer the prospect of complete elimination of nutrient waste inputs to coastal systems. In practice, this cannot ever occur because of their costs, and the nature of the sources of nutrients. Nonetheless, there are considerable engineering advancements that could be developed to assist with low-cost approaches. These, for example, include the biological stripping of nutrients from waste waters from mariculture operations, the more effective cultivation of land to reduce erosion and fertiliser loss, the more sustainable harvesting of forest resources to reduce soil erosion, and recycling and re-use of water in urban areas.

Impact assessment processes

Like end-of-pipe technologies, impact assessment procedures often lack the appropriate end-points. The key issue, apart from the common failure to implement an effective monitoring program, is the uncritical use of Environmental Quality Criteria (EQC) in the Environmental Impact Assessment (EIA) process. EQCs are somewhat arbitrary standards set for ambient levels of pollutants, and they are often used to manage the discharge of nutrients from industries, and to plan for the optimal siting of new developments in the EIA process. They can be used to minimise negative effects by locating nutrient-rich discharges away from potentially sensitive areas. However, EQCs also lack good and reliable connections with biological effects. So, for example, it is conceivable that an EQC that prescribes the levels of nutrients permitted in water might be never exceeded, yet slow and progressive build up of nutrients in the sediment may be occurring, to ultimately be released back to the water column during an extreme event such as after a major flood when the water column might turn briefly anoxic, or has a very reduced salinity. It is for this reason that the Australian Water Quality Guidelines (a form of EQC) do not provide numerical criteria for nutrients, but suggest that site-specific studies need to be conducted to determine the appropriate acceptable levels of nutrient input for each particular system (ANZECC, 1992).

So, overall, the lack of scientific confidence in the use of EQC in the EIA process means that, in planning new developments using EIA processes and EQCs, it is imperative to implement good monitoring programs to ensure that there is no irreversible damage of the "natural capital". More flexible approaches need to be developed that permit site-specific factors to be incorporated into predictive assessment frameworks, and more comprehensive spatial and temporal scales to be used. Most importantly, the values of conservation and sustainable use of all the natural resources should be included as equal partners in the EIA process. For this to happen rapid assessment methods need to be developed that will quickly identify the values of biodiversity, and the conservation objectives, for the area of concern, and in a manner that can be explicitly used in the EIA process.

Multiple Use Management

Multiple use management implies that marine and coastal systems can, if properly managed, accommodate more than one use of the "natural capital". However, at some places, some specific uses will conflict with each other and this might not be acceptable. For example, in a productive fishing ground it might not be acceptable to attempt to implement nature conservation (such as a marine park), or to site a major industry that will be permitted to discharge nutrients. This means that large regions may need to be zoned for specific uses, and incompatible uses clearly identified and constrained to small areas where they do not interact with each other. Of course, some areas may support several compatible uses. Also, it may be possible to adapt some uses so that they are compatible with other uses within specific areas. For example, oil exploration may be feasible in fishing grounds, given very careful management of activities.

Regions managed for multiple uses may support a number of potentially conflicting uses, provided that there is no spatial conflict, and that their activities do not adversely influence the objectives for the Region's "natural capital". Hence, the multiple use concept is scale dependent, and it is most sensibly applied to large areas (say a Region of many hundreds of square kilometres) within which otherwise conflicting uses can be accommodated. Decisions about which uses can co-exist in the Region, and in areas within the Region, depend on their potential to unacceptably degrade the natural capital *of the Region*., and not only on their local impacts. In other words, decisions about small scale uses, such as oil exploration or small sewage discharges, should be considered in the Regional context as well as the local context.

In the context of multiple use, the main issues to be addressed are:

- an acceptance by all parties that the management and conservation of biodiversity values is an important endpoint for management of the Multiple Use Region (without this, uses of the Region may never be ecologically sustainable);

- adoption of a precautionary approach for management and conservation of biodiversity resources; in addition to case-by-case assessments this might involve zoning of the Region for specific uses, including conservation, and very stringent controls on pollutant discharges;

- adoption of a regional approach to management for sustainable use — some of the key questions here are

  - what are the biodiversity resources of the Region (i.e. an inventory of "natural capital")?

  - what conservation strategies are needed?

  - what are the interim management strategies that need to be applied while more comprehensive plans are developed?

  - what are the effects of the existing uses on the biodiversity resources?

  - is there a need for interim reduction (or controls) on existing pressures on the biodiversity, say from fishing effort or from nutrient pollution?

- a broad agreement to the overall objectives for management of the Region, including indicators, targets and performance criteria for biodiversity, and a regional mechanism to develop and implement these.

Multiple use principles have been perhaps best demonstrated in the development and management of Australia's Great Barrier Reef Marine Park, although for the GBRMP, a number of uses are prohibited because of the unacceptably high risk of their possible detrimental effects on the GBR.

In developing a Multiple Use Region, the key steps are:

- identify a defined and agreed set of ecosystem-based boundaries;

- establish and formalise a regional marine management agency/group;

- establish an interim regional implementation framework, including

  - a set of interim management objectives for the natural capital of the Region

  - indicators, targets and performance criteria

  - implementation principles

  - voluntary arrangements and agreements over issues

- development and implementation of industry codes of practice for the key industries/uses.

- improve the knowledge base for the Region, particularly in the following areas:
  - identification of highly valued areas and species of the Region, together with important ecological processes *at the Regional scale*
  - identification and assessment of specific threats to biodiversity and sustainable use, such as the effects of commercial, recreational and traditional fishing practices, effects of nutrient pollution, shipping accidents, etc. *as a process to assess and prioritise the need for control/reduction measures to be implemented*
  - development of a set of agreed protocols and standard techniques for EIA research and monitoring programs in the Region, so that the routine data collected for statutory purposes associated with each approved use/development can be collated into a sensible database of information for the Region.

Integrated Catchment Management

Nutrient pollution in many tropical areas is generated by non-sustainable land-use practices. Improvements in catchment management can bring many benefits to coastal and marine systems, and particularly the reduction of pollution loads. The concept of integrated catchment management is similar to the multiple use concept, but for marine pollution purposes, a key objective of Integrated Catchment Management (ICM) is the reduction of nutrient loads to coastal waters. The target loads to be achieved depend on a knowledge of the impacts of nutrients in the local coastal waters, and the processes linking nutrients in river flows to effects of nutrients on the marine biodiversity and valued resources.

Process-level research

The key to improving our ability to manage pollution and its impacts is the increase in our understanding of the processes that maintain the natural capital, the processes that we use to manage those resources, the interactions between pollutants and the resources, and the extent to which we can conserve the capital in nature reserves or in off-reserve systems. Increasing our scientific knowledge about these processes must be a critical goal, if we are to move quickly beyond the trial-and-error methods used presently to manage pollution and its impacts.

WHAT ARE THE KEY RESEARCH NEEDS?

Process-level understanding

There are major gaps in our knowledge of nutrient pollution processes, and these substantially impede efforts to better manage the inputs and effects of nutrients in tropical marine systems. The gaps include:

- the natural dynamics of nutrients in water and sediments;
- the way in which nutrients support the growth of undesirable species;
- the land-management practices that lead to enhanced nutrient inputs and availability in estuaries and coastal systems;
- development of cost-effective indicators for nutrients and nutrient impacts;
- development of process-based ecosystem models capable of addressing management concerns.

Resource inventories

Management of the effects of nutrient pollution requires decisions about allocation of financial and human resources. Typically areas, issues and management strategies have to be prioritised. Priorities may be based on the value of the natural resources in question, and on the environmental cost of a likely failure of management. For such decisions to be made in an effective and sustainable manner, accurate assessments of the resources need to be used as the basis of decision making. The development of tools and technology to more rapidly assess the state of the natural resources of marine and estuarine systems is needed to be able to provide the necessary information in a timely manner.

Monitoring and assessment strategies

We know that monitoring plays a key role in assessing and managing the effects of nutrients in marine systems (see, for example, Ward and Jacoby 1992). However, the development of effective monitoring programs following the key steps outlined above is dependent on the correct choice of indicators. Methods for the rapid choice of indicators need to be developed so that monitoring becomes easily and quickly implemented in polluted places to track changes in their condition, or in unpolluted reference places to track the natural dynamics and "health" of ecosystems at large. Whilst a number of indicators have been used in various places to assess the extent of nutrient pollution and its effects, very few have been broadly tested for their applicability in other places. So, to encourage the implementation of effective indicators, cross validation of the value of preferred indicators in different places should be undertaken. For instance, is turbidity in the water a useful indicator of nutrient enhanced conditions in all tropical areas?

Protected area strategies

Many nations now recognise that their natural marine resources are under threat, and they are implementing marine and coastal reserves to protect these resources from complete degradation. However, many of the decisions about the location and the management of such reserves are made on a seemingly *ad hoc* basis, and the effectiveness of such reserves in actually protecting their natural resources from the effects of pollution and other stresses is questionable. It is therefore necessary to develop better ways for the identification, dedication, management and optimisation of protected areas to maintain biodiversity resources in the face of increasing pollution threats. Also, and probably most importantly, because few nations will ever be able to completely conserve their biodiversity in nature reserves that are completely free of pollution stresses, it is necessary to research and develop complementary strategies to maintain biodiversity in off-reserve situations, where some pollution and other stress will always be present. In order to determine if any of these strategies actually works to protect biodiversity (on- or off-reserve), better approaches to the assessment and monitoring of conservation strategies need to be developed, along with comparative risk assessments of the alternative conservation strategies.

CHALLENGES FOR OUR FUTURE

The environmental challenges facing us in the future can be articulated and used as guiding principles for our work in the near future. In the context of nutrient pollution of tropical marine and estuarine systems the challenges include:

- developing explicit measures of the costs to the environment (short and long term) of excessive nutrient inputs to coastal systems (particularly the linkage of nutrients to biological impacts);

- development of effective monitoring programs;

- developing practical and cost-effective management plans for the remediation of damaged ecosystems;

- developing practical and cost-effective Multiple Use and Integrated Catchment Management strategies using ecosystem endpoints as management indicators, and strategies that explicitly address and include environmental costs and benefits;

- meeting the international obligations with respect to pollution management and its effects on biodiversity, and adopting a global approach to stewardship of marine ecosystems.

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NUTRIENT AND SEDIMENT POLLUTION, AND ITS EFFECTS

Jon Brodie
Great Barrier Reef Marine Park Authority, Townsville

INTRODUCTION

Sources of coastal pollution can be grouped into several main classes: agriculture, sewerage, industrial discharges, urban stormwater, shipping activities, aquaculture and mining. The principal contaminant classes which may be present in discharges from these sources are sediment, nutrients, toxic metals, pesticides, oxygen depleting substances, pathogenic organisms, larvae of exotic species, litter and other toxic chemicals.

The input of many of these contaminants to coastal waters has changed dramatically in many states over the last few decades. Increased sewerage discharges are closely correlated with population increases while nutrient inputs from agriculture have risen sharply with the increased fertiliser use in most countries over the last fifty years. Dramatic rises in fertiliser use have occurred in many east Asian states with the introduction of high-yielding crop varieties (the 'Green Revolution') over the last twenty five years. Nitrogen fertiliser use in Indonesia increased from 350,000 tonnes in 1972 to over 1,500,000 tonnes in 1990.

The ecosystems present in coastal waters vary greatly ranging from coral reefs and mangrove shores in many tropic areas, seagrass beds in tropical and temperate areas, to kelp forests on temperate coasts. These ecosystems also vary in their susceptibility to water pollution from a range of contaminants. Mangroves are often considered to be resistant to nutrient pollution while coral reefs flourish in low nutrient conditions but degrade when nutrient inputs increase.

Many marine ecosystems in the region are already suffering severe habitat and species loss associated with marine pollution, the decline in coral reefs is a well documented example. Coral reefs in East Asia, South-east Asia, the inshore parts of the Great Barrier Reef and some Pacific Islands are in a critical state from organic and inorganic pollution, sedimentation and over-exploitation.

EUTROPHICATION

Eutrophication occurs when the nutrient supply (particularly nitrogen and phosphorus) to an aquatic system increases to an amount beyond that useable by the normal photosynthetic community in the system. The productivity of many aquatic systems is limited by the supply of a nutrient element, often phosphorus in freshwater systems but more often nitrogen in marine systems. An enhanced supply of the limiting nutrient will remove the restriction on plant growth. The definition of eutrophication used by the European Union "The enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, causing accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water concerned" encapsulates the idea.

When enhanced input occurs algae and phytoplankton whose growth is normally limited by the supply of nitrogen and/or phosphorus flourish, often at the expense of the resident photosynthetic community. Thus phytoplankton may bloom and the species present change to 'undesirable' types associated with 'red tides' and toxicity in fish and shellfish. In other ecosystems corals are overgrown and replaced by macro-algae while seagrass may be overgrown by epiphytic organisms. With phytoplankton blooms an increase in the presence of filter-feeding organisms such as boring sponges, tube worms and barnacles which feed on plankton may replace coral. With enhanced productivity comes increased organic matter in the water column and the potential for removal of oxygen from the water, particularly near the bottom. In conditions of zero oxygen (anoxia), anaerobic processes occur producing sulphides and methane. Fish kills and changes in benthic community structure may then result. Table 1 summarises examples of eutrophic systems from around the world and the associated problems.

LOCATION	NUTRIENT SOURCE	CONDITIONS
Seto Sea, Japan	Sewerage, agriculture, industry	* Phytoplankton blooms * Red tides
Black Sea	Agriculture, sewerage	* Ctenophore blooms * Fisheries collapse * Oxygen deficiencies
North Sea	Agriculture, sewerage	* Algal blooms, often toxic
Kaneohe Bay, Hawaii	Sewerage	* Loss of coral reef * Algal, filter-feeder overgrowth
Tolo Harbour, Hong Kong	Sewerage, industry	* Red tides, often toxic * Benthic community shifts * Fisheries reductions
Northern Adriatic Sea	Agriculture, industry, sewerage	* Algal blooms * Oxygen deficiencies * Bacterial slime fouls beaches
Taiwan coast	Shrimp farming	* Algal blooms * Shrimp farm disease & collapse
Cockburn Sound, WA	Industry, sewerage	* Seagrass loss * Fisheries reductions

Table 1: Major Impacts of Nutrients — Some Examples

Red tides occur when pigmented algae forms blooms under favourable meteorological and nutrient supply conditions. These blooms can be natural but may also be enhanced by anthropogenic nutrient inputs. Many such blooms are ecologically benign but others may consist of algae containing potent toxins. Toxins from algae such as *Pyrodinium bahamense* may then be incorporated into bivalve molluscs and pose a serious threat to humans when consumed. It is believed that toxic red tides are increasing in frequency around the world and in the Western Pacific. A major occurrence of toxicity associated with red tides and toxic bivalves, shrimp and fish in Manila Bay in 1988 affected an estimated 30,000-50,000 persons with 4 deaths.

SEDIMENTATION

Increased sediment discharge from land associated with forestry, overgrazing by stock, cropping on slopped land and urban and road construction may lead to severe effects on coastal ecosystems including sedimentation, turbidity-related light reduction and eutrophication.

Benthic communities such as coral reefs and seagrass beds are particularly susceptible to sedimentation and smothering. Coral reefs in the Ryuku Islands (southern Japan), particularly on Okinawa and Ishigaki, have been almost destroyed by land runoff of red mud associated with construction activity and agriculture. Similarly on the Great Barrier Reef (Australia) loss of coral on the reef flats of inshore reefs is considered to be associated with a fivefold increase in sediment discharge from the adjacent coast in the 130 year period since European settlement. In Westernport Bay (southern Australia) 80% (20,000 ha) of the total seagrass beds have been lost since 1973, blame being generally ascribed to increased sediment discharge from the surrounding catchments.

A second impact of sediment discharge is increased turbidity in the water column. Turbidity cuts light penetration through the water and inhibits the growth of organisms requiring light. The effects are most severe on benthic communities where the viable depth range for a community, such as seagrass, may be narrowed by loss of light. Particulate matter in the water column may also interfere with the feeding behaviour of zooplankton.

Sediment washed from agricultural and urban lands may also contain high levels of nitrogen and phosphorus and contribute to the problems of eutrophication previously outlined. Phosphorus is strongly associated with, and bound to, soil particulate matter. Particulate material eroded from soils which have been fertilised with superphosphate are likely to contain elevated concentrations of phosphorus.

ANOXIA

Anoxic conditions arise when oxygen utilising substances and processes in the water use up oxygen at a rate greater than it is able to be replenished by diffusion from the atmosphere or production by photosynthetic activity. The usual causes of anoxia are overloading of the aquatic system with oxygen-demanding substances (typically organic material) often combined with stratification of the water column which prevents oxygen transport from the atmosphere to the bottom of the water column. As discussed previously anoxia may be associated with eutrophication where the excess organic loading comes from algal blooms. Organic loading may also result from discharge to the water body of organic-rich wastes including sewerage and industrial effluents. Discharges from pulp and paper mills, sugar mills, vegetable oil processing plants and fishery factories are particularly characterised by high organic loading (i.e. their Biological Oxygen Demand, BOD).

Anoxic conditions may also occur naturally in the deeper waters of stratified water bodies. The Black Sea has an natural deep anoxic layer and only the top 150-200 m are normally oxic. However, in the Black Sea, continuous high organic loading from large rivers has increased the depth and area of anoxic and hypoxic (low oxygen) conditions. This change, along with eutrophication, overfishing and the introduction of a north American ctenophore, has had drastic adverse effects on the fisheries of the Black Sea.

Sudden anoxia can lead to fish and benthic invertebrate kills while prolonged anoxic conditions prevent the continuation of fish populations. Eventually in anoxic conditions anaerobic decomposition of the benthos and other organic matter leads to foul smelling conditions (sulphides in particular being produced).

Fisheries may be adversely affected in a range of ways by water pollution. As noted above increased anoxic conditions will lead to restrictions in fish habitat especially for inshore demersal fish although eutrophication in some cases leads to an initial increase in fish stocks as primary productivity increases. As eutrophication proceeds however the problems of anoxia, toxic red tides, shellfish poisoning and non-food phytoplankton blooms causes reductions in the fisheries resource.

SEWERAGE

Pollution by sewage may have severe adverse effects on the suitability of fish and shellfish for consumption. Problems range from direct contamination by pathogens e.g. typhoid, toxic trace metals and pesticides through contamination with toxins from red tide organisms. Being filter-feeders bivalves are particularly susceptible and the various types of shellfish poisoning [Paralytic Shellfish Poisoning (PSP), Neurotoxic (NSP), Diarrhetic (DSP), ciguatera] are now common in many parts of the world with PSP the most common in the Western Pacific.

Sewage treatment methods remove some of the pollutants with more effective removal as the sewerage processing stages increase. Sewage treatment is often described in terms of primary, secondary and tertiary treatment with increasing sophistication and removal of pollutants through the three stages respectively.

FARMING

Modern farming practices lead to inevitable water quality problems in the water bodies downstream of the farming activity. The principal pollutants involved are sediment, nutrients and pesticides and the issue is consistent across almost all of the western Pacific region. Logging is also associated with increased soil erosion and downstream turbidity and sedimentation problems.

Most south-east Asian, Pacific Island states and Australia have lost much of their forested areas on coastal catchments this century. For example only 25% of Thailand's original forests remain. Soil erosion and river siltation are considered more serious than organic pollution in Malaysian rivers. On Australia's Queensland coast it is estimated that sediment discharge from rivers to the Great Barrier Reef coastal lagoon is now about four times as great as it was before deforestation of the catchments and introduction of agriculture.

With the introduction of modern agriculture comes the intensive use of inorganic fertilisers. In most cases only a low proportion of the active ingredient of the fertiliser is incorporated into the crop the rest being lost to the wider environment. For many crops the proportion absorbed is about 30% with the rest of the nitrogen or other ingredients ending up in groundwater, overland runoff or lost to the atmosphere through volatilisation.

AQUACULTURE

Coastal aquaculture has expanded rapidly in recent years. Many water quality problems, as well as loss of mangroves and water resource overuse, are associated with some types of aquaculture. Prawn (shrimp) farming in particular produces grow-out pond effluents which have serious implications for receiving water quality as well as the long-term sustainability of shrimp farming itself. Intensive shrimp farming effluents contain algal cells (live & dead), nutrients, sediment and oxygen-demanding substances and may also contain therapeutic drugs, antibiotics and other chemicals. Intensive shrimp farming has suffered collapses in Taiwan (1988), Thailand and the Philippines (early 1990s) and in China (1994) due to poor water quality and associated disease problems.

Marine cage culture of fish has not developed in tropical seas to the extent salmonid farming has in temperate waters. The problems faced by salmonid farming i.e. uneaten food and faeces causing oxygen depletion in the areas around the cages, also apply to cage fish culture in Asia and the Western Pacific.

DETECTION AND MONITORING

Startling advances in our ability to measure vanishingly small concentrations of pollutants in water, biota and sediments over the last 30 years has created the potential to easily detect the presence of these pollutants in the environment. The methods now available include Graphite Furnace Atomic Absorption (GF-AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for trace metals; Gas Chromatography Mass Spectrometry (GC-MS) and Liquid Chromatography (HPLC) for pesticides and hydrocarbons; Organic Carbon Analysers (TOC); and Continuous and Segmented Flow Analysers (FIA) for nutrients. Satisfactory sampling methods for most media e.g. biota and sediments are now available except for water where severe problems still exist in taking uncontaminated samples for trace metal and trace organics. In-situ measurements of many critical parameters are now also straightforward with logging devices able to provide almost continuous records of salinity, pH, temperature, dissolved oxygen, turbidity, redox potential, chlorophyll concentration and current direction and speed.

Difficulties still exist however in the interpretation of trace contaminant/data. Our knowledge of what represent 'normal levels', what the natural variation in such levels is and what concentrations are likely to cause adverse effects on ecosystems is still fragmentary.

BIOLOGICAL EFFECTS METHODS

To avoid some of the problems mentioned previously in relating contaminant concentrations to biological effects an alternative set of methods has been developed which aim to measure actual biological effects directly in organisms. Biological responses to contaminants in the environment can be measured at all levels of biological organisation — molecular, cellular, tissue, individual, population and ecosystem. Methods have been assessed at a series of UN sponsored workshops in recent years. Typical methods include changes in enzyme systems, damage to DNA structure and function, membrane damage, antibody recognition tests, the Scope for Growth measurement, diversity indices and multivariate species assemblage analyses.

STATISTICAL CONSIDERATIONS

The determination of whether changes in contaminant concentrations, the presence of biological effects or changes in ecosystems in time are significantly related to water pollution may be very difficult to decide. Statistical methods have been improved greatly in recent years in an attempt to put the decision making on a sounder footing. Taking just three examples of this work we can consider BACI, multivariate and trend detection methods.

BACI (Before and After, Control and Impact) methods use hypothesis testing (usually univariate analysis of variance) techniques to determine whether biological change is related to a local impact. The importance of 'control sites' is stressed to guard against the possibility that local changes are related to a global changes and not associated with the local impact.

Multivariate assemblage analyses are used for assessing change due to stress in complex assemblages of many species. Such methods integrating changes in abundance patterns and species differences between sites have been shown to detect subtle effects of stress on natural systems. More recent methods allow possible causative agents to be related to the patterns found.

Long-term data sets on contaminant levels in a system or the abundance of an indicator (e.g. chlorophyll measurements) require analysis for trend. Robust methods have been developed which factor out seasonal signals, autocorrelation (the dependence of one measurement on the previous measurement in the set) and the natural variation in the signal to uncover the underlying trend. A good example of this is the analysis of 22 years of nutrient data from the Baltic Sea showing the overall upward trend in concentrations over time.

NUTRIENT DYNAMICS IN TROPICAL COASTAL SYSTEMS: CYCLING AND VARIABILITY

Miles Furnas
Australian Institute of Marine Science, Townsville.

This paper summarises key elements of nutrient cycling and variability in tropical coastal systems. While nutrients are responsible for eutrophication and for undesirable effects in many estuaries, bays and near-shore regions, they are also a natural part of the marine and estuarine environment. Eutrophication and blooms of algae are caused by excess nutrients, usually where inputs and loads of nutrients to coastal systems exceeds its capacity to disperse or incorporate these nutrients within the natural nutrient cycling processes, or where the excess nutrients overwhelmingly favours one species, permitting it to bloom. To complement this very brief overview of nutrient dynamics, an extensive bibliography is appended to guide readers to particular topics that may prove to be important for further detailed study.

FORCING AND VARIABILITY

A number of physical processes are important in driving variability in nutrient concentrations in water. They include the physical processes related to local and regional climatic factors such as wind, temperature, tides and storms. While in themselves they do not directly carry nutrients, the physical environment influences most nutrient-related processes.

TEMPERATURE

The many biological processes that both produce and consume nutrients vary with temperature. The effect of temperature on biological processes is commonly expressed using a Q10: the relative change in the rate of process for each 10 C change in temperature. For example, nitrite production by the benthos has a very different Q10 from the Q10 for ammonium production by zooplankton. As a result, temperature changes can have different effects on the magnitude of these processes (Berounsky and Nixon 1990).

LIGHT

Light is possibly the most important environmental factor regulating primary production in coastal waters. Its effects are not limited to the water column. Sediments play an important role in nutrient cycling, and where light can reach the sediment surface, nitrogen and phosphorus fluxes can be substantially affected by available light through the growth of benthic algae (Nowicki and Nixon, 1985).

SALINITY

Where seawater and river waters mix, the effects of variable salinity can also be responsible for influencing the chemical forms (the so-called "speciation") and therefore the availability of nutrients (Kaul and Froelich 1984). Individual species can vary in concentration proportional to the mixture of coastal and river waters, or become more or less soluble (Smith and Veeh 1989).

WIND

In shallow waters, the local effects of wind mixing can have a dramatic effect on nutrient concentrations in the water column. Both particulate and dissolved forms can be resuspended from the sediment surface. These resuspension events can occur over very short time scales, and over very local or very broad space scales depending on the nature of the wind.

SEASONAL EVENTS - MONSOON

Monsoonal climate changes are the dominant seasonal scale event in the tropics. In the wet-dry tropics, the onset of the wet season can drastically increase the input rates of particulate and dissolved nutrients to estuaries and near-shore ecosystems. Other variable seasonal factors include, in some places, change in light and temperature.

EXTREME EVENTS - CYCLONES

Cyclones can have profound effects on nutrients in both sediments and the water column. The associated rainfall, runoff, and wind stress result in major redistribution of particulate and dissolved nutrients, and this may feed resulting surges in primary production in the water column (Revelante and Gilmartin 1982, Fanning et al. 1982, Furnas and Mitchell 1991).

GLOBAL-SCALE EVENTS

Most continents are bordered by major boundary currents (e.g. Gulf Stream of the east coast of the USA, East Australia Current of the east coast of Australia). Variations in the intensity of these currents are can lead to upwelling of deeper nutrient-rich waters onto continental shelves. When these deeper waters are upwelled into the surface layers of the ocean then light becomes less of a limiting factor and the nutrients they contain may support enhanced primary production on the shelves. Any unusual behaviour in the boundary currents is likely to have an effect on the periodicity of upwelling and hence nutrient supply to shelf waters.

WATER COLUMN PROCESSES

Nutrient uptake

Phytoplankton are very efficient users of nutrients, and given the appropriate conditions, can rapidly take up a wide range of nitrogen species. Their use of individual dissolved nitrogen species is limited to varying degree by the availability of light. Nutrients dissolved in the water column are also effectively scavenged by heterotrophic bacteria, although their growth is often regulated by other factors such as amino acids and organic carbon sources (Wheeler and Kirchman 1986,
Caron et al. 1987).

Mineralisation

Zooplankton grazers consume phytoplankton and bacteria and excrete nitrogenous waste products (Glibert et al. 1992). Excreted forms of nitrogen (typically ammonium) are readily used by phytoplankton and bacteria and so nitrogen may be re-cycled many times before being lost to the ecosystem by deposition into the sediments as refractory organic material or to the atmosphere as a gas. Even if concentrations of free nutrients in the water column are low, there may be nonetheless high rates of utilisation and turnover, where the nutrients cycle amongst the various biological compartments in the water column and the sediments. This turnover is probably the most important process maintaining phytoplankton populations once they have become established, requiring little "new" nutrient to sustain them.

Nitrification/denitrification

Nitrification is the process whereby bacteria convert ammonium to oxidised fixed nitrogen (nitrate, nitrite). This can be achieved by both phytoplankton and bacteria. The reverse process (denitrification) where nitrate is consumed as a metabolic oxidiser is wholly carried out by specialised bacteria, which produce gaseous nitrogen and nitrous oxide which is ultimately lost to the atmosphere.

THE ROLE OF SEDIMENTS

Nutrient Storage

Most sediments, particularly fine-grained sediments, have very high bulk nutrient contents. They act as a major net sink for nutrients, so that refractory forms of nutrients become buried as a component of the organic and inorganic material. However, while there is almost always a net loss of nutrients from the water column into the sediments there may be considerable recycling of nutrients from the sediment into the water column (Smith et al. 1989).

Mobilisation

Nutrients may be mobilised from the sediments by a variety of processes. Mineralisation is the conversion of organic forms of nutrients into dissolved inorganic forms that are available for autotrophic use in the sediment surface or in the water column (Seiteinger and Nixon 1985). Sediments can be stirred into the water column by the physical processes described above, mainly wind and tides.

THE BALANCE BETWEEN THE WATER COLUMN AND THE BENTHOS

The relative balance between mineralisation within the benthos and water column depends upon the depth of water, levels of organic deposition to the benthos and standing stocks of nutrients and plankton. In very shallow waters (<10 m), the benthos will have a major impact on ecosystem processes. In deeper systems, pelagic cycling processes will predominate.

THE ROLE OF BUDGETS IN EUTROPHICATION STUDIES

Identifying Sources and Sinks

The construction of nutrient budgets for particular ecosystems provides a useful organisational framework within which nutrient loads and cycling between various biotic and abiotic compartments can be assessed. Nutrients can occur in many chemical forms (species). Because nutrient budgets must have a zero net loss/gain, i.e. there must be a balanced budget, the construction of a nutrient budget based on experimental measurements of loads, concentrations and rates can be an important process in identifying the magnitude of processes within an ecosystem. The construction of budgets assists in estimating concentrations and rates of individual nutrient species that are difficult to measure directly (Kemp et al. 1990, Lipschultz et al. 1986). Whilst construction of a nutrient budget may be an intensive exercise, and involve some detailed and complex measurements, it will generally prevent major losses or inputs of nutrients from being overlooked or grossly incorrectly estimated, and can reveal unsuspected pathways for nutrient recycling, input or consumption (Furnas et al. 1995). Quite often however, it is difficult to close budgets because individual processes can vary in time and space, and accurate data is not always available.

PROCESS STUDIES

The direct measurement of nutrient concentrations does not accurately reflect the rate that these materials are produced and consumed (as this occurs simultaneously, it is referred to as "turnover") within the environment. As a result, it is often necessary to carry out measurements of nutrient transformation rates (process studies) to measure rates at which important environmental transformations take place. In many coastal systems, the rates at which nutrients enter and leave pools is more important than the actual concentrations. Individual pools of nutrient species can be recycled over a wide range of time frames ranging between minutes and years. Moreover, pools of the same nutrient species in different habitats (e.g. the water column or sediments) can be used and recycled at vastly different rates. Process studies are necessary to resolve these important differences.

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**BIOLOGICAL EFFECTS OF NUTRIENTS IN THE WATER COLUMN:
THE TECHNIQUES**

Peter Thompson
CSIRO Division of Fisheries, Perth
Australia

INTRODUCTION

Nutrients in the water column often have a major effect on phytoplankton populations. Indeed, phytoplankton can respond very quickly, in some circumstances, to the increased availability of nutrients, and they may have a very important role in controlling (or at least buffering) the levels of nutrients dissolved in estuarine and marine waters. In this paper I will briefly consider the ecology of phytoplankton populations, then primarily focus upon the techniques which can be used to assess them. An outline of the equipment and techniques used in phytoplankton research and some of their advantages and disadvantages is presented. The physiological basis of phytoplankton acclimation to basic environmental variations is discussed in the context of interpreting field observations. An extensive and partially annotated reference list is provided to assist with further investigations of the role that phytoplankton play in natural and nutrient-contaminated waters.

FACTORS LIMITING PRIMARY PRODUCTION: NUTRIENTS

A number of chemicals can occasionally limit the growth of phytoplankton. These chemicals which may be able to limit phytoplankton growth in the marine environment are defined as nutrients. These nutrients include:

- carbon evidence for carbon limitation in the marine environment is mainly theoretical (published by Ulf Riebesell and others in Nature in 1992). There is some experimental evidence based on phytoplankton cells which can use only CO_2 and have no ability to use HCO_3, but there is no record of an ecosystem that has being polluted by excess CO_2.

- nitrogen

- silicate nitrogen, phosphorus and silicate are the three nutrients that are considered to have major roles in eutrophication. As well as nutrient concentrations, it is also important to consider nutrient ratios. There have been significant changes in nutrient ratios associated with changes in phytoplankton species composition in areas such as the Mississippi delta.

- iron the recent 1995 mid-ocean experiment demonstrated that Fe did indeed limit primary production of phytoplankton in a large area of the ocean. This may well be true over many areas, especially those far from large Fe sources such as rivers or land masses. The largest overall source of Fe for the oceans is probably atmospheric deposition, but in local near-shore areas rivers or coastal erosion may also be major sources of Fe.

- chelators
-
- other trace metals such as manganese, cobalt, zinc, molybdenum, nickel, selenium, cadmium, and also vitamins, have been shown to limit primary production occasionally, usually in oligotrophic systems.

Although probably not exhaustive, this list serves to illustrate the possible number of "nutrients" which can be added to the environment and (potentially) cause an increase in phytoplankton growth and primary production in marine systems.

Nutrient pollution is usually predominantly caused by nitrogen and phosphate, therefore most of this paper will be directed at the macronutrients N and P. It is worth noting however, that the other nutrients may be limiting at some time or in some locations depending on the specific circumstances. We will not be considering those polluting chemicals which adversely affect the environment by inhibiting phytoplankton (or other organisms), even though some of the above nutrients can become toxic if added to the environment in excess amounts. In other words, this paper will only consider the stimulatory effects of nutrients, and not their possible toxic effects.

FACTORS LIMITING PRIMARY PRODUCTION: LIGHT

One of the major impacts of anthropogenic nutrient pollution is often an increase in water column turbidity, primarily associated with an increase in phytoplankton biomass. Furthermore, since light and phytoplankton production are linked, measurements of light penetration through the water column can be very important. Although it is not the goal of this workshop to talk about the effects of nutrient pollution on the benthic community it would useful to point out at this time that measurements of light are essential for proper interpretation of water column primary production data and they are also very important in assessing the effects of nutrient pollution on benthic photo-autotrophs such as microphytobenthos, macro-algae and seagrasses.

Light as the energy source for primary production

- It is necessary to be able to measure irradiance precisely and routinely. For photosynthesis the wavelengths of primary interest are 400-700 nm, referred to as photosynthetically active radiation (PAR). Although phytoplankton don't use these wavelengths evenly, primarily using 400-480 and 670-690, the technical difficulty (additional costs) of measuring the precise spectra that phytoplankton do use has led to the routine measurement of irradiance over the PAR 400-700 nm range.

- Instruments for measuring irradiance are relatively expensive, with Licor™ instruments being the scientific community's most popular choice. However, if an instrument of this quality is not available then a similar and equivalent one is required for reliable and absolute measures of irradiance, so that photosynthesis can be quantified. The other water quality parameter of major interest, light attenuation, can be estimated with such a light meter or by using the Secchi disc. The Secchi disc is simply a 30 cm diameter white (and sometimes white with black quarters) weighted disc. The disc is lowered through the water column and the depth at which it disappears is recorded. With only cursory training this depth can be reliably measured and the data are very useful in estimating light attenuation. Because of the long history of data collections using Secchi methods, and the ease with which the measurements can be taken, there are many researchers who collect both sorts of measures — light meter and Secchi data.

Instrumentation requirements

Light meter (with the following desirable attributes/characteristics)

- provide absolute measures of irradiance, available with 4 pi sensors (i.e. all-around light measures, as opposed to only down or up welling light measures)

- available with underwater and air sensors

- PAR wavelength sensitive (400-700 nm)

- measure the number of photons rather than energy

Secchi disc

- cheap
- large historical data sets
- reasonable precision for measuring light attenuation
- not suitable for absolute measures

Transmissometers

- can measure light attenuation only.

Absorption of light

The absorption of light in water follows the following equation:

$$I_d = I_0 e^{-kd}$$

where I_d = light at depth (d); I_0 = light at surface; and k = extinction coefficient.

For Secchi disc measures k in the above equation is usually around 1.6/d.

So it is possible to determine an extinction coefficient from either light metre or from Secchi disc data. Either measure is useful since reductions in water clarity are one of the most likely consequences of nutrient pollution. However the light attenuation properties of many marine and estuarine environments are highly variable in time and space. Therefore a strong case that the environment has experienced a change in light attenuation caused by nutrient pollution requires a carefully designed sampling program to encompass the likely time and space scales. Such a sampling program usually features a large number of measurements.

BIOMASS OF PHYTOPLANKTON

Biomass = standing stock of phytoplankton
Production = rate of increase of phytoplankton biomass

It is important to realise that biomass and production are two very different things. Additional nutrients can result in an increase in one or the other, and sometimes in both, but not necessarily by the same amount. For example, the eutrophication of Lake Erie resulted in the tripling of the standing stock but a 20 times increase in the annual primary production.

It is possible to add nutrients and to maintain the same phytoplankton biomass in ecosystems that are light-limited, that have high advection (transport) of the phytoplankton, or have balanced production and loss characteristics (so that as production increases so do losses caused by grazing, sinking etc.). Conversely, addition of nutrients can produce more phytoplankton, especially in ecosystems that are nutrient-limited, where transport is low to moderate, or production exceeds loss processes. Also, ecosystems can switch between one mode and another on different time scales. So it is possible to have significant increases in nutrient loading without any change in phytoplankton biomass even in nutrient limited systems if losses keep pace with increasing production.

In any study of phytoplankton production it is necessary to identify the organisms involved. This is important for a variety of reasons but with regard to biomass it is possible to use literature values to estimate known species in terms of carbon. Where these data are not available for the dominant species, the addition of only small amounts of extra effort involving some measurements would permit the use of literature data on carbon:biovolume ratios. Such enhanced data can be used for modelling to better understand eutrophication.

cell counts = species numbers x biovolume ~ carbon biomass.

Collection of detailed data on phytoplankton species requires the following:

<u>collection techniques</u>

- bottles, or nets, or pumps, or tubes (integrated), see UNESCO manual for details

<u>counting techniques</u>

- settling systems and inverted microscopes
- other counting devices.

My personal preference is for integrated water column phytoplankton samples: these provide the greatest ecosystem information for the least cost and effort. Also I recommend the inverted microscope for counting of phytoplankton cells. A detailed discussion of these techniques is in the UNESCO manual. Many studies can be improved by assessing both the number of cells and their biovolume. Because phytoplankton have a very large range in size (~2—2000 μm in length), a large number of small species can be mistaken for the ecologically most significant, while a moderate number of intermediate-sized cells may contain far more biomass, and be more productive.

PIGMENTS IN PHYTOPLANKTON

Pigments are the universally accepted standard for reporting algal biomass. Like most measures they are not perfect, but they represent a reasonable compromise. Chlorophyll *a* (chla) measurements are more likely to represent live biomass than measures of particulate organic carbon (POC), nitrogen (PON) or phosphate in many ecosystems. Unfortunately since the fluxes we are usually trying to measure/model are POC or PON, variation in the chla:C or chla:N ratio can lead to interpretation problems.

Ecosystems are often classified into one of the following classes based on the overall range of their phytoplankton pigment concentrations:

0–2 (μg chl*a* l^{-1}) = oligotrophic
2–15 (μg chl*a* l^{-1}) = mesotrophic
$>$ 15 (μg chl*a* l^{-1}) = eutrophic

(NOTE: the boundaries of these classifications are not universally accepted.)

Pigment measurement techniques

spectrophotometer: this is the most widely accepted and applied technique. Although it is moderately time consuming, it can identify a number of separate pigments (Jeffrey and Humphrey 1975).

fluorometer: this can be used for *in vivo* or extracted chla determinations *in vitro*, and is much faster and more sensitive than spectrophotometer, although combinations of pigments are not handled as well (Lorezen and Jeffrey 1980).

HPLC: this is the most powerful technique. It can separate all the known pigments, but is by far the most time consuming and expensive to purchase.

OTHER MEASURES OF PHYTOPLANKTON BIOMASS

There are a number of other measures of phytoplankton biomass. They include:

Particulate organic carbon: this is only moderately time consuming but carbon (POC) analysers are expensive to purchase and operate. Typically they are unable to separate live carbon from detrital carbon.

Particulate organic nitrogen: this is usually done on same machine simultaneously with POC, and suffers from the same problems.

PRIMARY PRODUCTION IN PHYTOPLANKTON

Unlike phytoplankton biomass, there are no internationally agreed standards for defining an ecosystem's eutrophication status based upon measurements of primary production. Aquatic ecosystems can be classified as highly productive, but as long as the biomass does not accumulate in the ecosystem they are rarely considered to be eutrophic. Regardless, an understanding of the major carbon fluxes is important in any assessment of ecosystem ecology.

Primary production (PP) is the process of photosynthesis by photo-autotrophic organisms. Like all photosynthesis, the process is:

$$CO_2 + 2H_2O \xrightarrow{\text{(light)}} CH_2O + O_2 + H_2O$$

Thus the process of photosynthesis consumes CO_2 and releases O_2. However, the ratio of consumed carbon to released oxygen is not necessarily 1:1 as might be assumed from this equation. It may close to 1 in some situations, and in particular where cells are growing using ammonium as their primary nutrient. The ratio can be significantly greater when cells are growing on nitrate, because the energetic costs of growth on nitrate are substantially greater than those for growth on ammonium and these energy costs influence this balance. The internationally accepted ratio is 1:3. However, caution has to be applied here, because there are good data indicating that this ratio may occasionally reach 4–8. This is important because oxygen production is sometimes used to measure primary production.

Some methods used commonly for measuring primary production

<u>carbon dioxide consumption</u>

- carbon 14 methods
- infra-red gas analyser
- pH changes

<u>oxygen</u>

- Winkler
- oxygen electrode

<u>standing crop</u>

- theoretical equations using changes over time

See Li and Maestrini (1993) for a complete account of available techniques.

The Carbon 14 methods are the most commonly used for several reasons:

- quick
- relatively cheap
- modest labour requirements

They have the following major disadvantages:

- use radioactive substances, invoking radiation protection and management measures
- cost of a scintillation counter
- limited temporal and spatial coverage

There are many problems with ^{14}C incubations, and these have been well reviewed by many (Richardson 1991, Petersen 1980). In spite of all the problems ^{14}C seems likely to remain as the major technique for measuring primary production. However, because of the problems it would seem unwise to rely completely upon the data from ^{14}C incubations. Like all experimentally derived data, they represent additional evidence to be used in ecosystem studies.

The methodology that I recommend has several flaws (which I will return to later) but for the most part I see it as the best compromise between conflicting requirements. The advantages are:

- only small volumes are used

- only short periods of incubation are needed

- the whole process is completed in the scintillation vials (which means no filters are required to be handled, etc.)

- there is minimal handling of the samples

- there is relatively high carbon 14 activity, so scintillation measurements are quick and efficient

- artificial or natural lighting can be used

- acidification of samples is conducted in a fumehood after the sample incubation.

My personal preference is for small sample volumes incubated for short periods. The major advantages of this technique is the simplicity and speed. No filter papers are used, the samples are incubated in the scintillation vials, and a small amount of relatively high activity ^{14}C is added. After a twenty minute incubation, under artificial lights, the excess inorganic ^{14}C is driven off with acid (in the fume hood), the sample shaken, then neutralised. After adding fluorescing counting medium (fluor), the sample can be counted directly in a liquid scintillation counter. There is very little handling of the samples, and virtually none once the vials are inoculated with C^{14}.

Because this technique requires a minimum of labour it is possible to measure primary production in a large number of samples (in our lab one person can do 60 samples, from beginning to end, in three hours).

Regardless of which technique is used it would be worthwhile to invest some effort in assessing how it compares with some of the other techniques. Typically it is necessary to consider diel variation, bottle effects, net versus gross PP, photorespiration and respiration losses. I recommend some effort to assess these confounding factors in any ecological study which proposes to measure PP. Also you might wish to compare some results with two or more measures, such as O_2 and ^{14}C.

The basic data work-up procedures are given in Parsons et al. (1984). Briefly, once the raw data (disintegrations per minute) are available the process of converting those to some meaningful numbers can begin. The techniques given by Parsons et al. (1984) require salinities in the > 20 ppt range (above 20 ppt the error associated with estimating total dissolved inorganic carbon (DIC) based on salinity is small). For salinities below this, as might be encountered in a estuary, it is necessary to make an independent measure of DIC. Again, there is simple and quick method given in Parsons et al. (1984) for estimating this based upon measuring the pH before and after adding a known amount of acid. This will allow you to produce estimates of carbon fixed /unit water/time.

Standardisation per unit phytoplankton biomass

Significantly more information can be gained if the production is standardised to phytoplankton biomass. In many cases this would be to particulate organic carbon. Unfortunately this can be problematic in ecosystems where a significant portion of the POC is not active phytoplankton. For this reason primary production is frequently standardised to chlorophyll *a*.. However, because chla can also be inactive, some, notably Holm-Hansen, have advocated using production standardised to adenosine triphosphate (ATP).

Data Interpretation

Once the data are standardised to appropriate units (for example, grams carbon per gram chla per hour) they are often plotted against irradiance. The data are often a simple saturating curve. This allows for the calculation of some summary statistics such as:

- the initial slope, often called alpha
- the maximum photosynthetic rate (P_{max})
- the half saturation value (I_k)
- the irradiance where respiration equals PP (I_c).

Curve selection

The choice of curve to describe these data has attracted considerable attention (see Platt and Jassby 1976). Most data sets are not so precise that choice of one of these curves over another is really warranted. The initial slope is a measure of photosynthetic efficiency, with steep slope indicating a greater degree of carbon uptake per unit chla. The maximum rate of photosynthesis is generally accepted to be determined by the enzymatic process of carbon fixation. It is also generally accepted that the initial slope is relatively insensitive to temperature, while Pmax is likely to respond to variation in temperature. Further discussion of the interpretation of P vs I curves will come later under adaptations to irradiance.

PROBLEMS IN THE MEASUREMENT OF PRIMARY PRODUCTIVITY

Technical issues

Container materials: samples must not come into contact with toxic materials during sampling. Studies have shown that latex, metals, plastics, various pumps, and wood can reduce PP, although some of these toxic effects can be removed by pre-conditioning or aging the materials.

Conditions: acidic conditions can result in losses of radioactive carbon.

Decay of activity: counts should be made soon after incubations are complete to avoid decay of measured activity.

Length of incubations

The Joint Global Ocean Flux Study (JGOFS) is recommending 24 hour incubations but, while this may be preferable in theory, it can severely limit the number of samples. Also:

- Longer incubations are more likely to suffer problems with nutrient limitation, photoinhibition, bottle effects, and may measure something closer to net rather than gross PP.

- Light fields are not constant over time, therefore 24 incubations would have to be *in situ*, or simulated *in situ* (on deck). It is my opinion that the 24 hr incubation is not a significant advantage for coastal studies of PP.

Time of day

It is known that PP has a diel cycle. Where possible, incubations should all be made at one time.

Bottle effects

Bottles of different sizes have been shown to have different PP. The accepted reason for this is that some species are sensitive to the enclosure. In oligotrophic waters it may be necessary to use bottles which pass UV light (UV is reduced or eliminated by many types of glass bottles). However, this may not be important in areas of high turbidity.

Net versus gross PP

The difference between net and gross PP (i.e. the respiration due to phytoplankton) is usually difficult to measure accurately because of the inclusion of small heterotrophs in most field samples.

Incubations

Incubations *in situ* versus simulated *in situ* (on deck) and incubations under artificial lights may all give different results.

Additional problems

- differences between labs
- filter types
- quenching
- variable light versus constant light
- temperature
- nutrient limitation
- photorespiration
- data analysis problems

SINKING: LOSS MECHANISM # I

I consider the two major loss mechanisms for phytoplankton in the water column to be sinking and grazing. First, I would like to discuss the various methods of measuring sinking rates and later some for measuring grazing.

Settling column experiments

Settling column experiments (Bienfang 1981) are cheap, quick and can be easily manipulated. They can be used in the laboratory and at sea. Various measures of algal biomass can be used. In the laboratory experiments on sinking rates have used these variables:

- visual cell counts
- electronic cell counts
- optical density
- fluorescence
- particulate organic carbon
- particulate silicate.

This technique works well with all these variables in the laboratory but may not be sensitive enough for field work. It is possible to make sinking rate measurements with settling columns in oligotrophic systems using chla or, if the algal cells are first labelled, with radioactive carbon. The latter approach can yield sinking rates for individual species even in ecosystems with very low biomass.

Sediment traps

Sediment traps provide an alternative method of determining sinking rates. Their advantages are that they operate *in situ*, at low phytoplankton densities, and can integrate over time. However, their disadvantages are:

- don't work effectively in shallow environments, because of resuspension problems and because grazers can populate the traps (efforts to poison traps have not been very successful)

- horizontal advection can "deliver" much of the accumulated material to the trap from outside the area of interest

- they are expensive, and this usually means that only a limited number of samples and limited number of locations can be sampled.

There is a fair amount of controversy about trap design, processing techniques, and interpretation. If you are starting a project with sediment traps it would be worth investing some time in consideration of the recent literature prior to making the investment (Landry et al. 1992).

GRAZING: LOSS MECHANISM # 2

The techniques for measuring grazing include:

- examination of faecal material by microscope or electron microscope, to determine grazing from faecal production rate

- theoretical approach using measures of zooplankton biomass and known temperature-dependent grazing rates

- laboratory-based observations of animals held in tanks and provided with food; this method can determine growth and consumption by determining the reductions in phytoplankton cell densities

- animals given labelled foods, food substitutes etc.

The advantages of using labels or food substitutes is that the samples generated by the experiment can be counted later. In experimentation where the animals are consuming live food the samples need to be counted immediately. This problem can severely curtail the number of experiments which can be attempted. Fluorescently-labelled beads can be used as a substitute for phytoplankton cells. This seems to work very well:

- beads and phytoplankton cells are consumed equally
- animals could be preserved and the number of beads they consumed determined later
- quick and easy technique for the determination of instantaneous grazing rates.

THE ROLE OF BACTERIA

Some of the general attributes of bacteria might be of interest in an ecological study of primary production in coastal systems, including biomass, respiration rate, other metabolic activities (i.e. denitrification), growth rate, and the substrates they consume.

It may not be possible to determine all of these bacterial attributes in your ecosystem. The importance of any one attribute is difficult to predict, but in general, the list above is in order of priority. For specific ecosystems the relative importance may change. For example, in some ecosystems the N cycle and nitrifying and denitrifying bacteria are very important. However, this may not be true if the system is heavily phosphate limited.

Methods for work on bacteria

Agar plating: a traditional technique that can yield some information. Unfortunately many species of marine bacteria do not grow well on agar plates therefore it is not quantitative.

Liquid culture: this is also not quantitative, but is useful for presence or absence, rate measures, and dose responses.

Microscope work: this is the industry standard; considerable research is available on the techniques, mainly involving staining bacteria with one of several DNA stains (DAPI, acridine orange) and counting them on the microscope. Concentration prior to counting is often required and black filters are commonly used for this. The UNESCO phytoplankton manual has a good section on the microscopic techniques.

Bacterial production

The activity of bacterial populations are often measured using incubations with ^{14}C glucose, while their growth is measured using incubations with ^{3}H thymidine.

Biological Oxygen Demand

As an overall measure of heterotrophic activity in waters and sediments, a measure known as the Biological Oxygen Demand has been developed. It is a standard waste water analysis technique, and is documented in the American Public Health Association's "Standard methods for the examination of water, sewage, and industrial wastes".

LIMITING FACTORS

Variability in the Light Climate

On a worldwide basis light is probably the most limiting factor for phytoplankton production. In the tropics, however, daylength is relatively constant, and the skies are often clear resulting in adequate solar irradiance input to the surface of the water column. As ecosystems become more eutrophic one of the most common changes is an increase in the water column attenuation of light, often due to increased algal biomass. Therefore previously low-nutrient status (oligotrophic) systems with high light environments often switch to become low-light environments as nutrient loading increases. Of course, high loads of suspended materials are common in estuaries, and so primary production in these environments may also be light limited.

Cellular adaptations to low light.

Most commonly phytoplankton cells adapt to low light conditions by increasing their content of light absorbing pigments; the amount of chla per cell will normally rise. Pigment composition may also change, and there can be changes in Pmax and alpha, and the amount of carbon per cell may be reduced.

Variation in irradiance can change the nutritional value of the phytoplankton cells. Typically the same species of phytoplankton grown under lower light is less nutritious than when grown under high light. This can be important because, for example, the ability of herbivores to grow by consuming these cells may be reduced. The major reason for this effect seems to be the shift in fatty acid content associated with the different light regime.

Effects on species composition.

An increase in light absorption in nutrient polluted water columns can result in profound effects on the benthos. It can also result in shifts in the species composition of the phytoplankton community. Although diatoms are arguably better able to convert light energy into biomass than are other phytoplankton groups, they cannot hold their physical position in the water column. This means that as turbidity increases, if there is not some concomitant decrease in the depth to which the water is mixed (either bottom of the thermocline, picnocline or bottom of the water column), then diatoms will become increasing scarce in the environment. Generally this is a negative effect, because diatoms are usually considered to be good food for many invertebrates, and diatom biomass is generally thought to be easily transferred up the food chain.

In natural ecosystems and in nutrient polluted environments diatoms can be replaced with dinoflagellates as nutrient levels change. These motile cells can be either autotrophic (photosynthetic), heterotrophic or mixotrophic. Because they can swim they are able to regulate their position in the water column. This means they can make vertical migrations from deeper in the water column (where nutrients are often more available) up to near the water surface where the greater irradiance can be use for photosynthesis, and they may be able to do this in a cyclic manner so optimising the availability of the respective limiting factors.

Often one of the first signs of phytoplankton problems in marine and estuarine systems due to pollution will be the appearance of large scale dinoflagellate blooms. Of course these can, and do, occur even in pristine conditions so that the frequency, density and size of the blooms needs to be assessed to appreciate the magnitude of the pollution problem.

Ecosystems that are light limited can shift their status to become dominated by blue-green algae (cyanobacteria). Because blue-greens float they can intercept light energy at the water surface. Fortunately, blue-greens are not often a problem in marine waters, occurring mainly in freshwaters, and only occasionally in brackish and estuarine waters.

Effects of temperature

In general, temperature will limit phytoplankton growth and other cellular reactions if light and nutrients are sufficient. Typically this means that under conditions of high nutrient and high irradiance, temperature variation will control the rate of growth, photosynthesis and nutrient uptake. In many cases this will not be important, but in shallow estuaries, tide pools, aquaculture ponds etc. many flux rates will be temperature dependent. This can also influence comparisons between habitats as it will be necessary to sample both habitats under similar conditions.

Thermal pollution, such as the discharge of heated water (say from a nuclear power plant) or cold water (say from a diversion scheme) into the environment will have an effect. Here, we will consider here the effects of temperature both in its capacity to limit, or affect biology, and because cases of thermal pollution are becoming increasingly common.

In shallow waters, such as ponds and estuaries, there can be very great variability in water temperatures, on both daily and seasonal time scales. Also, increasing water column turbidity (often caused by nutrient-related phytoplankton blooms) will increase the absorption of solar energy and can lead to a marked increase in the overall water column temperature. Therefore there can be a synergy between phytoplankton populations and water column warming.

At the cellular level, temperature can limit the maximum rate of biological reactions (such as PP and BOD), it can control the maximum photosynthetic rate, the nutrient uptake kinetics, the biochemical composition and the nutritional value of phytoplankton.

At the ecosystem level, temperature can affect species composition and succession patterns. This is because individual species have different tolerances to temperature. Species have different responses to increases in temperature, i.e. their Q10's are markedly different. At the cellular level most phytoplankton species acclimatise to temperature by changing their physiology. Yet in the environment there are sharp temperature boundaries that appear to limit the species (see Eppley 1971 for examples) so that normal seasonal trends in temperature may be a factor in phytoplankton succession.

Nutrients

Nutrients mainly limit biomass, although at very low levels they may also limit flux rates. It can be important to try and ascertain the specific nutrient which most commonly limits biomass in a particular ecosystem. For example, if nitrogen is limiting, there is likely to be little benefit from an expensive program to reduce phosphate being discharged to waterways.

Although phytoplankton can be limited by the availability of a number of different chemicals, macronutrient limitation seems most likely in nearshore environments. The macronutrients are nitrogen, phosphorus, and silicate. A first approach to try to isolate the dominant limiting factor would be to examine the nutrient values for the water samples. Phytoplankton require nutrients in relatively fixed proportions — N:P 16:1, and Si:N 1:1 (diatoms). Any major deviations from these ratios will suggest potential limiting factors. Also if you are able follow a bloom closely, the nutrient to reach ~ zero first will probably be the most limiting in your ecosystem for that bloom. Repeated observations like this can provide powerful inferences about the nutrients that can be successfully manipulated to control phytoplankton blooms.

Bioassays: these involve incubating phytoplankton in samples of water. The water can be enriched with one or all-but-one nutrients (see Laws 1990). The samples can be inoculated with one species, a mixture of species or the naturally occurring community. In this way limiting factors can be determined.

FIELD WORK

Phytoplankton are both temporally and spatially variable. It is necessary to sample frequently – UNESCO recommends fortnightly. But note that the processes which allow phytoplankton blooms to occur do not adhere to planned research programs. So, sampling times should be flexible, possibly with more trips during times of high production or biomass. Sampling programs need to ensure that they cover both horizontal and vertical variability, therefore collecting large data sets can be required.

Usually the basic variables needed for field-based programs are temperature, salinity, pH, nutrients (N, P, Si), phytoplankton biomass, and phytoplankton species composition. More advanced sampling programs for say model development might require estimates of primary production, nutrient limitation -bioassay measures, sinking rates, grazing rates, and horizontal advection.

Automated data collection

Temperature, salinity and pH can all be monitored by inexpensive instruments, where the only constraint upon the number of samples is the ability to record the data. Fluorometers can be used to make reliable, rapid assessment of phytoplankton biomass. From my experience in the Swan River Estuary in Western Australia, phytoplankton biomass measured as chla on a spectrophotometer and fluorescence are correlated with about a 0.95 r^2 value. Since it is several orders of magnitude less time consuming to measure fluorescence we use this extensively for mapping algal blooms in the Swan River. Finally, the automatically collected data must be stored along with a spatial position. To accomplish this we use an inexpensive GPS, an A/D board and a computer on-board our small research vessel. A good review of this sort of field work is in Franks and Anderson (1989).

BIOMARKERS

Lipids

Many lipids, either fatty acids or sterols, are synthesised by phytoplankton and after consumption are incorporated without change into animal tissue. One study demonstrated that 98% of the fatty acids incorporated by zooplankton from phytoplankton were untransformed or transferred intact. Most zooplankton cannot synthesise polyunsaturated fatty acids and must obtain these essential components from their diets. Fatty acids are often diagnostic for certain phytoplankton groups and for eukaryotes versus prokaryotes, and so may be of value in a range of studies such as analyses of food webs. Typically, analysis of lipids as biomarkers is an expensive process, using sophisticated gas chromatography.

Pigments

Phytoplankton pigments can be detected in herbivores, but often they are degraded to identifiable metabolic products. Analysis of the degradation products can provide qualitative indications of the nature of food being consumed by grazers or herbivores. In general, this technique is most useful for determination of recently consumed foods. Samples are usually analysed using High Performance Liquid Chromatography (HPLC), and are relatively expensive.

Stable isotopes

Stable isotopes of carbon and nitrogen are changed only slightly by the processes of incorporation into herbivore tissue. Since the initial isotopic composition of different foods can vary significantly, this can be used as a tool to assess diet sources over the medium to long term. Samples are usually analysed in a mass spectrometer, and can be very expensive.

OVERVIEW OF SOME REMAINING PHYSICAL ENVIRONMENTAL ISSUES

Whether or not increased PP will result in sufficient BOD to produce anoxia within an ecosystem depends upon many factors. Amongst these are the physical factors: depth of water column, bathymetry and basin shape, and the nature of the prevailing physical forcing to create mixing (tides, wind, heating, cooling).

In deep ecosystems the volume of water below the productive zone is large and all of the organic carbon which will be consumed to create the BOD will spread out over a large body of water. If this body has even limited turnover or exchange then anoxia is unlikely. Even shallow systems may avoid anoxia if there is strong physical mixing that penetrates down to the bottom. For most ecosystems the risk of anoxia will be proportional to the amount of PP. Large scale anoxia events kill millions of fish and other organisms. Anoxia can occur quickly, particularly where there are strong diel cycles in highly productive systems.

In the Swan River estuary the major seasonal anoxic event is triggered by rainfall. In Perth we have a long dry summer. The estuary is quite productive but there is considerable wind mixing so that, although low oxygen conditions do occur in deeper parts of the river, they rarely spread. When the first autumn rains arrive they produce a freshwater layer on top of the brackish water column, and this acts as a barrier to mixing. A 10–20 km stretch of the estuary may turn completely anoxic within one week. Such large scale anoxia has the potential to trap and kill even mobile animal such as fish. Benthic invertebrates are usually more robust to low oxygen conditions, but they also can be killed by these sorts of events if they are prolonged.

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HARMFUL ALGAL BLOOMS AND THEIR IMPACTS IN THE TROPICS

Susan Blackburn
CSIRO Division of Fisheries, Hobart.

Algal blooms are normal events in the tropics. Blooms of the cyanobacterium *Trichodesmium* were recorded by Captain Cook in the 1700's (Maclean 1993). However, there is evidence that in recent times there has been an increase in frequency and intensity of blooms with an increase in anthropogenic eutrophication. There is also an apparent spreading of harmful algae due to both natural and man-made means. This paper will give an overview of the characteristics of blooms of harmful algae and examine the factors influencing blooms. While the emphasis will be on harmful algal blooms in the tropics, relevant information from temperate areas will be presented.

Algal blooms are proliferations of micro-algae. The single-celled micro-algae divide vegetatively, one cell becoming two, two becoming four, and so on under conditions conducive for growth. These conditions include suitable temperature, light, and high levels of organic and inorganic nutrients. Water column stability can be important, because many bloom species have mechanisms such as motility or flotation devices that allow them to become concentrated in calm conditions. At concentrations of a million cells per litre some species of micro-algae such as dinoflagellates can discolour the water red to reddish-brown leading to the name "red tides". Blue-green algae (cyanobacteria) also commonly form dense, very visible blooms, discolouring the water green to blue-green. However algal blooms do not necessarily need to be of a density great enough to discolour the water — some toxic species are harmful at concentrations of 10^4 cells l^{-1}.

The algal groups known to form blooms are the dinoflagellates, diatoms, raphidophytes, prymnesiophytes, silicoflagellates and chlorophytes and cyanobacteria. However out of many thousands of species only about 300 species from 20 genera commonly form blooms. Identification is based on cell morphology and requires detailed light microscopy or, in some cases, more sophisticated techniques such as electron microscopy. There is no single taxonomic reference for harmful algae. There are a number of useful references listed at the end of this paper. For the Asian region the book "Red Tide Organisms in Japan" (Fukuyo et al. 1990) and a series of leaflets to aid in identification of harmful algal species currently being produced by IOC-WESTPAC are particularly valuable.

Algal blooms can be harmless discolourations of water. However even when the micro-algae are harmless the bloom can be potentially very harmful because the high cell density and therefore high oxygen demand for respiration can cause oxygen depletion in the water column, leading to indiscriminate kills of aquatic animals. The unusual dinoflagellate *Noctiluca* is in this "harmless" category.

There are a number of different types of harmful algae. Some produce toxins potent to humans, others are harmful to fish and invertebrates. Hallegraeff (1994) gives a comprehensive review of harmful algal blooms on a global scale. Many of these toxic algae are problems in the tropics. Corrales and MacLean (1995) reviewed the problems in the Asia-Pacific region with reference to aquaculture.

Of the algae which are harmful to fish and invertebrates, some physically damage gill tissue e.g. *Chaetoceros convolutus* and *C. concavicornis*, while others produce haemolytic substances ('hemolysins') which cause gill damage and capillary haemorrhage. Other responses are gas exchange dysfunction, overproduction of mucus and secondary infections. In this category the raphidophyte *Chattonella* caused major shrimp and fish kills on the Malaysian Peninsula in 1983 and there have been extensive and frequent fish kills in the Seto Inland Sea, Japan (Okaichi 1989). *Heterosigma akashiwo* was implicated as the causative organism for a massive kill of cage-reared chinook salmon in New Zealand (Chang et al. 1990). There is evidence that production of these harmful substances is exacerbated by phosphorus limitation in the prymnesiophyte *Chrysochromulina polylepis* (see Hallegraeff 1994).

Of the algal blooms that produce toxins potent to humans, paralytic shellfish poisoning (PSP) and ciguatera are the most prevalent issues in the tropical marine and estuarine waters. Other toxin events are diarrhetic shellfish (DSP) and in fresh and estuarine or brackish waters hepatotoxic and neurotoxic cyanobacteria commonly from harmful blooms.

Ciguatera is a poisoning which results from eating tropical fish contaminated with toxins produced by a number of benthic dinoflagellates such as *Gambierdiscus toxicus* and possibly *Prorocentrum lima*, *Coolia monotis* and *Ostreopsis sramensis*. These produce the potent neurotoxins gambiertoxin and maitotoxin which accumulate through the food chain predominantly as ciguatoxin. Ciguatera is a serious health risk in tropical areas and, although it is known from historical times, there is evidence that reef disturbance, both natural and man-made, is allowing a greater proliferation of the causative dinoflagellates. More details are available in Gillespie et al. (1986) and Lewis and Ruff (1993).

Diarrhetic shellfish poisoning (DSP) involves polyether toxins (okadaic acid, dinophysis toxin – 1) produced mainly by *Dinophysis* species of dinoflagellates. It is non-fatal, causing gastro-intestinal poisoning similar to a bacterial infection. There is evidence that the toxins may also have a tumour-promoting effect. DSP has been reported from Thailand and Japan (Shumway 1990).

Cyanobacteria produce cyclic peptide hepatotoxins which cause diarrhea and liver damage in both animals and humans drinking contaminated water. *Microcystis* species, which produce a suite of toxins — microcystins — are common hepatotoxic cyanobacteria. A dramatic example of hepatoxicity was the poisoning of over 140 people on Palm Island, North Queensland, Australia in 1979 after the reservoir for the reticulated water system on the island had been treated with copper sulphate to destroy an algal bloom of *Cylindrospermopsis raciborskii* (Hawkins et al. 1985). An increasing number of cyanobacteria have been found to produce potent neurotoxins. Recently it was confirmed that one of the main causative organisms in over 1000 km of river blooms in Australia in 1991, *Anabaena circinalis*, produces the PSP toxins saxitoxin and its derivatives (Humpage et al. 1994). See Carmichael (1992) for a review of the toxins of cyanobacteria. Marine cyanobacterial blooms are not usually harmful, although *Trichodesmium* blooms can be very extensive in tropical oceans and there has been one record of neurotoxicity.

The biggest toxic algal bloom problem in the tropical Asia-Pacific is PSP produced by the dinoflagellate *Pyrodinium bahamense*. In this region there were over 3000 recorded cases of human poisoning and over 140 deaths by mid-1994 (Corrales and Maclean 1995). The areas most affected are the Philippines, Brunei Darussalem and Malaysia. The same species also caused considerable problems in Guatemala in 1987 with 187 people hospitalised and 26 deaths (Rosales-Loessener et al. 1989). The toxins are the neurotoxins saxitoxin and derivatives. They are accumulated by shellfish but do not adversely affect the shellfish. Humans can become very ill (dizziness, nausea, tingling extremities, difficulties with breathing). Death may occur by respiratory failure. Children are the most vulnerable.

Of significance both to the development and potential spread of blooms is the resistant resting cyst produced as part of a sexual life cycle in many of the PSP-producing dinoflagellates. The resting cysts (hypnozygotes) can survive conditions unsuitable for vegetative growth such as anoxia and sub-optimal temperatures. While most resting cysts have a dormancy period of several days to 6 months during which they cannot germinate, after this period has elapsed they will germinate under suitable conditions, therefore acting as "seed-beds" for potential blooms. Some resting cysts can be detected in the fossil record.

Survival under adverse conditions means that cysts can be transported to new areas either by natural means (e.g. storm events, currents) or in the ballast water of cargo ships. The impact of the transfer of toxic dinoflagellates has been extensively documented (e.g. Hallegraeff and Bolch 1992) and in November 1991 the International Maritime Organisation (IMO) ratified the introduction of voluntary guidelines for handling of ballast water by bulk cargo vessels.

MacLean (1989) compiled evidence of an apparent spread of *Pyrodinium bahamense* through the Indo-West Pacific region after the first record of *P. bahamense* causing PSP in Papua New Guinea in 1972 (MacLean, 1977). He demonstrated a relationship between the occurrence and intensity of blooms with the El Niño–Southern Oscillation (ENSO) climatological events (MacLean, 1989), suggesting global climatic phenomena may influence the development and spread of harmful algal blooms. Recent cyst evidence from Manila Bay suggests that *P. bahamense* is a relatively new introduction there (Fukuyo et al. 1994).

While algal blooms are natural phenomena there is mounting evidence that anthropogenic eutrophication from domestic, industrial and agricultural waste is exacerbating the problem. Okaichi (1989) documented the correlation between increasing red tides in the Seto Inland Sea, Japan and increasing chemical oxygen demand between 1965 and 1976, and similarly a strong correlation was found for an increase in red tides with increase in human population in Hong Kong Harbour between 1976 and 1986 (Lam and Ho, 1989). Since 1988 strict environmental requirements have been legally enforced for all new industrial and sewage effluents in Hong Kong Harbour.

In temperate Western Australia a strong correlation was found between phosphorus loading of winter river flow from the use of fertilisers in the predominantly agricultural catchment of the Peel-Harvey Estuary system and the subsequent development of blooms of the toxic cyanobacterium *Nodularia spumigena* (Hillman et al. 1990). This system also demonstrates the complex interaction of environmental factors, because low salinities and low turbidity are required for the development of blooms. Attempts at remediation involve reducing phosphorus input from the catchment and increasing flow and salinity in the lower part of the system by construction of the Dawesville Channel between the inlet and the ocean.

Often, such as in the case with the Seto Inland Sea, these highly eutrophic embayments are also important aquaculture areas. In 1972 a *Chattonella* red tide killed 14 million cultured yellow-tail fish there. Equally harmful algal blooms may develop in grow-out ponds for cultivated species such as prawns. Two recent reviews cover the impact of harmful algal blooms on aquaculture in developing countries and the Asia-Pacific region (Maclean, 1993, Corrales and Maclean, 1995).

It is clear that harmful algal blooms are a continuing and increasing issue. Rising populations and use of the coastal zone for conflicting needs, such as waste disposal and expanding mariculture operations, highlight the need to be aware and minimise the factors influencing the development and spread of harmful algal blooms. If blooms are already an established problem remediation strategies are possible in some cases, but can be very expensive.

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EUTROPHICATION: BIOLOGICAL EFFECTS ON CORAL REEF SYSTEMS

Terry Done
Australian Institute of Marine Science, Townsville.

CONCEPTUAL FRAMEWORK FOR REMEDIATION OF CORAL REEFS

Programs for remediation of degraded coral reefs should be undertaken within a framework which recognises the full range of factors which govern the structure, diversity and productivity of coral reefs. In this workshop, the primary focus is eutrophication, and indeed, the restoration of good water quality to polluted areas can be a key component in successful rehabilitation of a severely degraded reef. However there are many cases where eutrophication is not the sole or even the primary cause of reef degradation. The following notes therefore review the nature and causes of degradation of coral reefs in the context of their natural variability, and the implications for policy makers or managers considering remediation of damaged areas. The ideas presented here have been covered and referenced in more detail in Done (1992), Done (in press) and Done et al. (in press); see also Munro and Munro (1994).

EUTROPHICATION – DIRECT AND INDIRECT EFFECTS

Coral reefs are particularly vulnerable to coastal discharge of pollutants (freshwater, soils, domestic and industrial sewage). Direct and indirect effects are recognised (see also Birkeland 1987, 1992):

- Direct effects: When reefs are within coastal embayments, or when the reefs themselves form embayments with long water residence time, sediments, dissolved nutrients and freshwater can impact directly on reef benthic communities, stressing or killing corals and other calcifying organisms, and fertilising benthic algae (competitors of corals). The fertilisation effect may take place in short periods of elevated water-column concentrations of available N and P. Particulate organic matter (raw sewage) can support communities of non reef building filter feeders (sponges, oysters, worms) which can occupy space formerly occupied by reef building organisms. Chronic pollution can also lead to the following indirect effects.

- Indirect effect 1: phytoplankton blooms. Nutrient uptake by phytoplankton may chronically or periodically increase occurrence of phytoplankton blooms. These in turn can impact on reefs in several ways, not all of them deleterious:

    - Death of phytoplankton blooms in reefal habitats, especially lagoons, causing remineralisation of N and P, and increased biological oxygen demand (BOD) of decomposition, thence respiratory stress and/or mass kills in higher reef biota.

    - Living blooms cause reduction in light available to phototrophic organisms such as corals, algae and seagrass

- Living blooms provide a food source for some species of soft corals (Fabricius 1995), potentially to the detriment of reef-building corals.

- Indirect effect 2: Sedimentary accumulations. Terrigenous sediments accumulated in a `coastal wedge' act as a microbe-rich sponge which exchanges organic matter and nutrients with the water column, the latter compartment being periodically made available to planktonic and/or reef systems.

ECOLOGICAL AND AESTHETIC DEGRADATION

There are numerous examples around the world of coral reefs which are in a degraded state (Brown 1988, Salvat 1987). The symptoms of the degradation are seen in two key services which the degraded coral reefs once provided to smaller human populations; fisheries production and maintenance of reef structure with its attendant benefits to humans.

A reef may be considered `ecologically degraded' (compared to a former condition) under the following circumstances:

- It no longer provides the production of fisheries (especially fish and molluscs) that it did in times past

- It no longer sustains healthy coral populations in its coral-producing zones, these zones instead being either bare, or invaded by excess populations of `non-reef building' organisms such as algae, soft corals or zoanthids.

- Both of the above.

These are fundamental aspects of ecological degradation. In addition, increased levels of littering, breakage and reduced water clarity are forms of aesthetic degradation which may or may not have functional consequences in terms of ecosystem services.

For policy-makers and managers wanting to remediate degraded reef fisheries and/or reef benthic communities and hence structure, there are two other indisputable facts.

- Land runoff, including point and diffuse sources of pollution, is only one impact which may need managing to achieve the required result. Indeed, it may just as important, or even far more important to eliminate over-fishing and/or destructive fishing methods in many circumstances (McManus et al. 1993). Birkeland (pers. comm.) believes only subsistence fishing is sustainable. i.e. current technology and human population sizes far outweigh the natural replenishment capacity of populations to sustain production at useful levels

- In some circumstances, remediation may be unnecessary or futile in the context of natural cycles of destruction and regrowth.

Degradation — when is it `permanent' and when is it a transient and natural condition? Sometimes, so—called `degraded' reef states are apparently normal stages in a succession initiated by natural disturbance. For example, in some regions or localised geographic settings, widespread coral death can be caused by extreme high or low temperature anomalies, extreme flood events, or extreme waves associated with cyclones (hurricanes; typhoons). In the absence of live coral, the non—reef building benthic organisms mentioned above (algae, soft corals, zoanthids) can dominate the reef for a period of years to decades. Alternatively, the area may remain `bare reef' where there are abundant grazing fish and/or invertebrates (such as sea—urchins). In `pristine' reefs, well supplied with coral larvae, recolonisation by corals in a normal cycle should take place over those same years to decades.

`Bare reef' can be a cause for concern, when an over-abundance of grazers destroy reef framework at a faster rate than it can be replaced by coral recruitment and growth. Humans may affect grazer abundance through overfishing of the predators of grazing fish and overfishing the grazing fish themselves. In Jamaica, this overfishing led to increased sea-urchin abundance which kept algae grazed bare and allowed corals to settle and grow (Hughes 1994). However a pathogen spread through the urchin population, it crashed, and failed to recover, leaving the reefs covered in a mat of fleshy algae which prevented corals from re-establishing. In east Africa, the urchins have not crashed, and in places are severely eroding reef structure (McClanahan 1994). In other contexts, surfaces are free of macro-algae, but coral resettlement is prevented by increased amounts of silt in and on the reef matrix.

RISK ANALYSIS

Managers and policy makers need to assess the likely efficacy of potential remediation measures. Specifically, they need to address the following questions:

- Will a particular course of action lead to restoration of reef qualities?
- Over what spatial scales will the beneficial outcome be obtained?
- Over what time-frame can the outcome be expected?

The general approach of ecological risk assessment (ERA) (Suter 1993) provides techniques and tools for such assessments. ERAs involve use of transport and fate models, biological effects models, and determination of the likelihood of exceedance of critical biological thresholds under pre- and post-remediation conditions.

Done (in press) notes that in a context of decision making for coral reef management, a formal ERA will not be necessary where there is clear cut cause and effect between source and response, such as will be the case in many coral reefs close to centres of human population. For example, it may not be necessary to do a formal ERA to evaluate diversion of sewage outside a reef lagoon, because cause (sewage) and response (filter feeders and/or algal overgrowth of corals in close proximity to a point source of pollutants) are clearly apparent in the distribution of the effect.

However formal ERA may be warranted where:

- there is a substantial economic and/or social cost in undertaking remediation (such as changing human resource-use practices; redirecting a sewage outfall, treating sewage, or otherwise modifying inputs into coral reef environments); and

- there is any doubt about the geographic extent over which the remediation will benefit coral reefs. Where water exchange is high (open coasts or lagoons with fast turnover of water through passes and over the reef), and dilutions are such as to suggest the value of undertaking remediation is doubtful, a formal ERA and cost-benefit analysis may be warranted.

However there are potential pitfalls along the way. For example, simple hydrodynamic models may not capture some important aspects of dispersion of a deleterious pollutant (Wolanski 1994). In addition, there is a dearth of data on the key biological thresholds of nutrients or pollutants which may lead to degradation, either directly or indirectly. Where decisions are made on the basis of such uncertainty, the ERA, though not always able to provide a certain answer, at least provides a formal process by which consideration of key ecological, physical and chemical processes are laid out in a formal way.

CONDITIONS NECESSARY FOR RECOVERY

It cannot be assumed that removal of a pollutant will by itself lead to restoration of vigorous coral growth and production of protein (e.g. fish, molluscs, crustaceans). Two other essential conditions are:

- restoration of `on-site ecological conditions' which initiates a succession leading towards a coral dominated and productive state.

- availability of `propagules' of key reef building and reef-associated taxa.

Restoration of `on site ecological conditions': In the poorly flushed embayments which are most prone to eutrophication, remediation may require radical engineering solutions to flushing out accumulated silts and/or pollutants (e.g. use of suction dredges; temporarily (or permanently?) breaching reefs to increase circulation from the open sea. Obviously, such actions may have major detrimental short-term effects, either localised to the immediate engineering site, or more generally throughout a bay or lagoon. In extreme cases, the actions could set the reef back to being a comparatively bare and depauperate biological system, but one which is more capable of supporting a succession leading towards a coral dominated and productive system than that which was formerly present.

Availability of `propagules': This succession towards a coral dominated and productive system relies absolutely on a supply of propagules of appropriate species. Very localised remediation may benefit from transplanting of coral species and other benthic species once it is considered that on-site conditions will support them.

However the success of remediation in the long term requires there is a long-term natural supply of larvae of corals, other invertebrates, plants, and fish from other `source' reef areas. Dispersal rates and composition of propagules being swept into a specific reef location are very unpredictable. The location of the reefs which are the most likely `sources' for a particular reef under remediation can be guessed at on the basis of the direction of the prevailing ocean and coastal currents, but few experts would have confidence in making links between specific reefs and their sources. The most prudent strategy for policy makers and coral reef managers is to provide protection for as many reefs distributed as widely as possible throughout regions, irrespective of national boundaries.

CRITERIA FOR SUCCESSFUL REMEDIATION

From a purely structural and productivity point of view, there will be a relatively small group of critical coral, algal, macro-invertebrate, and vertebrate species whose restoration could be considered a measure of success of the remediation program. Increasing percentage coral cover over periods of years would provide encouragement that the project is successful. In the longer term, the attainment of old age and large size in individual corals or coral stands, and the accumulation of reef framework, are real evidence of success in managing for structural integrity. From a biodiversity points of view, success would be measured in terms of the long-term viability of diverse populations without obvious functional importance. Many of these ideas are discussed in more detail in Done (in press) and Done et al. (in press).

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NUTRIENT IMPACTS IN KANEOHE BAY, HAWAII: AN HISTORICAL PERSPECTIVE

Laurence McCook
Australian Institute of Marine Science & CRC Reef Research Centre, Townsville.

Kaneohe Bay, Hawaii, is one of the best studied examples of nutrient disturbance in tropical marine/coral reef ecosystems. The bay was the site of a sewerage outfall from the 1950s to 1977/8, after which the outfall was diverted from the bay. Extensive work by Smith et al. (1981 Pacific Science 35: 279-395) and Maragos et al. (1985 Proc. 5th Int. Coral reef Symp. 4:189-194) monitored the chemical and biological status of the Bay before and after diversion of the sewerage. The sewage appeared to cause changes in amount and types of plankton and benthic (bottom dwelling) organisms, with increases in plankton, some reef algae and filter feeding animals. Importantly, hard corals appeared to be out-competed by a bloom of the common reef green alga *Dictyosphearia cavernosa*. Reef fish diversity was also reduced.

Removal of the sewage input caused rapid reversal of some but not all of these impacts. Reef communities initially recovered rapidly, but have not continued to recover, in part because corals are slow-growing, and because other human disturbances continued.

The studies demonstrated that in this enclosed bay, most of the inorganic nitrogen and phosphorus were taken up by phytoplankton without being flushed from the bay. Nutrient cycling between water column, sediments and benthos and between trophic levels were important to the chemical and ecological dynamics.

Thus, the Kaneohe Bay events provided an invaluable and detailed example of eutrophication and recovery on a tropical coast. However, several aspects of the events have limited interpretation about the mechanisms and generality of the impacts.

First, the sewerage discharge not only increased nutrient supply in the bay, but also added large amounts of sediments and freshwater. Each factor (nutrients, sediments and freshwater) were likely to have had substantial interactive or cumulative effects. This has confounded a strict interpretation of the mechanisms by which the sewage affected the reef, since the impacts of nutrients, sediments and freshwater can not be unambiguously separated. On the other hand, sewage commonly has these characteristics, so it is valuable example of the impacts of the combined factors.

Second, much of the study was anecdotal, and it was un-replicated, relatively small in spatial scale and confounded by other impacts (human and natural). An assessment of the long-term impacts of the sewerage is confounded by other continuing impacts. Thus the results observed in Kaneohe Bay are unique to this bay in space and time, and should be extrapolated with great caution to other circumstances.

Third, benthic community monitoring was unavoidably crude, and taxonomic resolution was poor. This has limited the ability of the study to detect low-level reef degradation, and is of only limited value in predicting impacts elsewhere, based on comparisons of species abundances.

BIOLOGICAL INDICATORS OF NUTRIENT STRESS

David Yellowlees
James Cook University, Townsville

In tropical waters some animals have developed a strategy to overcome the typically low levels of free-living phytoplankton. These organisms have entered into a symbiotic relationship with certain species of marine phytoplankton. Organisms in this category include hermatypic corals, sea anemones, giant clams and certain jellyfish. In return for providing a safe haven for these phytoplankton the animal avails itself of much of the photosynthetically produced food that these phytoplankton make. Both organisms therefore profit from the association.

During the past 5 years we have been investigating the effect that nutrients have on giant clams. During this period we have made a series of interesting observations that have the potential to be used in environmental monitoring.

When nutrient levels are increased in the environment they become available to all organisms that can utilise such inorganic sources of nutrients. Free-living phytoplankton are one of the main organisms able to use such nutrients. But those phytoplankton which live in symbiosis with corals and giant clams will also come into this category. Symbiotic phytoplankton can utilise dissolved nitrate, ammonium and phosphate and as a result will increase their productivity. This will result in an increase in their numbers within the symbiotic host and as a result will provide the host with more food from photosynthesis. As a consequence the host organism has the potential to grow faster. The additional nutrients at first might seem beneficial for these organisms. However these symbioses have prospered because they have an advantage over other organisms in these nutrient poor tropical waters, and are adapted to low-nutrient conditions. An increase in nutrients removes that advantage and enables competing organisms to flourish. Where high levels of nutrients have been flushed into the sea, coral reefs have suffered badly and in many cases have been destroyed. Kaneohe Bay in Hawaii is a classic example of this. This bay has recovered significantly since the problem was highlighted but it will probably never return to its original condition.

Why use clams as environmental guinea pigs? These molluscs are now the subject of a number of successful aquaculture ventures throughout the Pacific and South-east Asian area. They can therefore be bred in large numbers. Environmental monitoring may require the sacrifice of some native organisms for analysis. Positioning of clams from cultured stocks eliminates this need as they could be placed in strategic positions where regular monitoring is necessary. The native population is therefore not disturbed. Also, clams have the advantage of being relatively robust and therefore can be transported and survive a range of conditions. This means that they may be also used for monitoring in situations that are not completely suitable for natural populations, reducing the need for cross-validation of monitoring data to other species.

What then happens to clams under nutrient level increases and why have they the potential to be useful? Our studies have indicated that they respond in characteristic ways to increases in both nitrogen and phosphorus. Both short and long-term changes have been observed.

Monitoring may require information about both present and past nutrient levels. In the case of the present nutrient levels, clams show characteristic and readily measurable responses to increase in nutrients. This can either be done by destructive or non-destructive sampling. Determination of historic exposure to nutrients is more difficult, and requires destructive sampling. It is also technically more demanding and therefore expensive but can be achieved.

THE GREAT BARRIER REEF MONITORING PROGRAM

Jamie Oliver
Great Barrier Reef Marine Park Authority, Townsville

Monitoring programs on the Great Barrier Reef cover a range of variables over several different spatial and temporal scales. The principal reasons for monitoring are to:

1) document long-term natural variation of important reef attributes;

2) to compare this natural variation to postulated human impacts; and

3) to verify the effectiveness any management action which has been implemented.

There are several long-term monitoring projects on the Great Barrier Reef which examine specific organisms or physical variables, including long-standing programs to monitor dugongs, sea turtles, meteorological, oceanographic and water quality variables. In addition the Great Barrier Reef Marine Park Authority supervises a range of site-specific monitoring programs designed to detect localised impacts from commercial developments on the Great Barrier Reef.

The largest monitoring program on the Great Barrier Reef is being conducted by the Australian Institute of Marine Science. The AIMS long-term monitoring program was initiated in 1992. Its primary objectives are to detect and quantify changes through time in the distribution and abundance of corals (and other macro-benthic organisms), fish, nutrients and crown-of-thorns starfish on the Great Barrier Reef. The project is intended to deliver timely advice to reef managers on the status of the Great Barrier Reef, and to generate long-term data sets on natural spatial and temporal variation for a variety of physical and biological variables. The project design also allows the accumulation of information regarding the possible effects of terrestrial runoff on the biotic status of adjacent reefs. The project has completed a two year methodological development phase, and in 1994/95 the full set of 52 reefs were surveyed in detail for fish, benthos, water quality and crown-of-thorns starfish, with an additional 58 reefs surveyed by manta tow for crown-of-thorns starfish and coral cover, and a further 40 sites samples for water quality. The project is the most extensive long-term monitoring program on a coral reef ecosystem in the world, and has secure government funding. Although modifications to the sampling design and measurement procedures may still be warranted, the project has already accumulated valuable synoptic information for a large number of reefs on the Great Barrier Reef and on changes over a 2-3 year period.

THE GREAT BARRIER REEF ENCORE EXPERIMENT

Andy Steven
Great Barrier Reef Marine Park Authority, Townsville

The ENCORE project is described in an article published in Marine Pollution Bulletin. The abstract of that article is shown below:

"An *in situ* reef fertilisation experiment is being undertaken on the Australian Great Barrier Reef, to investigate the response of coral reefs to nutrient enrichment. This experiment, known as ENCORE, is designed to quantify the fate of nitrogen and phosphorus within a coral reef, and compare their impact on a variety of coral reef organisms. Co-ordinated by the Great Barrier Reef Marine Park Authority (GBRMPA), 30 scientists from eight Australian and three overseas organisations are undertaking research encompassing cellular through to community level responses. This research will provide a scientific basis for developing appropriate water quality management strategies in coral reef environments, and may identify a number of sub-lethal indicators of nutrient stress."

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CATCHMENT MANAGEMENT ISSUES ON THE WET TROPICAL COAST OF NORTH EAST AUSTRALIA

Andrew Johnson
CSIRO Division of Tropical Crops and Pastures, Townsville.

INTRODUCTION

The region commonly referred to as the wet tropical coast (WTC) of north Queensland extends from Cape Tribulation in the north, south to Ingham and west to Herberton. The WTC occupies a relatively small area in the Australian context, but it has a unique combination of landforms, climate, soils and vegetation which have given rise to an equally unique range of natural features, rich in diversity and beauty. The region is also unique in having two World Heritage listed areas, the Wet Tropics and the Great Barrier Reef within its confines. Like many other parts of the coastal zone of Australia, the region is a major focus of competition between alternative uses of resources which poses serious threats to its future economic, environmental, social and cultural potential.

The aim of this paper is to discuss a range of catchment management issues affecting the WTC that are both important at present and which are likely to be important in the future. While the focus of the paper is not on the marine environment *per se*, a number of significant land/water issues that are central to the maintenance and function of coastal and marine resources are discussed. The paper also introduces some recent development in policy and legislation that will impinge on future management and speculates briefly on their likely implications.

REGIONAL DESCRIPTION

Three general landforms characterise the region; coastal plains, coastal ranges and tablelands. Of these, the coastal plains and tablelands are the more extensive in area, heavily populated and utilised for primary and secondary production. The WTC normally experiences warm humid to sub-humid summers and mild dry winters. Large rainfall and temperature gradients exist. Rainfall, and consequently runoff is highly seasonal, with a distinct summer bias. Rainfall is strongly influenced by the incidence of cyclonic activity in the November to May period. In terms of the surface hydrology, the river systems have similar drainage patterns in that they rise in mountainous areas to the west, cross a coastal plain and enter the sea via mangrove deltas. With the exception of the Herbert River catchment (ca. 10,000 km^2), most river basins in the region are small in area (ca. <3000 km^2) by both national and international standards, however they do have the highest rainfall to runoff ratios in Australia and consequently large volumes of freshwater are delivered to the adjacent estuarine and marine environments.

Major resource use activities include, agriculture, horticulture, fishing, aquaculture, mining and forestry. Agriculture contributes approximately 11% of the regions GDP, with the main industries being sugar, bananas, beef and dairy cattle, peanuts, vegetables, other tropical fruits and tea (ABS 1995). The region also supports a substantial commercial and recreational fishery. Forestry has declined in importance since the World Heritage listing of the rainforest resource, with timber production now primarily focussed on exotic softwood plantations. Tourism is also of high importance on the WTC, with access to major attractions such as the Great Barrier Reef and tropical rainforests now much improved through development of local infrastructure and upgrading of facilities at both Cairns and Townsville airports. The population of the region has increased rapidly in recent years and currently approximately 195,000 people live on the WTC, with Cairns being the largest urban centre (ABS 1995). This population is expected to increase by additional 80,000 to 100,000 persons over the next 20 years (Anonymous 1995).

NATURAL RESOURCE MANAGEMENT ISSUES – CURRENT AND FUTURE

Since the mid-1980's, the WTC has experienced strong economic growth, underpinned predominantly by solid performance by its agricultural and tourist sectors. It logically follows, that the performance of these sectors in the future is dependent on the ecologically sustainable development of the natural resource base. Current natural resource use on the WTC is having an impact on terrestrial and riverine systems, and on the adjacent marine environment (Drummond and Associates 1993). The frequency and magnitude of these impacts is catchment specific and often very difficult to quantify (Bramley *et al*, 1994, Mitchell *et al*, 1995a, b). However while this is an obvious difficulty in terms of the development and implementation of useful management strategies, there remains a set of issues that relate to impacts common to all catchments that can focus this discussion. Issues that have current prominence and which are expected to be important for the future include: control of weeds within riverine systems; re-establishment of riparian vegetation; maintenance and enhancement of wildlife corridors along river systems and their tributaries; reducing rates of erosion and sedimentation (particularly in upper catchment areas) which have the potential to smother organisms and reduce the range of available in-stream habitats; protection of estuarine areas which are of regional, national and international biological significance; and the potential impacts on freshwater wetlands through draining and/or filling for agricultural or other purposes.

Sedimentation

Although it can be argued that there has been some increase in sediment accession to riverine and marine environments since European settlement, sediment deposition has not had a major impact on the characteristics of the rivers of the WTC over the last 50 - 100 years (e.g. Drummond and Associates 1993). Sediment input to the WTC river systems may have been increased by clearing and cultivation of land for sugar cane, boat wash in the lower reaches, grazing and damage of river banks by livestock, grazing, cropping and mining activities in tableland areas. However, despite the fact that the precise rate and impact of sediment delivery to estuarine and marine environments since European settlement remains unknown, some corrective action has been undertaken. The adoption of green cane harvesting-minimum tillage (now used for example on 99% of cane farms in the Herbert River coastal plain and to a lesser extent in the other catchments) has been an important step in decreasing sediment supply to the coastal zone from agricultural lands. Prior to the introduction of green cane harvesting, average annual losses for sugar cane cultivation were in the order of 150 t ha^{-1}, with the range of annual measurements being 70-500 t ha^{-1} (Prove 1991).

Sediment loss from grazing lands (particularly immediately following periods of severe drought) remains problematic. Strategies to manage sedimentation include improving land management in the grazing areas, controlling bank erosion throughout the catchment and managing appropriate levels of sand and gravel extraction from river systems.

Riparian vegetation

Riparian vegetation plays an important role in maintaining the biological health of the aquatic and terrestrial ecosystems associated with watercourses (Raisin 1995). The most important ecological functions of riparian vegetation are assisting in maintaining bank stability, providing a filter strip which reduces sediment input into the watercourse, creating habitat for fish and other aquatic organisms, the deposition of leaf litter into the watercourse which is a major component of the food chain and provision of habitat for terrestrial birds, mammals, reptiles and amphibians and insects. The maintenance of riparian vegetation is paramount to the maintenance of a healthy and functional stream ecosystem which is productive, aesthetically attractive and suitable for all the other uses (e.g. recreation, water supply, irrigation, fisheries production, etc.).

Considerable areas of the riparian vegetation have been removed from the stream banks in the WTC. In the Herbert River catchment for example, approximately 20 km of the right bank riparian vegetation has been cleared and approximately 24 km of the left bank riparian vegetation in the Herbert River itself (Perry 1995). Mangrove areas have remained mostly intact although some clearing did occur in the 1960's and 1970's. Large areas of riverine rainforest with patches of eucalypts and the riverine rainforest have also been cleared. Most of the major tributaries have retained a reasonably intact riparian vegetation, albeit quite narrow in most places. Most of the cleared stream bank areas have been invaded by weeds such as para grass, bamboo, thunbergia and African tulip trees which tend to suppress the process of natural revegetation. Recent management activities have focussed on removing exotic vegetation present in riparian zones and replacing it with native tree species.

Coastal wetlands

The wetlands, swamps, billabongs and waterholes of the WTC are important wildlife habitat areas and form an integral part of a hydrological regime. Changes to the hydrological regime of these swamps and wetlands (e.g. drainage) alters both the habitat and the vegetation. These wetlands are important habitat for wetlands birds, amphibians and other wildlife. They are also important as nursery areas for several species of commercially important fish such as barramundi (McLeod 1995). Maintenance of these values is dependent upon annual flushing and recharge during wet season floods. Clearing for agricultural purposes in the region has taken its toll on this habitat type. In the Johnstone Rivers system for example, there has been a 60% reduction in the area of coastal wetlands between 1951 and 1992 (Russell *et al.* 1995). This loss of coastal wetland habitat is a serious problem on the WTC that has implications for both terrestrial and marine biota.

Diffuse source pollution

Given the landuse characteristics of the region, diffuse source pollution has a large potential to generate water quality problems. The major potential sources and the types of pollutants generated are summarised in Table 2. These sources have generally increased in strength in recent years and have been predominantly associated with expansion in agricultural land use.

Diffuse Sources — Potential Pollutants					
Land Clearing	**Agriculture and Grazing**	**Burning-off and Wildfires**	**Urban and On-farm Development**	**Stormwater Runoff**	**River Recreation**
sediments	sediment	sediments	sediments	sediment	nutrients
nutrients	nutrients	nutrients	nutrients	nutrients	hydrocarbons
particulates	herbicides	particulates	particulates	herbicides	
	pesticides		hydrocarbons	pesticides	
	hydrocarbons			hydrocarbons	
	particulates			particulates	

Table 2: Potential Sources and Types of Pollutants for the Herbert River Catchment
(Source: Drummond and Associates 1993).

Recent research (e.g. Bramley and Johnson 1995, Mitchell *et al.* 1995) has shown that nutrient concentrations in streams of the WTC are generally below the guidelines detailed by ANZECC (1992) for freshwater. Exceptions were generally associated with peak flow events during the wet season period (December to April). Nutrient concentrations in streams associated with sugar cane production were generally greater than in those associated with other land uses, and any differences between these were only seen during wet season peak flow events. Further work by Furnas et al (1995) in the marine environment adjacent to the WTC has shown that direct external inputs of N and P through point sources are currently small relative to natural nutrient inputs. Riverine inputs of N and P comprise a large proportion of external inputs, but are still small relative to internal recycling fluxes. Data on riverine inputs of N and P are currently inadequate to reliably partition river nutrient inputs into natural and anthropogenic components.

These results suggest that the downstream effects of agricultural production in the WTC is governed to a large degree by the climate, in particular its seasonality, and the volume and intensity of rainfall. Within individual catchments, climatic spatial and temporal variability may also be significant. The results suggest that nutrient loss rates from land under intensive agriculture is likely to exceed that from other land uses *irrespective of the type of intensive agricultural production undertaken*. Hence, it is the general nature of intensive agricultural land use and the relatively high inputs that this activity involves, rather than the specific production system in operation, which results in an increased export of nutrients downstream relative to that from lower input land uses such as rough grazing or forestry. Minimisation of nutrient loss off-farm is therefore likely to depend on carefully matching actual land use to land use suitability. In the WTC, the latter is governed largely by drainage characteristics and position within the catchment.

Because the extent to which nutrient export impacts on ecosystems downstream has not been quantified and may be location-specific (ANZECC 1992), and given that the concentration of nutrients in stream water is generally below levels that have been deemed ecologically acceptable by ANZECC (1992), motivating the agricultural community to minimise the export of nutrients and other agro-chemicals downstream remains largely a question of economics. To date, the costs of ameliorating environmental degradation, real or perceived, have not been considered to be costs of production in Australian agriculture. As a result, the adoption of technologies aimed at minimising the downstream effects of agricultural production (eg. Bramley and Wood 1995, Freebairn *et al.*, 1995) may be dependent on the participatory community approach espoused by programs such as Integrated Catchment Management (Dawson, 1995). However, although nutrient levels are currently low in marine waters adjacent to the WTC and external inputs are small relative to natural fluxes and stocks, understanding of ecosystem behaviour is not sufficiently developed to the extent that the assimilative capacity of these waters for enhanced nutrient inputs can be predicted with any certainty. Hence, a cautious approach to water quality management is warranted.

RECENT INITIATIVES IN LEGISLATION AND POLICY

A revised policy framework

In response to community concerns about the sustainability of the States' natural resources, legitimate but different and often conflicting societal interests related to resource degradation, conflicting state and federal government policies, different line agencies with statutory responsibilities leading to programs and activities not always being complementary, and increasing expectations from the "public" to be more actively involved in planning and management decisions, the Queensland government has developed and, in a number of cases implemented, several new policy initiatives. There are three key initiatives that have had, or will have, a major impact on natural resource management in the WTC: Environmental Protection Legislation; Natural Resource Management Legislation; and Integrated Catchment Management.

Environmental Protection Legislation

The Queensland Government has recently released a draft Environment Protection Bill for public consultation. The draft Environment Protection Bill is intended to implement the concept of ecologically sustainable development. This concept refers to the use of natural resources in a way which meets the needs of present generations without compromising the ability of future generations to meet their needs. The need to implement the concept of ecologically sustainable development arises from the Inter-governmental Agreement on the Environment signed on 25 February 1992 by state and territory governments, the Commonwealth Government and the Local Government Association of Australia.

The Queensland Government has also agreed that the promotion of ecologically sustainable development requires policy making and program implementation to be based on the following principles:

precautionary principle environmental measures must anticipate, prevent and attack the causes of environmental degradation. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation;

intergenerational equity the present generation should ensure that the next generation is left with an environment which is at least as healthy, diverse and productive as the one the present generation experiences;

irreversibility public and private decisions need to be based on careful evaluation to avoid, wherever possible, irreversible damage to the environment;

valuation of environmental assets the valuation of environmental assets should take into account all relevant values including economic, ecological, aesthetic and social values;

polluter pays those who generate or benefit from pollution should bear the costs;

user pays the users of goods and services should pay prices based on the full life cycle of providing them, including the use of natural resources (including the global commons) and the ultimate disposal of any wastes.

The legislation is intended to control environmental contamination and degradation. The legislation will repeal the Clean Air Act 1963, Clean Waters Act 1971 and the Noise Abatement Act 1978. The legislation is complemented by the Contaminated Land Act 1991 which commenced operation on 1 January 1991. The draft Environment Protection Bill applies to both the private and public sectors. The Bill provided a broad framework specifying mechanisms for: the development of environmental standards; the management of environmental contamination and degradation; the enforcement of the legislation; and the administration of the legislation. The legislation however, does not deal with environmental impact assessment. This will be the subject of separate legislation. The proposed Environmental Impact Legislation will establish mechanisms for evaluating the environmental significance of human actions whether they be development projects, policies, plans, products or programs.

The key aspect of the legislation that will impact on natural resource management on the WTC is that it will impose a duty of care on all citizens. To assess duty of care towards the environment and test the principle of due diligence, the Act will rely on a mixture of statutory regulations, codes of practice and voluntary guidelines. In response, many industries active on the WTC have already begun the process of developing voluntary codes of practice for sustainable farming as well as floodplain management guidelines, with the sugar industry being the most prominent in these activities. The development of codes of practice and other forms of action that require voluntary compliance, is a central activity that facilitates the linkage between the legislation and the requirements of two other initiatives, namely Integrated Catchment Management and the proposed Natural Resource Management Legislation.

In Queensland, there also has recently been a reassessment of the policy position concerning State and privately owned resources and to provide a context for the consideration of comprehensive legislation. A new policy position has been circulated for comment in a discussion paper titled "Sustainable Use and Management of Queenslands Natural Resources" (QDPI 1994). The overall objectives of the new framework are to produce an integrated natural resource management (NRM) policy with non-regulatory strategies and a minimum of legislation, and to integrate the existing natural resource legislation administered by QDPI "to see an effective planning and management framework in place that provides for ecologically sustainable development for natural resources" (QDPI 1994).

The need for NRM policy is related, in part, to the following challenges: providing for the equitable and efficient allocation of State-owned or controlled water, forest and fisheries resources; maintaining the availability of natural resources for the economic development of rural industries; maintaining and enhancing the quality of natural resources and protecting them from degradation; minimising or preventing the environmental impact of natural resource use; and enhancing the economically efficient and effective use of natural resources.

The paper emphasised the need to develop appropriate behaviours through non-regulatory strategies such as information, education and extension programs, research, market incentives, and Codes of Practice. In addition to this behavioural change on the part of individual resource managers, it was realised that NRM policy would have to be linked with other resource-related policy and legislation. For instance, land use planning decisions made under the *Local Government (Planning and Environment) Act 1990* were to be informed through natural resource assessment and land capability information.

Reform of existing legal arrangements was a final component of the discussion paper. Legislative options to overcome the "overly prescriptive", "highly variable" and "fragmented" nature of QDPI-administered Acts included: a single piece of legislation to replace the nine existing Acts and which incorporates Integrated Catchment Management (ICM); retention of the existing nine Acts with amendments, together with the preparation of an additional piece of legislation for ICM; preparation of umbrella legislation that sits across the existing Acts and that for ICM; and amalgamation of the existing Acts intro three broad category Acts of land, forests and water. The first of these options is currently being pursued and will be introduced into Queensland Parliament in September 1996.

Like the Environmental Protection legislation, the key aspect of the NRM for the natural resource management on the WTC will be legislation that imposes a duty of care on all citizens. Similarly, it will also rely on a mixture of statutory regulations, codes of practice and voluntary guidelines to achieve its objectives. However, one key implication is that much of the responsibility for natural resource management will be devolved from the state government to local government authorities. This outcome is potentially problematic given the limited amount of human (especially technically qualified staff) and financial resources available to local government authorities (such as Councils) on the WTC to implement NRM policies and plans.

Integrated Catchment Management

In October 1991, an Integrated Catchment Management Strategy for Queensland was released by the State Government. The Strategy was developed under the auspices of the Queensland Integrated Catchment Management Steering Committee, an independent ministerial advisory group representing a wide range of industry, conservation and government interests. The principles on which the Strategy is based are:

- land and water resources are basic and interactive parts of natural ecosystemsand their management should be based on river catchments as geographic unitswhich account for the interactions between these resources;

- river catchments are continuously changing in response to natural processes and human activity, and their management must be dynamic so as to recognise these changes;

- the management of land and water resources must be coordinated, with decisions based on the best available information;

- in a democratic society, sound land and water management is best achieved through the informed action of individual users and managers of these resources;

- a balance between economic development and conservation of land and water resources must be maintained.

The Strategy provides a framework for fostering cooperation and coordination between landholders and other resource users, community groups and government agencies involved in the use and management of natural resources. It is dependent on landholders, the community in general and government having a sound understanding of the interactions between natural resources and the need for a coordinated catchment-wide approach for addressing issues affecting these resources. Community and government are encouraged to promote an understanding of the value of an ICM approach and its underlying principles. Importantly, it also recognises that many existing community groups can play a significant role in promoting the ICM approach.

Implementation of the ICM Strategy in Queensland has occurred primarily in coastal catchments (although recent activity has focussed on inland catchments that form part of the Murray Darling Basin). It is in these coastal areas that issues such as water quality, land use conflict, habitat alienation and stream bank erosion have been identified as important issues requiring a new approach. A plethora of groups and organisations are considered as stakeholders in these coastal areas, making coordinated action more difficult. At present, ICM programs are being conducted in all catchments on the WTC. Of these, the Johnstone River program is the most advanced and will be used in this paper as an example of integrated catchment management in the region.

Development of a catchment management strategy

The focus of activities in the Johnstone River Catchment (JRC) was the preparation of a Strategy for future management of the catchment's natural resources. The development of the Catchment Management Strategy required a complex process of strategic planning and negotiation on issues relating to the use and management of the catchment's resources. This involved broad community and agency input and the consideration of many often conflicting views to reach an agreed position on these issues. This process involved community participation, information sharing, inquiry, familiarisation and negotiation by and within the Johnstone River Catchment Coordinating Committee (JRCCC). At the commencement of the program, little information was available relating to the condition of the catchment's natural resources on which to make an objective assessment of priority issues. Initial activities focussed on development within the JRCCC of an appreciation of the catchment, its resources and the issues relating to them. This involved compilation and presentation of existing data and knowledge in a discussion paper, briefings, seminars, inspections and workshops involving a range of industry and community representatives, government agencies and research institutions.

High initial interest in ICM amongst professionals working in natural resource management resulted in the formation of 11 Technical Advisory Groups (TAGs). TAGs assisted the JRCCC in identifying key issues and prepared overview position papers on land degradation, stream management, water quality and habitat. Members of the JRCCC were active in the preparation of these papers. The JRCCC reviewed and endorsed the content of the position papers and a public information and consultation phase began. The addition of action plans "transformed" these papers into draft Catchment Management Strategies. Following extensive review by both technical experts and the community, the papers were released as draft Catchment Management Strategies in March 1993. They provide a guide to all users and managers of natural resources in the catchment, of important catchment issues and actions that can be taken to reduce or rectify these issues. Following its release in March 1993, the JRC Draft Management Strategy was reviewed extensively by government agencies (at both the policy and operational level), community groups and research organisations. The responses from these organisations were reviewed by the JRCCC in the preparation of the final Strategy.

Identification of key issues

Development of the Catchment Management Strategy required the initial identification and confirmation of the key interrelated natural resource management issues which were of concern to management agencies and stakeholder groups in the catchment. By a process of consultation, inspection, and workshops involving industry and community groups and Government agencies, a large number of issues were identified. These were prioritised and grouped under four Key Issue Areas (KIA) namely, land management, water management, riverine management and habitat management. Specific issues were outlined under these KIAs, with each KIA addressed in terms of an introduction, overview, goals and objectives, principal recommendations and strategies.

Strategies addressing the specific issues identified under each of the four KIAs were developed. Recommendations to key industry and stakeholder groups with specific recommendations relevant to the particular group were also made. Each strategy is documented in which key actions required to address particular issues, and those organisations with a lead responsibility for undertaking actions are identified. Outcomes which the strategy will deliver and targets for achieving milestones are also given. For the four KIAs, 26 separate strategies were developed to address specific issues identified during early stages of the strategy development process. Collectively, these strategies contain 130 separate actions with lead responsibility for action initiation being shared among more than 20 different organisations and private individuals. Some organisations have a major responsibility across a wide range of issues, while others are only directly involved in a small number of specific areas. Major responsibility for action falls to QDPI, the Queensland Department of Environment and Heritage (QDEH), Local Authorities (JSC and ESC) and the River Improvement Trust (JRIT), and the JRCCC.

Implementation arrangements

The strategies identify the priority actions and responsibilities required to address the management of natural resources in the catchment. They demonstrate that integration is required between and within Government agencies, Local Authorities and the JRCCC. Hence, implementation of the Catchment Management Strategy required mechanisms to coordinate the existing and new responsibilities and actions of these organisations. The model for implementation of the Strategy provides mechanisms and processes for cooperative and coordinated action. It provides for: formal arrangements linking agencies to directions identified in the Strategy; effective coordination and efficient application of existing resources; no new agencies or levels of bureaucracy; establishment of mechanisms to enhance accountability of management agencies; establishment of processes for resolving future management issues; and open and accountable decision making processes with a high level of stakeholder involvement. Key elements of the implementation process include the formation of an incorporated Johnstone River Catchment Management Association (whose Management Committee acts as the permanent JRCCC), nomination of lead government agencies, and a Memorandum of Understanding (MOU) between the JRCCC and the lead agencies. Implementation also includes regular catchment conferences and a permanent catchment information centre to be based in the largest population centre (Innisfail).

Strategy implementation

Strategy implementation will be achieved largely by and through government agency programs, complimented by funds and resources which may be available through other Government and non-government sources and local community resources. Two main mechanisms are proposed: implementation plans for KIAs; and focus activities. The key to the implementation process is the MOU and catchment conferences which this agreement provides for. The MOU will define and formalise the roles and responsibilities of the parties based on a cooperative and equal partnership. Under this partnership arrangement, catchment conferences will develop and review Implementation Plans and Activities, review the Catchment Management Strategy and identify new and emerging issues for consideration; and monitor and review progress in priority R & D projects and identify and promote emerging research needs. To be most effective, the conferences will be scheduled to mesh with agencies' budget planning cycles and the process for project funding from major funding sources.

The review process

Following the release of the Draft Catchment Management Strategy, the ICM program has recently completed the review stage. There were two facets to this stage. The first was an invitation to the public to obtain copies of the Draft Strategy and offer comment. The second was a deliberate effort to draw a widely representative sample of community and government agencies into the process by way of review panels. Membership of the panels was established by inviting key stakeholder groups to nominate representatives, as well as placing advertisements in the press inviting interested members of the public to participate. Other persons were also invited to participate to ensure that panels were representative of all interests and areas of the catchment. Three review panels were established, namely, a panel comprising local community and industry interests, a technical review panel with membership drawn from the TAGs, and a policy review panel with membership from the nominated lead agencies.

Information received from these reviews was used to make adjustments prior to the release of the completed Strategy. The completed Strategy and the Committee's recommendations were finalised for presentation to the Minister for Primary Industries, who then successfully presented them to State Cabinet for endorsement. The Committee, as a final task, is currently establishing the implementation arrangements to commence the process of translating the Strategy into real outcomes on the ground.

Current state of ICM in the Johnstone River and further implications

The formation of the JRCCC and development of a Catchment Management Strategy represents a significant advance, and strategies to address KIAs are being implemented. A number of reasons why ICM has been able to achieve its present standing in the JRC are:

(1) by identifying, prioritising and then concentrating on key issues and not trying to address the multitude of problems that exist, ICM has maintained focus in the catchment;

(2) formal recognition by each group of the values held by other groups, particularly between farming and conservation interests has been an important achievement and has had a major impact in fostering community cooperation;

(3) the importance of demonstrations and publicity in maintaining community enthusiasm, momentum and commitment. In so doing, community scepticism that ICM is just another government induced "talkfest" has been limited;

(4) planning and documentation have deliberately been targeted and have been kept simple with a minimum of technical complexity for non-technical groups;

(5) strong political support in the catchment for ICM has come from government agencies. The Minister for Primary Industries has had a personal involvement in the program and this has had significant positive impact on the bureaucracy;

(6) staff from other government agencies and research institutions have, in most cases, set aside traditional territoriality and have been supportive of ICM. They have also provided a significant amount of goodwill;

(7) implementation of the Strategy and its recommendations has been driven from the bottom up and by the JRCCC, hence empowering the community.

While there has been widespread support of ICM, it would be unfair not to mention some criticisms that have emerged. Indeed, while the concept of ICM can be regarded as being successful at the policy level, only time will reveal if it is effective at the private landholder level. Many of these criticisms are not unique to ICM, but have been focused at ICM due to its high profile in the catchment. Criticisms include:

(a) ICM Committees have the potential to form a fourth layer of government;

(b) "Planning means controls";

(c) how is ICM different from other government agency programs?;

(d) public participation and consultation are ineffective as "governments don't listen";

(e) the integrated approach requires people to move out of their "comfort zones" (especially for professionals in TAGs who were asked to provide wider perspectives on issues outside their disciplinary expertise). By definition such a move causes discomfort;

(f) differences in opinion can emerge regarding what ICM means and how it should be applied in the catchment;

(g) landholders have difficulty in recognising or coming to terms with the concept of a catchment. This situation can be exacerbated when inconsistencies exist between physical catchment boundaries and entrenched socio-economic divisions;

(h) many participants have great difficulty in reconciling short term issues with those that could be regarded as long term or fundamental. Difficulties in determining the relative importance of issues with different spatial and temporal dimensions also exist;

(i) State government personnel can become confused by the relationship between ICM and other policies and programs;

(j) Continuous consultation without participation and action can lead to disillusionment amongst community and industry groups;

(k) what is the net gain of ICM compared with ensuring that all agencies and private individuals manage their resources according to established environmental guidelines?

The Johnstone River experience has provided a number of additional insights into the effectiveness of ICM. Perhaps most important, is that irrespective of resource availability, people have to make ICM function. Priority has to be given to promoting the goodwill and trust necessary for ICM to work. Further, the role of the catchment coordinator is central. The formal inclusion of industry and community groups is essential, however these groups must have representatives who are committed, of a high calibre and who can made a significant contribution over a sustained time period. Representatives must have credibility within the community and indeed it is these "champions" who have contributed to the success of the JRCCC to date. Their continued involvement is crucial to the future success and survival of ICM in the Johnstone River.

There is also a need for ongoing research and development (R&D), and whilst the formation of TAGs has facilitated community access to products of R&D, future R&D will need to focus on developing a better understanding of the processes of natural systems (including a capability to integrate research from the plot or farm scale to the catchment scale). R&D is needed in the development of means of assessing the status of natural resources, and in particular, of relevant bio-indicators of resource health. Only when these tools are developed, can the impacts of development and practices on natural systems be predicted and only then can a capacity exist to develop truly sustainable farming systems. Improved processes to translate natural resources outcomes into statutory instruments in an ICM environment are also required. An example is the apparent dichotomy between environmental management and statutory planning as it is currently practised. Science has developed an enviable record in its ability to analyse systems — the challenge is to develop linkages to allow whole systems to be synthesised and modelled. Furthermore, an improved understanding of the sociological processes which are central to the ICM approach (including the mechanisms for effective information transfer and for the facilitation of attitudinal and behavioural change at both the individual and institutional level) is critical.

CONCLUSIONS

This paper has outlined some of the challenges confronting catchment and natural resource management on the WTC. If they can be met, then the opportunities and benefits to local and regional communities and Australia as a whole are likely to be substantial, including reduction of pollutant loads into coastal waterways. The new policy initiatives of the Queensland Government hold some promise. Ideally, effective implementation of these initiatives will be accomplished through voluntary codes of practice. While this approach is one of the least intrusive forms of coercion, its adequacy to address problems is uncertain. Effective implementation will likely require a mix of initiatives — education, technical incentives, cost sharing programs, tax incentives, and regulation. Coordinating these efforts across a diverse landscape is a major challenge facing the government. At present, it is unclear how the State government intends to address this challenge.

In conclusion, it must be remembered that there are no perfect or "quick fix" solutions to addressing legitimate but often conflicting societal values and interests. However new initiatives in catchment management such as ICM, with their ability to facilitate a common approach and, importantly, to provide the critical linkage between stakeholders and policy makers, have the potential to deliver important benefits to coastal ecosystems, including estuaries and adjacent marine waters.

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THE MANAGEMENT OF CORAL REEFS: A SUMMARY OF THE ISSUES

Chris Crossland
CRC Centre for Reef Research,
James Cook University, Townsville

INTRODUCTION

Reef management is about managing people and their activities both within the reef environment as well as within the adjacent areas where human enterprise — such as land use in river catchments and urban developments and discharges to land, water and atmosphere — can lead to effects on reefs.

The situation of the Great Barrier Reef (GBR) will be used as a case study to develop the topic. As a broad reference source, the 25-year Great Barrier Reef World Heritage Area (GBRWHA) Strategic Plan is relevant not only to the GBR but also can be viewed as encapsulating issues relevant to global coral reef areas. Global, regional and local concerns will differ only by degree, reflecting the scale and intensity of human pressures and the effectiveness of management regimes.

The GBRWHA extends across about 350,000 square kilometres and is comprised mostly of the GBR Marine Park. The GBR Marine Park is a multiple use, protected area with zoning plans for allowable use patterns being the main tool for Reef management. A number of estuaries and nearshore areas, and mainland catchments which abut the GBR Marine Park, contain human activities which influence the GBR environment. The GBRWHA region supports direct economic activities estimated to be worth in excess of A$1 billion per year to Australia.

The discussion on Reef management issues will consider the present status of nutrient pollution in the GBR, dealing with:

- main issues resulting from uses and impacts;
- key considerations and responses; and
- needs for sustainable use.

USES AND IMPACTS

Major uses of the GBRWHA and adjacent mainland which lead to actual and potential impacts of nutrients and nutrient pollution on the GBR environment include:

1. *Agriculture*

Catchment and land use changes provide increased discharges of nutrients and sediments to rivers, overland flow and groundwater.

2. *Urbanisation*

Urban infrastructure and development contributes discharges from stormwater and drainage, sewerage, landscaping, landfills, transportation and roads surfaces; atmospheric transmission from industrial and suburban areas; and drainage and groundwater modification. Modifications to coastal habitats, such as the loss of wetland and mangrove natural filtration ecosystems, permit the increased discharge of surface runoff to rivers, estuaries and the coast.

3. *Ports & Industrialisation*

Discharges to atmosphere, water and sediments from industries and support services, port bulk terminals and loading facilities; dredging and sediment disposal including land fill and coastal reclamation; modification of coastal hydrodynamic regimes.

4. *Shipping*

Operational and other discharges from ballasting and cargo loss in accidents.

5. *Fishing*

Benthic habitat modification disruption; resuspension of sediments and changes to substratum oxygen/redox regimes; resource and biodiversity depletion from fish harvesting and destruction/disposal of bycatch.

6. *Tourism*

Transportation, food and support services; demographic shifts and changes of loci for population pressure; marine operations including small vessel/yacht waste discharges.

In general, the GBRWHA remains relatively pristine with the impact of nutrient and associated pollutants and sediments localised to the areas near towns and cities, and those associated with ephemeral seasonally-flowing rivers, the estuaries, coastal deltas and discharge plumes. The relatively small population and localised population centres, along with active regulation and management regimes (from integrated catchment management on land to controlled/permitted activities in GBR waters) and directed public awareness programs, have served to minimise the actual and potential impacts of people's activities.

The 1995 State of the Marine Environment Report for Australia determined that the GBR is in "Excellent – Good" condition with respect to human impacts. This condition is not accidental but has resulted from major national commitment of political will, funding, people skills and the development and application of management approaches to minimise human effects while maintaining access and use.

KEY CONSIDERATIONS AND RESPONSES

The effects of changes and increases in human activities in the GBR region which cause nutrient pollution require further scientific knowledge and evaluation in close collaboration with management agencies to address in particular:

- expanding populations, rapidly increasing tourism activities (on the GBR and in the mainland catchments) and mainland support infrastructure and services particularly accommodation);

- high productivity farming practices and land-use changes; and

- increased effort and changes in fisheries (recreational and commercial) practices.

Increased nutrients (and sediments) discharged to the GBR enhance the potential for eutrophication and shifts or changes in benthic habitats. In order to manage potential and actual impacts of nutrients, there is a clear need to be able to measure changes (often subtle and incremental), to have improved understanding of causal relationships, and to interpret (or predict) changes. Responses to meet these challenges and to address the earlier issues require improved information (scientific and socioeconomic) and data measurement "tools". An active and prepared management framework is needed which utilises regulatory and surveillance approaches, especially for short term results, and education of users and the community, for long term benefits. Challenges remain, especially our ability:

- to discriminate between changes due to human effects and natural events (e.g., seagrass loss associated with major river flood discharge — due to high sediment loads versus sustained freshwater pulse?);

- to place the measured and observed effects within a context of environmental background (e.g., lagoonal water column nutrients resulting from riverine discharges (and human influences) versus shelf upwelling events?);

- to recognise and interpret events across appropriate ranges of time and spatial scales; and

- to have enhanced capabilities for monitoring changes, events and opportunity and willingness for implementing different management options in the context of an adaptive management approach.

NEEDS FOR SUSTAINABLE USE

It is imperative that mechanisms be in place for strong communication and links between researchers, managers, reef-users, politicians and other decision-makers. This will make sure that issues are identified, relevant information is gained and integrated, and that a response or action results and is supported by appropriate resources. Sustainable use and management of nutrient pollution needs, *inter alia*:

- knowledge of resources and processes (databases and information);
- monitoring of impacts (ability to measure);
- rehabilitation and remediation (ability to respond);
- education and training (public awareness, manager/technologist skills);
- key technologies (amelioration, impact minimisation);
- planning of resource use (allocation, access and use);
- management of resources and uses (regulation, limits, integration).

The response in Australia to these needs has been taken in the context of the ecologically sustainable development (or use), as more recently contained in the Brundtland Report in 1987. The commitment of the national government to this approach, along with the good scientific skills and knowledge development, and management and institutional arrangements see these needs being addressed, in the main, is now in place for the GBRWHA.

MONITORING PROGRAMS: DESIGN AND EVALUATION

Charles Jacoby
CSIRO Division of Fisheries, Perth

In order to formulate a successful paradigm for environmental management, we must compare examples that have been fully implemented and evaluated. Unfortunately, many existing management paradigms can not be compared because we lack detailed evaluations of their success. We could assess and compare management paradigms better if we adopt a unified approach to environmental management that is based on operational definitions of critical concepts.

OPERATIONAL DEFINITIONS

Environment

An operational definition of 'environment' is:

- the biological, physical, social, economic and cultural aspects of the surroundings and activities of people

This definition emphasises people's views, values, desires and activities; it is an anthropocentric view of the environment. A strict interpretation of this definition would lead to environmental management that focuses primarily on human activities and disruptions to these activities. People's views and concerns will always drive environmental management because people are the managers and management primarily directs human activities, but a broader approach will improve prospects for sustainable use of natural systems. A broad interpretation shifts the focus of management from disruptions of human activities to undesirable changes in natural systems. This approach is more likely to be sustainable because human activities are usually affected by environmental change only after the natural system has been significantly degraded. The broad interpretation focuses on the natural system; it is an ecocentric approach.

Management

Environmental managers can use an ecocentric approach to determine the targets for management, but they also need an operational definition of management to provide a design framework for strategies designed to achieve their objectives. Management can be viewed as a process with five components (Figure 1).

- <u>control</u>: methods to regulate the activities of people, examples relating to environmental management include legislation, non-statutory tools, standing orders and operating procedures
- <u>organisation</u>: establishment of administrative structures, memoranda of understanding and other cooperative arrangements between governmental and non-governmental bodies

- planning: details of current and future uses of the environment; plans, schedules and procedures for controlled use of the environment; concrete strategies for altering activities if undesirable changes are detected (includes plans for amelioration or remediation)
- implementation: resourcing for control, organisation, planning and monitoring, which includes funding, administration, management and supervision
- monitoring: detecting changes in the environment, auditing activities subject to managerial control and disseminating the results of these actions in order to provide a basis for adapting management according to the functioning of the managed system, assess the effectiveness of management strategies and display accountability

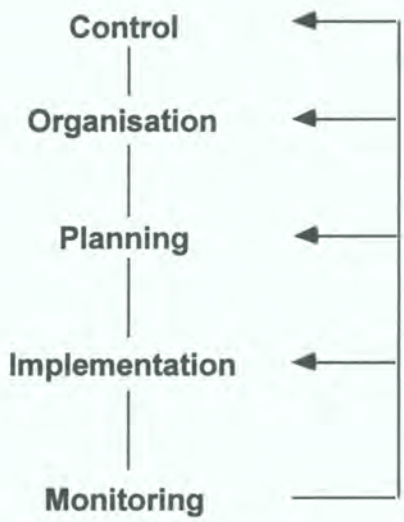


Figure 1. A management framework

This definition emphasises management as a process. Processes can function at more than one scale. The scale of effective management will need to be set by a combination of the objectives of the managers and the functioning of the system to be managed. Management objectives and system functioning may not lead to identical limits. For example, managing a bay as a natural ecosystem leads to consideration of influences arising from activities in the catchment. In this case, the same limit is appropriate for the management objective and the functioning of the ecosystem. In contrast, one section of a bay can not be managed as a natural area without considering the bay's catchment. Here, the limit to effective management is set by the functioning of the system rather than the narrower management objective.

As it is defined here, much of management applies to managing people and their activities. Control, organisation, planning and implementation deal mainly with people and their actions or products (e.g., laws, memoranda, plans and money). These anthropocentric aspects of management must also be managed or the overall goal will not be attained. The management process, including monitoring, should be scaled to the objectives set in each of these areas. For example, clear objectives and useful monitoring would establish which of the following approaches tends to be successful:

- control: legislation or voluntary compliance

- organisation: central agency with overriding powers or memoranda of understanding
- planning: promulgation of a centralist policy or public participation
- implementation: long-term central funding or a locally-based business plan

More importantly, monitoring would provide the information needed to learn from our mistakes and to adapt approaches to improve their success. Learning and adaptation are critical because a single approach will not be successful in all cases or for all time in any instance.

Environmental managers must also have a set of ecocentric objectives that target the natural environment and its functioning. These objectives may be more difficult to formulate and monitor given our current level of understanding. Understanding of both the natural environment and its functioning plays a critical role in both setting sustainable levels of human activity without imposing unnecessary restrictions and separating manageable, anthropogenic changes from natural variation.

An understanding of the components of natural systems and a concern for their functioning is essential because successful and sustainable management of the environment requires detection of change in natural systems. Obviously, all human activities will alter the natural functioning of the environment; therefore, ecocentric management relies on controlling human activities so that changes do not exceed agreed limits. Limits of acceptable change are the kernels of management objectives, and methods to regulate human activities form the basis for management strategies. Such an approach requires a fairly detailed understanding of natural systems, how activities affect or perturb systems, and how systems respond to perturbations. Because our knowledge of these factors is imperfect, the objectives and strategies of ecocentric management should be revised on the basis of continual feedback from monitoring of both human activities and the functioning of the natural system.

NATURAL SYSTEMS

Environmental managers that adopt an ecocentric approach need to understand natural systems. A natural system is not cultured, farmed or otherwise managed in a manner that forces environmental or ecological variations to remain within tightly set limits. In addition to being highly variable, natural systems are extremely complex, and they do not have distinct boundaries because all aspects of the world interact at some level. Managers need to select key properties of the system and set operational boundaries to separate external inputs (perturbations) from internal attributes. Key attributes can be selected and boundaries can be set by considering management objectives in conjunction with the functioning of the system.

The relevant spatial and temporal boundaries of a natural system will differ among functional levels. Functional levels of natural systems can be classed as physical, chemical and biological. The biological level can be further divided into a hierarchy consisting of four organisational sublevels, suborganismal (e.g., physiology and genetics), individual (a single organism), population (a group of individuals in the same species) and assemblage (a group of species). Physical and chemical processes operate on a range of temporal and spatial scales, but an enclosed body of water and its catchment form a basic unit. Population and assemblage sublevels operate on larger spatial and longer temporal scales than the suborganismal and individual sublevels. For example, populations of some organisms in a single bay may be supplied with recruits that originate in other bays; therefore, individual bays may not function as isolated units for some species.

INPUTS TO NATURAL SYSTEMS

Once boundaries and levels of interest have been set, inputs to the system from outside its designated boundaries can be assessed for their importance. Every input will cause a change in a natural system at some level, but the change is not always at a level that is of interest. If a change occurs at a level of interest, the input that caused the change can be termed a stress. For example, a decrease in salinity may cause a suborganismal, physiological response in an animal but it may not lead to death of the individual. If the level of interest is the individual, a decrease in salinity is not a stress.

Natural stresses, such as rainfall and recruitment, cause systems to vary continually through time and in space. This natural variation can be quite large, and it generates background 'noise' against which the 'signal' of stress due to human activities must be detected.

People influence the natural functioning of a system through accidental or deliberately induced stresses (e.g., fishing, oil spills or harbour developments). In some cases, people are willing to accept the changes caused by anthropogenic stresses, e.g., fishing reduces the abundance of fish, but people accept this change as long as the stock remains viable. In general, people will determine whether stresses cause acceptable or unacceptable changes. Stresses that cause unacceptable changes can be termed impacts. In most cases, management and monitoring have focused on prediction, surveillance and control of anthropogenic impacts because they can exert some control over anthropogenic inputs. Managers must realise that they can not predict which activities will become impacts with complete certainty, and they will not detect unacceptable changes if they do not have monitoring programs that can identify and filter the noise generated by natural stresses.

RESPONSES TO INPUTS

Managers will set more effective objectives and allocate resources more efficiently if they understand the three properties that determine how natural systems respond to perturbations. Inertia refers to the maximum perturbation which will not cause a stress (i.e., a change at a given level of interest). Stability refers to the rate at which a component will recover to its former state or level of functioning following a given stress. Resilience is the maximum stress from which a component will recover.

Accurate knowledge of a system's responses to perturbations would allow managers to produce management strategies that both control impacts and allow the widest possible range of human activities. For example, stringent controls will be needed on inputs that will impact a population of a species with low inertia, poor stability and low resilience. Such a population will be stressed by low levels of input, will recover slowly from stress and may disappear in response to a low level of stress. In contrast, a population of a species with high inertia, good stability and high resilience can be subjected to more stress before it is seriously affected.

THE EFFECT OF UNCERTAINTY ON MANAGEMENT

An environmental manager armed with a detailed list of anthropogenic inputs, accurate predictions of the system's responses to those inputs and a means of managing inputs that can be classed as impacts would be extremely effective in preventing unacceptable changes without unduly restricting human activities. Unfortunately, this situation is highly unlikely. Managers seldom have extensive information on all inputs, because some are always un-predicted or poorly understood. In addition, inputs may interact in unknown ways to generate an impact. Furthermore, our understanding of ecosystem functioning (especially in highly dynamic, marine systems) is not sufficient for reliable predictions of responses to either single inputs or interactions among inputs. Finally, management strategies are often inefficient and un-validated.

In some cases, the complexity of management issues and a lack of information has led to attempts to eliminate most human activities in order to protect a natural system. Excluding people is not always a desirable or viable option; therefore, anthropocentric and ecocentric approaches must be combined with available knowledge to formulate other management strategies. These strategies should explicitly acknowledge and identify sources of uncertainty. One approach to managing in the face of uncertainty is to make management an adaptive process, i.e., adjust management strategies on the basis of regular monitoring of both the status of the managed system and the effectiveness of management actions.

OPERATIONAL DEFINITION OF A MONITORING PROGRAM

A monitoring program comprises several components with foci provided by its objectives. Monitoring should consist of a complete, integrated program with clear objectives not a series of isolated or unconnected research projects.

A complete monitoring program includes the following components:

- observations: measurements of indicators chosen to assess the efficacy of management, the inputs into a system, the state of a system, or the functioning of a system; these observations ultimately determine the quality of the monitoring program
- database: a useable system to permanently hold and access large amounts of data
- models: the means to analyse, test and interpret observations; models always exist and they should be made explicit
- links to management actions: feasible management strategies to be implemented if the results and interpretations of monitoring indicate a need; these links are critical if monitoring is to be effective
- assessments of management actions: a means to determine if management is being effective; such evaluations should result from the cycle of observation, analysis, testing and interpretation
- feedback mechanism: a way to present results and interpretations to the relevant stakeholders, managers, regulators and scientists in a form that promotes improved observations, databases, models and management strategies

- feedout' mechanism: a program to disseminate the results and implications of monitoring (both successful and unsuccessful) to the general public, as well as to managers, regulators and scientists that are not directly involved in the management of an area; this effort ensures a high quality program that remains visible and accountable

CONCERNS ABOUT MONITORING PROGRAMS

Monitoring programs designed to assist environmental managers are not commonly implemented in Australia or other parts of the world. The lack of examples means that there are no proven recipes to use as guides. Monitoring programs need to be designed, implemented and evaluated with the recognition that this work has a large research and development component. Some general concerns must be addressed during the design and implementation of all monitoring programs.

OBSERVATIONS

Designing a program of observations relies on choices about the key components that need to be tracked. Key inputs and internal attributes can be identified by considering management objectives and system functioning. Once inputs and attributes are selected, indicators that can be measured need to be chosen. An indicator is chosen because it is synonymous with a key input or attribute or it acts as a surrogate for one of these key components. Inputs include management actions and attributes include the concerns of people.

Indicators should be chosen with three key properties in mind; specificity, sensitivity and relevance. Specific indicators relate to a single input or key attribute, e.g., imposex in molluscs as an indicator of tributyltin contamination. Sensitive indicators respond to change relatively rapidly, e.g., bacterial growth in response to organic enrichment. Relevant indicators provide information that is of interest; e.g., loss of commercial fish populations.

In general, these three properties can not be maximised simultaneously; they can only be optimised. For example, highly sensitive indicators are unlikely to be highly specific. Relevance is a key characteristic of indicators because managers typically have little use for specific and sensitive answers to the wrong questions, i.e., monitoring programs with pseudopower. The risk of pseudopower is high for most natural systems because we have limited understanding of the system's functioning. This risk is an important justification for retaining a broad base to ecocentric monitoring in addition to monitoring that targets specific management issues.

DATABASES

Monitoring programs generate large amounts of data. Planning of monitoring should include the design and implementation of a database to safely hold and allow access to data. The database should not require unusual or expensive equipment or software because this will limit its accessibility. Data must be accessible to a wide range of users, but it must also be protected to ensure integrity. Databases should be subject to rigorous validation and quality control procedures. Entries in the database should include coding to identify the time and place of collection, the organisation or individuals who collected the data, the accuracy and validity of the data and the planned use of data (e.g., the rationale and sampling design behind the collection of the data).

MODELS

The model used for analysis and interpretation of observations should be explicitly stated with a clear understanding of the underlying assumptions and the limitations that apply to use of the results. Whenever possible, the model should establish direct causal links between changes and stresses. Unfortunately, a lack of relevant information about the processes that link changes to stresses often obviates this goal for natural systems. The model may only be able to establish strong correlations between changes and stresses. The premise underlying this approach is to obtain evidence that unusual changes have occurred after a stress and only at sites near the stress. This approach requires data from control sites and times, i.e., data from times before the stress and from areas that are not subjected to the stress. These data provide an objective basis for categorising a change as unusual.

LINKS TO MANAGEMENT STRATEGIES

Monitoring will be of little or no use if the results and interpretations are not available in real time and clearly linked to feasible management actions. Detection of change must be linked to management action through a response plan. Response plans must be developed in conjunction with managers who are charged with setting and achieving appropriate management objectives.

ASSESSING MANAGEMENT ACTIONS

Monitoring that targets highly specific management objectives is needed to assess the success of management actions. Regardless of the issue specific monitoring developed as a result of discussions with managers, an overall framework based on monitoring of ecosystem performance will continue to be necessary. A broad-based monitoring program will lessen the chance of pseudopower, i.e., detailed monitoring of the wrong indicators.

ADAPTIVE MANAGEMENT AND MONITORING

Monitoring plays a critical role in assessing the success of management actions and providing a basis for improving observations and management strategies. An adaptive approach to management recognises that initial attempts to manage natural systems will not be completely successful. Fortunately, most systems are resilient and they may survive several attempts to establish proper management.

PUBLIC INVOLVEMENT

A monitoring program should not become a closed loop. Monitoring programs must convey information to managers, regulators and scientists that are not involved in the program, as well as, to the general public. This approach will improve the monitoring and management program by providing access to a wider range of experience; increasing the general knowledge base; and fostering understanding, appreciation and ownership in the general community. In addition, this effort will ensure that both the program and the management decisions arising from it remain visible and accountable.

ENVIRONMENTAL INTELLIGENCE

In order to be useful in adaptive management, monitoring should yield environmental intelligence not just data (Figure 2). Environmental intelligence involves analysis, interpretation and synthesis of data. Without quality data, environmental intelligence will be useless. Observations yield the required data; therefore, they are the base of the pyramid comprising all further work. Managers should recognise that observations will require considerable resources compared to other aspects of monitoring and management. This need arises because of the number of observations required and the logistics involved in collecting them.

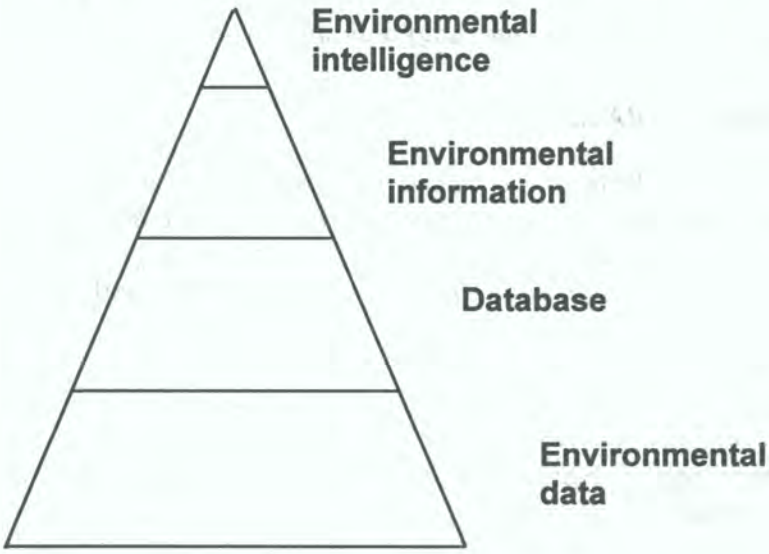


Figure 2. Conceptual approach to use of data from monitoring

ROLE OF MONITORING

Monitoring plays a key role in the management process regardless of the objective that sets the focus for the process. Unfortunately, this role is not widely recognised. In some documents detailing management plans, monitoring is linked with research under an objective that is separated from management objectives like conservation, sustainable use and education. This separation equates to dismembering the management process. As a result, the success of management strategies can not be evaluated. In addition, there will be a lack of progress toward a successful management paradigm due to a dearth of comparable performance measures for different approaches.

Perhaps, monitoring is linked with research because both involve observations made in a rigorous manner or because the observations needed to monitor progress toward ecocentric management objectives may be best made by scientific researchers.

This approach will lead to confusion because it introduces an objective that is not on equal footing with others like conservation, sustainable use or education. Research to improve monitoring is a suitable and very useful objective, but monitoring should not be removed from its key role in management toward all other objectives. In addition, care should be taken to keep the structure of objectives parallel in all cases because this will enhance our ability to assess the success of management. For example, objectives based on other parts of the management process will be suitable if the focus is on improving the process (e.g., improved control through better legislation or improved planning through public participation).

Monitoring may be dissociated from the rest of management because it requires resources and produces accountability. Certainly, monitoring in support of ecocentric objectives will require relatively extensive resources because natural systems are difficult to understand. Furthermore, quality monitoring may well indicate that ecocentric management strategies are not moving us toward the lofty objectives set forth in many management plans (e.g., preservation of biodiversity). Perhaps, a new paradigm for environmental management should involve designing and providing resources for monitoring programs as a precursor to formulating implementable management strategies that are grouped into clear and achievable management objectives. Such an inverted approach may ensure that we do not promise environmental protection that we can not deliver and that we clearly document the means by which we deliver any environmental management.

ADAPTIVE ENVIRONMENTAL ASSESSMENT AND MANAGEMENT: SOME NOTES

John Parslow
CSIRO Division of Fisheries, Hobart.

These workshop notes are based heavily on the pioneering texts by Holling (1978) and Walters (1986), and I quote extensively from those texts. I strongly recommend that interested readers obtain and read these texts:

- Holling, C.S. 1978 Adaptive Environmental Assessment and Management. Wiley-Interscience, Chichester.

- Walters, C.J. 1986 Adaptive Management of Renewable Resources. MacMillan, NY.

Adaptive environmental assessment and management (AEAM) is a conceptual and methodological approach to management of complex systems, developed by groups in Canada and Austria (Holling 1978, Walters 1986). It is designed to bring together scientists, managers and policy-makers in modelling workshops, and focuses on ways to address uncertainty in environmental prediction and management. Based on experience in a wide variety of environmental decision problems, the approach recognises that, in dealing with complex ecological and socio-economic systems, we will always have limited knowledge and predictive capability, but have to make management decisions now. These decisions should be based on the best available knowledge and understanding, drawn from diverse sources, requiring better 2-way communication between scientists and managers. They should be implemented in a manner that encourages us to learn about the consequences of those decisions and actions so that we may improve the quality of our environmental decisions in the future.

All too often, environmental decisions are still based on classical environmental impact assessment, consisting of a one-off study of the likely impact of development, commissioned after the development design is complete. Such environmental impact assessments have often involved rather unfocused comprehensive "state-of-the-system" surveys, with no plan for follow-up monitoring or management action, and making no allowance for learning from errors.

The original proponents of AEAM proposed a series of myths (i.e. false assumptions) of environmental assessment and management (Holling 1978), many of which still (commonly) apply today.

POLICY DESIGN AND DECISION MYTHS:

- Central goal is to produce policies and developments that result in stable social, environmental and economic behaviour.

- Development programs are fixed sets of actions that will not involve extensive modification, revision or additional investment.

- Policies should be decided on the basis of economic and social goals, with environmental impacts considered as a subsequent constraint.

- We cannot treat environmental concerns until we change institutional constraints.

MYTHS ON HOW TO DO ENVIRONMENTAL ASSESSMENTS:

- Environmental assessments should consider all possible impacts.

- Each new assessment is unique. There are few relevant background principles, information or even comparable past cases.

- Comprehensive "state of the system" surveys (species lists, soil types, etc) are a necessary pre-requisite step.

- Detailed descriptive studies of the present state can be integrated by models to provide overall understanding and prediction.

- Any good scientific study contributes to better decision making.

- Boundaries based on watersheds or political jurisdiction provide sensible limits for impact investigations.

- Model analysis will allow selection of the best alternative from several proposed plans.

- Ecological evaluation and impact assessment aim to eliminate uncertainty regarding consequences of proposed developments.

In a more recent volume on management of renewable resources, Walters (1986) argued that the promise of management based on scientific research has not been fulfilled. He attributed this to two causes: a failure to account for socio-economic dynamics; and problems with the standard scientific approach. The basic scientific reductionist approach is to break systems into components, and then integrate understanding at the component levels through modelling. Walters argued that workshops to develop models to address management problems always identify significant gaps in component understanding. These gaps are generally associated with processes at large space scales / long time scales. This is not surprising, because scientific study is focused on tractable projects, generally at small scales, with results on short time scales. Walter's conclusions about the implications for management could be summarised as follows:

- No matter how large the knowledge base, there is generally a large uncertainty in predictions, and the largest uncertainty is unquantifiable: it comes from neglected processes.

- We should accept that management is a gamble, get the best information on the odds, and where possible conduct management experiments to learn about the system and reduce the odds.

ECOLOGICAL SYSTEM PROPERTIES

Holling (1978) identified a number of key properties of ecological systems, which affect the way we manage them.

- Parts of an ecological system are connected to each other in a selective way (everything is not strongly connected to everything else).

- We can break ecosystems into sub-assemblies that are tightly connected within themselves, but loosely connected to other sub-assemblies.

This has implications for monitoring, for experiments, and for modelling. A division into sub-assemblies may be made on the basis of physical separation, or on the basis of functional groups. For example, when dealing with eutrophication in estuaries, one would usually separate catchment dynamics and estuarine dynamics. Within the estuary, one might deal with nutrient cycling through plankton in the water column separately from organic matter breakdown and recycling in the sediments. Sub-assemblies are not completely isolated from one another, but the interconnections and feedback loops within sub-assemblies are much stronger and more numerous than those between sub-assemblies.

THE DISTRIBUTION OF IMPACTS IN SPACE

In dealing with any management issue, we have to decide what spatial boundaries to draw around the problem. In dealing with local actions such as an input site or a development site, we often start with a mental model in which impacts fall off smoothly with distance from the site. This is not necessarily a good model. Even when we are dealing with physical dispersion of pollutants, simple diffusive models are not always appropriate. Real circulation patterns may result in high concentrations at a distance. Furthermore, chemical and biological processes may act to concentrate pollutants in sediment or biota some distance from the site, or produce ecological impacts over much larger scales than the scales of pollutant dilution. Socioeconomic factors can then intervene to produce impacts in completely unexpected directions. For example, if a local fishery fails, local populations may turn to exploitation of other natural resources, terrestrial or marine.

Stability and resilience

These are concepts based on analysis of simple ecological models. In a mathematical model, the components of the system which change over time (eg nutrient concentration, seagrass cover) are called state variables. The state of the system at any one time is determined by the values of all of the state variables. We can imagine in principle plotting the current state of the system as a point in a state space with as many dimensions as there are variables. The line traced out by this point over time as the system changes is known as a trajectory. In simple models, these trajectories may tend to approach a stable equilibrium point, or a stable limit cycle, from a large set of initial states. The set of initial states from which this occurs is known as the domain of attraction. More complex behaviours have been identified recently, in which trajectories never display regular or repeatable behaviour (chaotic systems).

Even simple dynamical systems can have multiple stable states: this means that one-off perturbations can lead to permanent switches in system behaviour. Resilience measures the size and scope of the domain of attraction of the current stable state: that is, how big a perturbation can a system withstand and return to its previous state? Some kinds of perturbations will change the current state variables eg increase the nutrient concentrations. Others may shift the parameters governing the interactions among state variables. It is possible for gradual changes in system parameters to lead to sudden shifts in system variables and dynamical behaviour.

Evolution of System Behaviour

Holling argues that systems evolve to match the level of perturbation that they are exposed to over time. If the environment is constant, the resilience decreases. If we artificially maintain a constant environment, and resilience decreases, the system may become more vulnerable to moderate perturbations. The classic example is control of fire in forest systems, where artificial elimination of frequent small fires means that forest systems become susceptible to much larger fires.

These ecological system properties have the following implications for assessment and management (Holling 1978):

- Everything is not strongly connected to everything else, so we don't need to measure everything. We do need to determine the significant connections.
- Understanding qualitative structure is more important than precise measurement of quantity.
- Changes in one variable can have unexpected impacts several connections away.
- Events at one place can have impacts at distant places.
- Monitoring the wrong variable can indicate no change even when drastic change is imminent.
- Impacts are not necessarily immediate and gradual: they can appear abruptly and with a time lag.
- Variability of ecological systems, including major disruptions, maintains and determines system resilience.

Holling argues that many existing impact assessment methods assumed that none of these can occur.

INSTITUTIONS AND MANAGEMENT.

The nature of ecological systems, and our limited ability to predict their response to perturbation, have implications for how management should be approached.

Environmental considerations should be introduced at the beginning of the development or policy design process, and given equal weight to economic and social considerations. Policy development should recognise the benefits attached to increasing information on key parts of the system, and assign an explicit value to this information (adaptive management).

Experiments designed to increase information may be research experiments done in parallel with management, but should also be designed into the management process (experimental management).

Monitoring and remedial plans should be designed into a program, not be post-hoc additions. Recognising the uncertainties in our ability to predict the consequences of human actions, we may need to consider a choice between policies designed to prevent errors (fail-safe), and policies designed to adapt to failure (safe-fail).

Walters (1986) proposed a more formal approach to adaptive management of renewable resources, involving 4 steps:

- Define and bound the management problem in terms of objectives, constraints on actions, and indicators.
- Represent the existing understanding of managed systems in terms of explicit models of dynamical behaviour.
- Represent uncertainty and its propagation through time in relation to management actions.
- Design policies that provide for resource production while probing for better understanding and new opportunities.

MODELLING WORKSHOPS

A central feature of the AEAM approach is the use of modelling workshops to conduct environmental assessments. Workshops offer an ideal way to achieve the following outcomes:

- The problem is bounded or delimited so that it is tractable and manageable.
- Information and expertise that is scarce or widely dispersed can be applied to the problem.
- The results and recommendations are effectively transferred to decision makers and the public.

Other approaches to dealing with complex systems have been tried. One is to consult a wide variety of experts who report independently about the likely consequences in their area of expertise. The main problem with this approach is that interactions are not treated adequately, and there is no system overview and integration. The second is to assemble a large interdisciplinary team to provide data for a simulation model. The danger here is that specialists exert continual pressure and forceful argument to treat their component in more and more detail. Without central control and focus, the model becomes more and more complex, and eventually defies understanding and analysis.

AEAM uses modelling workshops as a way to overcome these problems. Workshops encourage cross-disciplinary interaction, while, given good leadership, keeping the focus on management issues and requirements. Workshop teams can conduct successful impact assessments on short time frames with few resources. Some problems may require and justify large research studies. In these, initial and subsequent modelling workshops provide a continuing focus, and can prevent them from disintegrating into diverse special interests.

In a typical AEAM workshop, the participants consist of:

1) a core assessment team: assessment manager, modellers / programmers, and 2-3 specialists with a broad overview of the problem;

2) a broad group of subject-matter experts;

3) managers and policy-makers.

A first workshop is used to define and bound the problem, to select variables, to develop the model framework, to identify the model structure and rough parameter values, to identify data needs and assign responsibilities. Subsequent workshops are used to refine the model, and incorporate new data and understanding. A final workshop is used to finalise model structure, to undertake policy analysis with managers, and develop communication strategies.

Define and bound the problem

This involves the following steps:

- Agree on management goals, overall objectives; consider possible alternative objectives.

- Identify the indicators that managers will use to decide whether objectives are met.

- Identify the range of management actions available.

- Define temporal horizon and resolution.

- Define spatial domain and resolution.

This is essentially a description of the inputs and outputs of concern. This list is critical: it determines whether the scope of the model is sufficient. In this phase it is important to take a flexible approach, and to look at the problem from different perspectives, to make sure that any issues that might ultimately be important are considered as early as possible in the assessment process.

Developing an initial model

The model ultimately plays the role of linking inputs (management actions) to outputs (indicators). In order to do this, it is often necessary to introduce new variables and processes which lie between inputs and outputs. To provide a structure for the model development process, it makes sense to divide the system into the subsystems referred to earlier. To make the workshop process more efficient, we can assign the experts to corresponding sub-groups to develop submodels in parallel.

A process is needed to ensure that the interactions between subsystems are recognised, and to restrain each group from developing unnecessarily complicated submodels. In this process, called looking outwards, each specialist is asked to prescribe inputs needed from other components and to describe the nature of the outputs to be generated from their own submodel. This process, after some iterations, identifies interactions amongst the submodels, and harmonises the units of currency and level of detail to be used in the model.

MODELLING: GENERAL CONSIDERATIONS.

Why use models?

Management requires predictions and all predictions involve models, even if they are unstated or even subconscious. Mathematical or simulation models force us to be explicit about our assumptions and approximations. The model is a device to promote honesty and objectivity. It allows objective analysis of the importance of different processes. Many "important" processes from the specialist point of view turn out to be unimportant in the management context and at the system level.

The different kinds of models

Models come in many forms; the jargon is complex, and the boundaries between model types sometimes very fuzzy. The following is a brief glossary.

Process-based simulation models represent the abundance or biomass of important system components, and prescribe changes in these components over space and time by considering lower level ecological or physiological processes such as chemical transformations, or biological growth and mortality. The sub-models governing these processes can be regarded as physical or chemical laws, or their biological equivalents. The level of complexity is up to the modeller, but it is very easy to generate quite complex process models, especially if the modeller sets out to make the model more "realistic" by incorporating more variables and processes.

Statistical or empirical models are used where system structure and processes are poorly known or unknown. These rely on statistical analysis of observations to establish direct relationships between inputs and outputs.

Rule-based qualitative models (expert systems) are sets of decision trees which are often designed to mimic the decisions of experts with long experience with similar systems.

Static vs dynamical models: most process models are dynamical models and prescribe the rate of change of state variables over time. Some empirical models are purely spatial models: they may predict the equilibrium state of the system in response to given forcing.

Deterministic vs stochastic models: deterministic models predict a unique system trajectory in response to given initial conditions and forcing. Stochastic models predict a probability distribution of outcomes for given input distributions. A deterministic model may become stochastic by allowing for uncertainty or randomness in initial conditions, in environmental forcing, or in process parameters.

Choosing models

Typical environmental assessment problems vary greatly in complexity, in amount and quality of data, and in the degree of conceptual (process) understanding. Therefore, a range of models may be used in AEAM, and in any one assessment.

The complexity of the problems depends on:

- the number of different management actions and output indicators;

- the number of state variables (although including the age structure or spatial structure of a population of animal or plant species may add a large number of similar variables without increasing the complexity proportionally);

- spatial complexity (the number of spatial cells and their connectivity);

- presence of processes acting on different time scales, time lags, etc.

Amongst the types of environmental data that are often available, or used, for AEAM, we can distinguish:

- data available for parameter estimation or model calibration;

- data available for model testing;

- data used for model initialisation and setting of boundary conditions.

Not all data are equally useful. Data on critical variables may be missing, and may need to be gathered in a field survey program. This highlights the importance of preliminary (or conceptual) model development when considering the design and implementation of field studies.

Process understanding

Our understanding of the processes (physical, chemical and biological) operating in the problem are derived from the scientific literature or specific experiments and research. Knowing the appropriate formulation for a process greatly reduces data requirements. However, we will generally have an uneven level of understanding of model processes. As an exercise, the reader should list the marine ecological processes which are already well-studied / understood?

Process models

We have a good deal of basic ecological understanding of the processes of growth, reproduction, competition, predation. They can be used as building blocks in any model construction, and often relate to an important outcome. It is important not start each study from scratch, ignoring earlier studies and models, or basic ecological theory, because the basic data requirements are likely to be vast, and hence either consume a vast amount of the available resources in data capture, or preclude the capture of field data because of excessive cost.

Models useful for management purposes are generally required to perform outside the range of experience / observations, to look at "what-if" scenarios. A limitation of statistical models is that we cannot confidently extrapolate outside the range of observations on which they are based. However, there is always some uncertainty about model response to novel conditions. In the AEAM approach, we can modify, build on, and adapt a logical causal structure in a model, based on constituent processes, to improve our understanding of the problem.

Model complexity.

Models should not be more detailed than is necessary to capture the essential behaviour of the system. Apart from the issues of resources needed to build a complex model, we need to be able to analyse and understand model behaviour: it is very difficult to do this with complex models. As the level of detail in a model increases, we have more interacting components, and we have to specify how these interact, and parameter values for each interaction. Model performance (predictive capability, robustness) will eventually deteriorate as model detail and complexity increase. This is true of empirical models (e.g. multiple linear regression) as well as for process models. Therefore, in building models useful for management purposes and in AEAM we should aim for breadth rather than depth.

Simplification for analysis and understanding

Despite our best efforts, models tend to become complex. The model complexity may arise through spatial complexity of the problem, or through the number of key variables. We need to simplify in order to understand the model behaviour.

Understanding model behaviour differs from prediction, and involves developing an intuition about model behaviour, and its dependence on parameters and initial conditions. Numerical sensitivity analyses involve systematically varying each model parameter by a fixed amount (say 10%). These have been the standard approach to investigating parameter dependence of model results, but they have serious limitations when applied to complex nonlinear problems.

We can tackle these problems by developing simple models as caricatures of complex models, and even developing a hierarchy of models of increasing complexity. These simplified models are important tools for analysis of management strategies, and communication of results.

There are a number of available methods of simplification. Amongst these are:

- isolate submodels and study their behaviour in isolation (e.g. study a single spatial unit rather than all).
- treat the system as "well-mixed" as opposed to having a vertically or horizontally structured water column.
- develop simpler analogues of the whole system, by aggregating variables eg species or age-classes.

- separate fast and slow processes operating at very different time scales.

- conduct qualitative analyses of model dynamical behaviour: e.g. identify steady-state or periodic solutions and their stability domains.

Model predictions

Ecosystems have extremely high levels of nested complexity, and we cannot expect to make precise quantitative predictions using ecosystem models in the way that we might expect from a physical or engineering model. What is reasonable to expect from ecosystem models in terms of prediction? Exact quantitative predictions are generally neither possible nor necessary for addressing management issues. It is generally more important that models reproduce key qualitative patterns of behaviour. For example, in a plankton model:

- it is probably not reasonable to expect to predict the fine spatial structure of plankton patchiness;

- we might expect to predict mean and variance over some time - space domain within reasonable error margins;

- we should be able to predict the timing or magnitude of seasonal cycles;

- we would want to get the correct qualitative response to major perturbations such as river runoff events.

The predictive capability of a model depends on its structure and design. Where performance is critical to management objectives, additional effort can be expended in model design and calibration.

Testing models against data

We can never validate models, only invalidate them. Our "degree of belief" in a model will increase if it passes rigorous tests, and if proves to be correct in routine applications. Often, evaluation of management policies requires predictions of the system response to novel perturbations, not encountered in the available observation set. Exposing the model to tests that involve unusual perturbations analogous to likely management actions is therefore an important strategy.

Whilst testing the model against observed data is important, often the available observations do not correspond directly to model state variables. It may then be necessary to develop observation models to link observations to state variables. For example, a fisheries model may include stock biomass, but observations will be restricted to catch and effort. An observation model will then be used to link biomass to catch per unit effort. In many marine models, the model state variables may represent averages over large areas, while observations consist of point samples. A statistical model is then needed to compare the two.

One needs to be especially cautious in comparing historical data with models. Typically, the methods used to capture the data have not been fully documented, or the data have been collected without quality control procedures so that their quality is unknown. While it is a standing joke that modellers are inclined to reject data that disagree with models, in some cases this may be appropriate.

Model calibration

The parameters used in models are often only weakly constrained by literature data or by knowledge derived from direct experiments. Model calibration involves the adjusting (tuning) of model parameters to achieve an improved match between predictions and observations. In more complicated models, with large numbers of nonlinear interactions, it can be very difficult to estimate a best parameter set. If data are adequate, we can use sophisticated nonlinear parameter estimation techniques to minimise the differences between predictions and observations.

There is always a risk that parameter-fitting procedures will produce a good fit between predictions and observations for the wrong reasons, particularly if there are many parameters to adjust. One way to protect against this is to hold back part of the observations from the parameter estimation procedure, and use this part to test the fitted model.

USE OF MODELS IN EVALUATION OF MANAGEMENT POLICIES

The following terminology is used here to discuss management policies:

- Actions: specific deeds available to a manager.
- Indicators: measures of system behaviour.
- Objectives: desired goals in terms of indicators.
- Policies: rules by which actions are initiated in response to indicators, in order to achieve objectives.

In making decisions about our use of the environment and its resources, we need to consider alternative management policies, because we can only evaluate one policy by comparison against another. To make comparative evaluations of alternative management strategies, we run the model, using a given policy and applying it to predicted indicators, and measure performance in terms of indicators against the goals.

There are a number of issues involved in comparing time series of predicted indicators. It is normal in economic analysis to attach less current value to future returns than to current returns. The relative weighting is determined by the discount rate, and this often strongly affects the relative merits of different policies. Managers may have a number of different objectives, which can turn out to be incompatible or conflicting. Managers may also have different reactions to uncertainty or risk. Many managers are risk-adverse; some managers are risk-prone. Utility analysis is a formal procedure for identifying trade-offs among objectives and the response of managers to uncertainty. In some cases, it may be possible to identify an objective function: this converts indicators and objectives into a common currency (utility) and allows managers to rank policies along a single line, and to use optimisation techniques to select a best policy. However, where there are several potentially conflicting objectives, it may be more useful to have several dimensions to the performance measure, and plot performance measures for each objective separately.

COMMUNICATION

Communication of results and their dependence on model assumptions is critical. In order for the whole exercise to be worth doing, managers must adopt the model. This can be encouraged through managers' participation in workshops, through putting effort into transferring models to management agencies and conducting gaming exercises exploring the results of following different policies. Obviously, model transfer and adoption by managers is greatly assisted by supplying high quality interactive graphic user interfaces.

UNCERTAINTY

We can distinguish a number of sources of uncertainty in models and management. Surprisingly often, there is confusion about management objectives. Uncertainty in model predictions can arise from uncertainty in model structure, in model parameters, and in future environmental forcing. The uncertainty in model structure needs to be addressed by deliberately developing alternative models. The uncertainty in model parameters can be addressed quantitatively by ascribing *a priori* probability distributions for parameters, and by updating these based on model-data comparisons. The uncertainty about future environmental forcing can be addressed by developing suitable stochastic models for weather, runoff, etc.

These sources of uncertainty span a range of classes of ignorance, from situations where a probability distribution can be specified, to situations where an event can be imagined and partly described, but we cannot reasonably specify a probability, to completely unanticipated events.

MANAGING UNDER UNCERTAINTY

Modelling cannot eliminate uncertainties, but can reduce and help to quantify them. Management decisions are essentially gambles, and managers have different reactions to uncertainty. One typical reaction is to do nothing, wait and see. Unfortunately, a decision to do nothing is still a decision, and often has nasty consequences. Another common approach is known as certainty-equivalent analysis: i.e. build the best model possible, use the best parameter estimates, and then act as if model predictions are certain.

Neither of these approaches is likely to produce the best management outcomes. There is a formal framework for making decisions in the face of uncertainty, known generally as Decision Theory. This normally involves the following steps:

- develop output from the model as a set of possible outcomes with probabilities attached;

- compare policies in terms of expected values of outcomes.

- choose optimal policies, allowing for risk aversion.

ATTACHING PROBABILITIES – FORMAL INFERENCE TECHNIQUES

In order to use formal Decision Theory, we need to attach probability distributions to model predictions. Ideally, we would like these distributions to take into account both our prior knowledge, and additional information obtained from testing model predictions against observations. There is a formal procedure to do this, known as the Bayesian approach. This is a technique which requires the modeller to attach prior probability distributions to model parameters, or even alternative model structures, based on background knowledge. Given a set of observations, the approach then uses Baye's Theorem to attach a posterior probability distribution to parameters or models, based on the relative likelihoods of the observation set conditional on each alternative parameter / model combination. This process can be very computationally intensive, but increases in computer power mean that it is increasingly being applied to quite complex models.

MONITORING

In assessment of one-off developments, monitoring is needed at least to assess the validity of predictions and learn from our mistakes, and often to support development of plans for remediation or mitigation. In management, monitoring is essential to feedback, to provide the indicators to translate policies into actions, and to assess the performance of model predictions. Ideally, it is part of an adaptive or experimental management program. Monitoring programs need at minimum to include management indicators, but ideally should include observations of other model variables which can be used to evaluate model predictions and improve model assumptions.

FORMAL ADAPTIVE MANAGEMENT SCHEME

The Bayesian approach can also provide a useful framework for the formal specification of an adaptive management scheme. We begin with an initial model/parameter set, with an initial probability distribution, and an initial optimal strategy. At each time step, we obtain a set of observations of indicator variables. We use Baye's theorem to update the probability distribution, and re-determine the optimal policy. We then apply this policy to determine the appropriate management action. Monitoring of the response to this action then provides the input data for the next time step.

EXPERIMENTAL MANAGEMENT

Adaptive management policies continually adjust and improve the current model of the system over time, and choose an optimal management strategy based on the updated model at each time step. Experimental management strategies look further ahead, and recognise that the model will change or improve over time, and that different management strategies may retard or accelerate this improvement. By attaching an explicit value to improved knowledge of the system, we may find optimal experimental management policies which deliberately perturb the system to learn more about it. Both adaptive and experimental management policies are in their infancy in marine environmental management, and are much further advanced in fisheries management.

CHANGES IN MANAGEMENT APPROACHES: IMPLICATIONS FOR AEAM

There is a move in Australia towards integrated regional management of coastal development impacts, mariculture, fisheries resources, and recreation. This means a move from assessment to management, from one-off decisions to management over time, and from local impacts to multiple-use regions. Regional managers can hope to learn from mistakes and from experiences. Regional managers need to address broad interactions among different sectors, institutions, and components.

The AEAM methods encourage a focus on management issues in order to keep models simple. However, a single model developed to address a broad range of regional issues could become very complex. A possible solution is to divide models into two parts: a core model designed to be useful for a broad range of issues, and add-on modules to address specific issues.

Core common processes and model components could include regional models of circulation, sediment transport, and nutrient and toxicant cycling.

Specific modules to address specific issues could include nested high-resolution models to address outfalls, or specific construction sites, and empirical or process-based modules for assessing impacts at the level of ecological communities, or impacts on higher trophic levels such as fish, mammals, birds e.g. bioaccumulation models, toxicological models.

The risks involved in developing regional models are that models will become too complex, unwieldy, and expensive, or too inflexible, as adaptive procedures break down. We might hope to avoid this by:

- retaining a capability for model simplification, analysis;
- maintaining a hierarchy of models at different levels of complexity;
- adopting a modular approach to monitoring, feedback, adaptive management;
- building in transferability at core levels.

REGIONAL MANAGEMENT: NEW SCALES, NEW OBJECTIVES, NEW POLICIES?

A regional approach to marine environmental management creates new opportunities for management at different scales, with different objectives and actions. An example is the zonal management strategy used by GBRMPA for the Great Barrier Reef. Here, the management action controls activity at the level of individual reefs or groups of reefs. Management objectives relate not so much to the quality of individual reefs or components of individual reefs, as to the distribution of these properties over the entire spatial array of reefs. Having this large array of spatial subunits allows the possibility of experimental management at the level of individual reefs, without the degree of risk aversion that would apply if one was managing an individual reef in isolation. A key new factor which must then be studied is the degree to which individual reefs or groups of reefs are truly independent, given connections in terms of larval transport, fish migration and water circulation. Similarly, the performance of the overall set of reefs must be monitored to ensure that objectives for the system as a whole are achieved.

EVALUATION OF THE WORKSHOP

Trevor J. Ward

As part of the workshop delegates were asked to anonymously assess the value of the workshop for their purposes. Each of the 9 delegates were asked to fill in a form that examined the workshop both quantitatively (scores against 3 categories) and qualitatively (written comments). The evaluation process is based on a strategy developed by Simon Woodley (Great Barrier Reef Marine Park Authority) and Helene Marsh (James Cook University), and adapted to suit the specific circumstances of this EAS Workshop.

SOLICITED COMMENTS

With the small number of delegates, it was possible to invite each of them to comment in their own words on the workshop. All the comments were positive, and most commented favourably on the workshop process and organisation. Most delegates identified new concepts or techniques brought to them in the workshop they could apply in their own work, and new ways of implementing concepts they already knew about. Several mentioned adaptive management as a new and promising approach for assisting with their own issues.

To represent the delegates responses, I have chosen just one of the positive comments written by a delegate about the workshop overall:
"warm welcome, excellent accommodation, good organisation, comprehensive lessons, rich of knowledge and materials, all resource team are experts on their field of study".

QUANTITATIVE SCORES

Delegates were asked to rank each day of the workshop in three categories:

Value: The extent which the subject matter and activities were valuable in increasing your ability to do your job;

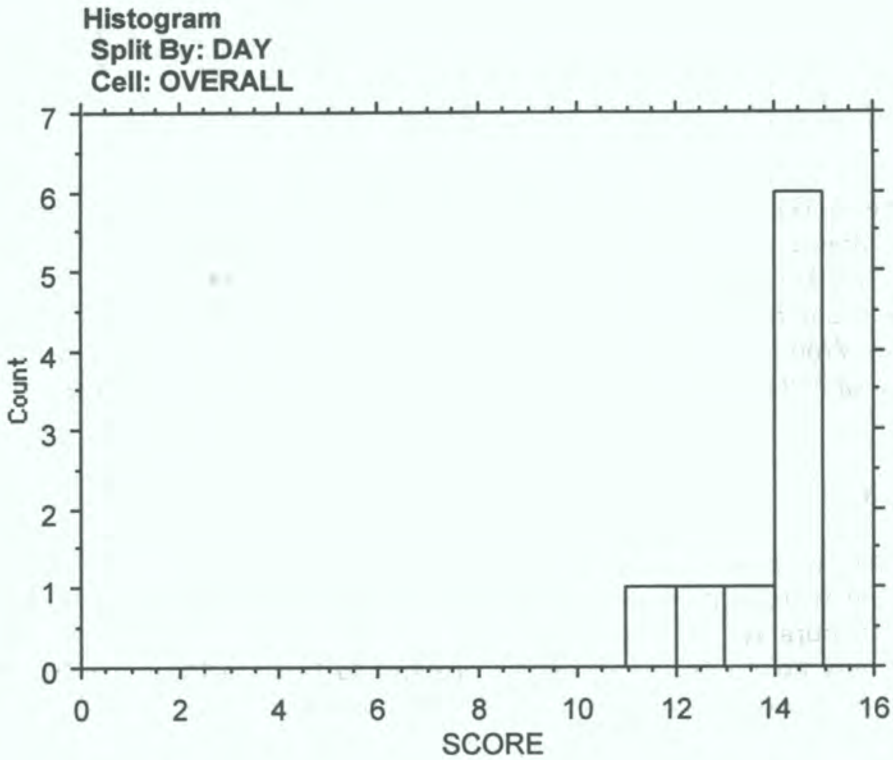
Enjoyment: the degree of enjoyment or dislike for the event or presentation;

Relevance: the degree to which the subject matters and activities are relevant to your job/studies.

In each category, delegates were invited to rank their responses on a scale of 1 (= poor) to 5 (= very valuable). To assess their rankings, the scores for each day were summed, making a maximum possible point score of 15 for each delegate on each day.

For most days the mean point scores were above 13, and for the workshop as a whole the delegates awarded a mean points score of 14 out of a possible 15.

For the workshop as a whole, 6 of the 9 delegates ranked it at the maximum of 15 points (see histogram below of delegate's responses).



On these grounds, the Townsville workshop can be classified as a success. Of course, the real success of the workshop series will depend on the extent to which countries implement the concepts and techniques delivered to them during the three workshops, and the extent to which this influences conservation and management practices in COBSEA nations in the coming decades.

RECOMMENDATIONS

Trevor J. Ward

One of the key objectives of the EAS-33 series of workshops is the establishment and maintenance of a network of technical specialists and laboratories in the East Asia region. The need for such a network, and for an ongoing series of workshops focussed on specific issues, is well recognised (see for example pages 48-49 in GESAMP "Biological Indicators and Their Use in the Measurement of the Condition of the Marine Environment" Report No. 55, 1995). The delegates considered that there were three main areas of priority needs to assist them to effectively address pollution issues. It was recognised that some are not directly related to pollution, and might better be recognised under other EAS initiatives, but delegates felt they formed key blockages in the better management of pollution issues.

A MARINE POLLUTION NETWORK

Delegates discussed a number of options for further development of the informal network of pollution expertise and laboratories that has been developed in EAS-33. It was felt that there was a critical need to continue with the development of the pollution network, to capitalise on the excellent start provided by EAS-33. It was decided that the EAS-33 pollution theme should continued into a proposal for a new EAS project. In developing ideas for a new EAS project it was decided that the focus would be on pollution aspects, even though all such matters are central to good environmental management and planning, and might be considered in passing in other EAS projects underway (such as Watershed Management, or Integrated Coastal Management).

The preferred model for continued development and implementation of the pollution network established by EAS-33 is the use of an ongoing series of workshops focused on discrete key issues of relevance to the East Asian Seas region. To initiate and implement this a small (say 5 members) core group of technical experts should be established to guide the workshop identification and implementation process, in consultation with technical groups in each country. However, it was also recognised that the ad-hoc EAS-33 network itself would be best maintained if all members had good access to Internet communication facilities. The development and maintenance of both a technical group of pollution experts and communication facilities should be supported by COBSEA. This would facilitate cheap and effective communications amongst the existing group of experts on pollution (and other) issues of common interest.

The delegates agreed that regional issues (such as those of the seas of East Asia) had an important bearing on global matters. In particular this is true for marine biodiversity, which has its global centre in the region. It was therefore considered important that regional and global communication issues were of high priority.

MAPPING OF MARINE HABITATS USING REMOTELY SENSED DATA: TRAINING WORKSHOPS

All countries in the region need to map and evaluate the natural marine resources in their control. Without appropriate inventories of the resources, decisions about their use in local areas will be made without knowledge of the regional status of the resources. Habitat maps permit the zoning of areas for specific uses, and form the basis for informed and effective management plans. However, broad-scale mapping of marine habitats by SCUBA divers is very expensive and unlikely to be feasible except in very specific circumstances such as reef-scale monitoring using the ASEAN-Australia Project monitoring tools.

The management of pollution inevitably involves trade-offs, and these usually involve prioritising the use of scarce human resources in the assessment and management of such issues as new development proposals in coastal wetlands. With better information about the extent and inherent values of natural habitats, managers faced with competing demands on the use of these habitats (including pollution) can more competently evaluate the costs and benefits of any particular choices. Thus they can make more effective recommendations and choices about existing and future conflicts over the use of coastal and marine resources.

Remotely sensed data is widely available (from satellites and from aircraft scanners) but the interpretation into reliable habitat classes is difficult and time consuming. Specialist technicians are required to develop and apply algorithms to correct for atmospheric and water interferences, and to validate classifications against ground truth. There are a number of centres in the Asia region that specialise in remote sensing, and in marine habitat mapping. This proposal is to identify the relevant centres of technical expertise, and to design and conduct intensive training workshops.

CONTROL OF POLLUTION IN COASTAL ECOSYSTEMS: IMPROVING MANAGEMENT OF SHRIMP MARICULTURE SYSTEMS

Mariculture is a growing industry in most East Asia countries. A common problem is the use of coastal habitats for shrimp farms (and fish cages), resulting in the alienation of mangrove habitats, the pollution of adjacent waters with waste nutrients, and possibly growth promotants, antibiotics, or other chemicals. This proposal is to examine typical impacts of shrimp mariculture ventures, including construction impacts and operational issues, and to highlight common problems and train managers in identifying the problems and techniques available to mitigate the impacts.

The focus of the project would be on development of simple empirical effluent management models. This would involve the development of a set of simple generic models to use for the assessment of the impacts of shrimp ponds on receiving water quality, to improve the use/waste of foods, to control the loss of pollutants, and to investigate the biological processes in the ponds. These models could also be used to improve management of mariculture industry, particularly the location and efficiency of the ponds, and to reduce their impacts on adjacent waterways.

The models would be coupled hydrodynamic-water/sediment quality-nutrient cycling models, containing simple empirical links to shrimp production. These would enable improved management of feeding and water flow regimes, improving efficiency in the pond systems. This in turn would reduce losses of pollutants to adjacent receiving waters. The models would permit the value of waste-water treatment strategies to be explored, including such strategies as additional ponds for waste water polishing or the downstream culture of seaweeds, oysters, clams, etc to reduce pollution of adjacent waterways.

APPENDIX 1

WORKSHOP TIMETABLE & AGENDA

Tuesday 8 August

0730	Welcome Breakfast, GBR Aquarium (Dr. Ian McPhail)
0930	Introduction to workshop (Trevor Ward, GBRMPA)
1030	*Morning Tea*
1100	Regional research capabilities and programs : a 5 min. presentation by a delegate from each country to briefly describe any major pollution research and management programmes underway in their country
1230	*Lunch*
1330	Key Issues and Sources of Nutrients in Tropical Systems (Jon Brodie, GBRMPA)
1500	*Afternoon Tea*
1530	Nutrient Chemistry (Jon Brodie, GBRMPA)

Wednesday 9 August

0830	Nutrient Dynamics in Tropical Coastal Systems (Miles Furnas, AIMS)
1030	*Morning Tea*
1100	Biological Effects of Nutrients in the Water Column (Peter Thompson, CSIRO)
1230	*Lunch*
1330	Biological Effects of Nutrients in the Water Column continued (Peter Thompson, CSIRO)
1500	*Afternoon Tea*
1530	Toxic Algal Blooms (Sue Blackburn, CSIRO)

Thursday 10 August

0830	Management and Research • Kaneohe Bay - a review (Laurence McCook, AIMS) • Biological Indicators of Nutrient Stress (David Yellowlees, JCU)
1030	*Morning Tea*
1100	Management and Research continued • GBR monitoring program (Jamie Oliver, GBRMPA)
1230	*Lunch*
1330	Management and Research continued • Encore experiment (Andy Steven, GBRMPA) • Herbert River issues (Andrew Johnson, CSIRO)
1500	*Afternoon Tea*
1530	Reef Management Issues (Chris Crossland, Reefs CRC)

Friday 11 August

0830	Management of Nutrient Pollution Introduction to adaptive management • basic concepts (John Parslow, CSIRO)
1030	*Morning Tea*

1100 • management endpoints - VECS, baselines;
• role of process level knowledge etc.

1230 *Lunch*

1330 Monitoring programs: design and evaluation
• management objectives
• indicators
• causal links
(Charles Jacoby, CSIRO)

1500 *Afternoon Tea*

1530 • power and pseudopower
• hypothesis generation
• scales of measurements

Saturday 12 August

0830 Models for use in Adaptive Management
• management issues
• data acquisition
(John Parslow, CSIRO)

1030 *Morning Tea*

1100 Models for use in Adaptive Management continued
• adapative process, simulation, exploration and hypotheses predictions
(John Parslow, CSIRO)

1230 *Lunch*

1330 Models for use in Adaptive Management (Charles Jacoby)

1500 *Afternoon Tea*

1530 Models for use in Adaptive Management continued
(Charles Jacoby, CSIRO)

Sunday 13 August

Field trip to Magnetic Quays development, Magnetic Island.
The focus of this full-day field excursion will be:

- to examine the process of impact assessment and management of pollutants (particularly sediments)
- management of the conflict between natural resource values (reefs) and coastal development pressures
- role of monitoring, evaluation and research in management of the Keys development

(Mike Bugler & Simon Woodley, GBRMPA)

Tuesday 15 August

0830 Eutrophication: biological effects on coral reef systems
• tropical reefs - review of nutrient effects
(Terry Done, AIMS)
• site assessments
(Lyndon DeVantier, AIMS)

1030 *Morning Tea*

1100	Eutrophication: biological effects on coral reef systems cont. • risk analysis • 3 reefs model (Terry Done, AIMS)
1230	*Lunch*
1330	Madrigal Sea Hypothetical video and analysis (Trevor Ward, GBRMPA)
1500	*Afternoon Tea*
1530	Ecotrekker (Trevor Ward, Mat Vanderklift, GBRMPA/CSIRO)

Wednesday 16 August

am	Summary and wind-up; evaluation; feedback; next steps, implementation etc. (Trevor Ward)
pm	Participants depart Townsville

APPENDIX 2

LIST OF DELEGATES

KINGDOM OF CAMBODIA

Mr. Chou Sophark (Shophark)
Technical Assistant to the Gen. Director
Ministery of Environment
#38 Samdech Preah Silanouk
Tonic Bassac, Chamkamon
Phom Penh
Cambodia
Phone & Fax: (885) 7844

PEOPLES' REPUBLIC OF CHINA

Dr. Zhao Junlin (Junlin)Director, Inst of Environ Sciences
Beijing Normal University
Beijing 100875
China
Phone: (86-10) 201 2288
Fax: (86-10) 201 3929
Email: zhaojl@bnu.ihep.ac.cn

INDONESIA

Mr Iswahyudi
Staff to the Assistant Minister for Environment
Ministry for Environment
Indonesia
Phone:
Fax: (62-21) 374 307

REPUBLIC OF KOREA

Dr Hi-Sang Kwak (Kwak)
Principal Researcher
Korea Ocean Research & Dev Institute
Ansan PO Box 29
Seoul 425-600
Korea
Phone: (0345) 400 6000
Fax: (0345) 408 5820

MALAYSIA

Ms Poh Sze Choo (Poh Sze)
Senior Marine Fisheries Officer
Fisheries Research Institute
Aquatic Ecology Section
Fishery Research Institute
11700 Glugor, Pulau Pinang
Malaysia
Phone: (604) 657 2777
Fax: (604) 657 2323

PHILIPPINES

Ms Davina Cleofe Gonzales (Dada)
Senior Environment Management Specialist
Dept. Environment & Natural Resources
Environment Management Bureau
Topaz Building
99-101 Kamia Road
Quezon City 1102
Philippines
Phone & Fax: (63-2) 924 7540

THAILAND

Mr. Somkait Khokiattiwong (Somkiat)
Phuket Marine Biological Centre
PO Box 60
Phuket 83000
Thailand
Phone: (076) 391 128
Fax: (076) 391 127

SOCIALIST REPUBLIC OF VIETNAM

Mr Hong Van Nguyen (Van)
Researcher
Centre for Marine Env. Survey
Research & Consultation
208D, Doican, Hanoi
Socialist Republic of Vietnam
Phone: (84-4) 454 976
Fax: (84-4) 333 039

SINGAPORE

Ms Karenne Tun (Karenne)
Research Assistant
Dept of Zoology
National University of Singapore
Lower Kent Bridge Road
Singapore 0511
Phone: (65) 778 7112
Fax: (65) 778 6155
Email: zooktpp@nus.sg

APPENDIX 3

LIST OF PRESENTERS

Dr. Trevor Ward
Marine Biodiversity Specialist,
Great Barrier Reef Marine Park Authority, and
CSIRO Division of Fisheries
PO Box 25
Floreat. WA 6014
Australia
Phone: (61-9) 3870321
Fax : (61-9) 3870121
Email: trevor.ward@per.dms.csiro.au

Mr. Jon Brodie
Director, Research & Monitoring
Great Barrier Reef Marine Park Authority
PO Box 1379
Townsville QLD 4810
Australia
Phone: (61-77) 818 811
Fax: (61-77) 726 093
Email: Jon_Brodie@gbrmpa.gov.au

Dr. Miles Furnas
Research Scientist
Australian Institute of Marine Science
PMB 3 Townsville MC
Townsville QLD 4810
Australia
Phone: (61-77) 534 211
Fax: (61-77) 725852
Email:M_FURNAS@aims.gov.au

Dr. Peter Thompson
Research Scientist-Phytoplankton Ecology
CSIRO Division of Fisheries
PO Box 20
North Beach WA 6020
Australia
Phone: (61-9) 246 8288
Fax: (61-9) 246 8233
Email: peter.thompson@per.ml.csiro.au

Dr. Sue Blackburn
Research Scientist - Toxic Algal Blooms
CSIRO Division of Fisheries
GPO Box 1538
Hobart TAS 7001
Australia
Phone: (61-02) 325 222
Fax: (61-02) 325 000
Email: sue.blackburn@ml.csiro.au

Dr. Lawrence McCook
Research Scientist - Coral Reef Ecology
Australian Institute of Marine Science
PMB 3, Townsville
Townsville QLD 4810
Australia
Phone: (61-77) 534 211
Fax:(61-77) 725852
Email: L_MCCOOK@aims.gov.au

Dr. David Yellowlees
Associate Professor in Biochemistry
Department of Biochemistry and Molecular Biology
James Cook University of North Queensland
Townsville QLD 4811
Australia
Phone: (61-77) 81 4463
Fax: (61-77) 251394
email david.yellowlees@jcu.edu.au

Dr. Jamie Oliver
Monitoring Coordinator
Great Barrier Reef Marine Park Authority
PO Box 1379
Townsville QLD 4810
Australia
Phone: (61-77) 818 864
Fax: (61-77) 726 093
Email: jamieo@gbrmpa.gov.au

Mr. Andy Steven
Acting Coordinator - Water Quality
Great Barrier Reef Marine Park Authority
PO Box 1379
Townsville QLD 4810
Australia
Phone: (61-77) 818 864
Fax: (61-77) 726 093
Email: andys@gbrmpa.gov.au

Dr. Andrew Johnson
Resource Scientist
CSIRO Division of Tropical Crops and Pastures
Davies Laboratory
Private Bag
Aitkenvale QLD 4814
Australia
Phone: (61-77) 538507
Fax: (61-77) 538650
Email: andrewj@tvl.tcp.csiro.au

Prof. Chris Crossland
Director - CRC Reef Research Centre
James Cook University
Townsville QLD 4810
Australia
Phone: (61-77) 814 976
Fax: (61-77) 814 099
Email: crc.reef@jcu.edu.au

Dr. John Parslow
Principal Research Scientist
CSIRO Division of Fisheries
GPO Box 1538
Hobart TAS 7001
Australia
Phone: (61-02) 325 222
Fax: (61-02) 325 000
Email: john.parslow@ml.csiro.au

Dr. Charles Jacoby
Principal Research Scientist
CSIRO Division of Fisheries
PO Box 20
North Beach WA 6020
Australia
Phone: (61-9) 246 8288
Fax: (61-9) 246 8233
Email: charles.jacoby@per.ml.csiro.au

Dr. Terry Done
Principal Research Scientist
Australian Institute of Marine Science
PMB No. 3
Townsville QLD 4810
Australia
Phone: (61-77) 534 344
Fax: (61-77) 725 852
Email: t.done@aims.gov.au

Lyndon DeVantier
Coral Reef Ecologist
Australian Institute of Marine Science
PMB No. 3
Townsville QLD 4810
Australia
Phone: (61-77) 534 344
Fax: (61-77) 725 852
Email: l.devantier@aims.gov.au

APPENDIX 4

RESOURCE TEAM

Trevor Ward
Great Barrier Reef Marine Park Authority and CSIRO,
Perth, WA.
Australia

Mathew Vanderklift
CSIRO Division of Fisheries,
Perth, WA.
Australia

Simon Woodley
Great Barrier Reef Marine Park Authority,
Townsville., Australia

Mike Bugler
Great Barrier Reef Marine Park Authority,
Townsville, Australia.

Janelle Craig
Great Barrier Reef Marine Park Authority,
Townsville, Australia.

Helen McGregor
Great Barrier Reef Marine Park Authority,
Canberra, Australia.

Michelle Morrison
Great Barrier Reef Marine Park Authority,
Townsville, Australia.

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