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Water Quality in the Great Barrier Reef World Heritage Area: Past Perspectives, Current Issues and New Research Directions

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Elevated sediment and nutrient concentrations have long been regarded as the pre-eminent water quality threats to the Great Barrier Reef, with the potential risk posed by other pollutants such as heavy metals, persistent chlorohydrocarbons, PCBs and petroleum related compounds considered to be of lesser consequence. However, the management focus on these latter types of pollutants has recently shifted to acknowledge the potential impact posed by diuron, dioxins, dieldrin, and mercury and cadmium concentrations detected in sediments and biota along the Great Barrier Reef and southern Queensland coastline. In general, these threats originate from areas dominated by intensive cropping agriculture and are exacerbated by high rainfall and erosion rates in the wet tropics region of the Queensland coast. Maintenance of long-term monitoring programmes, which utilize innovative data acquisition techniques will enable assessment of change in environmentally relevant pollutant concentrations over time. However, improved land management practices, which include an immediate minimization of vegetation clearance and responsible use of pesticides and fertilizers in Queensland are essential if water quality in the Great Barrier Reef World Heritage Area is to be maintained and protected. © 2000 Elsevier Science Ltd. All rights reserved.

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The Great Barrier Reef World Heritage Area

The Great Barrier Reef is situated adjacent to the Queensland and north-eastern Australian coast, and is the largest reef system in the world. The Great Barrier Reef was proclaimed a World Heritage Area in 1981 and consists of an archipelagic complex of over 3000 reefs covering an area of approximately 350 000 square kilometres (Craik, 1992; Wachenfeld *et al.*, 1998). A majority of these reefs are situated on the mid and outer continental shelf and are located away (20–150 km) from the continental landmass. However, a significant number of reefs (*ca* 750) exist at inshore sites (Furnas and Brodie, 1996). The Great Barrier Reef World Heritage Area also supports extensive areas of nearshore and deeper water seagrass beds (Lee Long *et al.*, 1993). The Great Barrier Reef is the largest of the world's 552 World Heritage Areas and provides habitat for a diversity of marine life and a number of endangered animals including dugong, cetaceans and turtles (Lucas *et al.*, 1997).

Current Great Barrier Reef Water Quality Issues

Although population growth and urban expansion in Queensland have been rapid (a 27% increase between 1986 and 1996), the northern Queensland coast still remains relatively sparsely populated (Anon, 1999). Only 700 000 of the State's 2.9 million residents live in the coastal areas adjacent to the Great Barrier Reef World Heritage Area. Despite this low population pressure, extensive land modification has occurred over the last 200 years since European settlement (Anon, 1993). Today, 80% of the land area of catchments adjacent to the Great Barrier Reef World Heritage Area support some form of agricultural production (Wachenfeld *et al.*, 1998; Gilbert, in press). To place Queensland land-use and vegetation clearing activities into perspective, more than 50% of the State's original 117 million hectares of woody vegetation have been cleared primarily for agricultural purposes since European settlement (Anon, 1999). As a consequence, runoff resulting from land-based agricultural activities

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cattle grazing, vegetation clearance and intensive cropping) is the primary influence on water quality in the Great Barrier Reef World Heritage Area (Bell, 1991; Moss *et al.*, 1992; Anon, 1993; Brodie, 1994, 1997). Increased soil erosion is estimated to have resulted in a 3–4 fold increase in the export of sediment loads into the Great Barrier Reef environment over the last 140 years (Moss *et al.*, 1992; Neil, 1997). It is estimated that the total nutrient influx to reef waters (principally nitrogen and phosphorus) has increased by [illegible]% during this time (Brodie, 1997). Most of this increase in nutrient export has occurred during the last 40 years, a consequence of agricultural expansion, and the more than threefold increase in fertilizer usage by the agricultural industry over this time (Pulsford, 1996). Urban and industrial development can also cause locally important water quality impacts from stormwater, sewage and industrial discharges into the adjacent World Heritage Area (Reichelt and Jones, 1994; Brodie, 1994).

Jurisdictional issues present obstacles in the management of marine water quality in the Great Barrier Reef, as catchments adjacent to the Great Barrier Reef Heritage Area are outside the jurisdiction of Marine Park managers. The *Great Barrier Reef Marine Park Act 1975*, created to protect the Marine Park, provides little scope to control land-based activities which produce damaging run-off (Wachenfeld *et al.*, 1998). While there is some provision in the Act to prohibit '*acts that pollute water in a manner harmful to animals and plants in the Marine Park*', control of adjacent catchments is primarily exercized through the *Environmental Protection Act 1994*, (administered by the Queensland Environment Protection Agency) and the *Water Resources Act 1989* (administered by the Queensland Department of Natural Resources). Local governments are also involved in water quality management with respect to urban planning and drainage and the licensing of industrial sources of pollution. A major review of the multi-authority complexities involved in the management of the Great Barrier Reef World Heritage Area has highlighted these jurisdictional difficulties and recommended stronger collaboration between Commonwealth and Queensland State authorities and agencies in order to achieve effective co-management of the World Heritage Area (Sturgess, 1999).

Historical and Current Risk Assessment of Pollutant Impacts on the Great Barrier Reef

Elevated sediment and nutrient concentrations have long been regarded as the pre-eminent water quality threats to the Great Barrier Reef (Wolanski and Jones, 1981; Baldwin, 1990; Bell, 1991; Bell and Elmetri, 1995). Potential risk posed by other pollutants such as heavy metals, persistent chlorohydrocarbons, polychlorinated biphenyls (PCBs) and petroleum related compounds were considered to be of lesser consequence (Dutton, 1985; Brodie, 1997). This risk assessment was based on the low reported concentrations of these pollutants in the Great Barrier Reef World Heritage Area compared with locations elsewhere in the world. The only exceptions were sites adjacent to urban and industrial development such as commercial harbours, which were considered to be moderately contaminated by a range of pollutants (Dutton, 1985).

There has been considerable debate regarding the current nutrient status of Great Barrier Reef inner, central and outer shelf waters (Bell, 1991; Furnas and Brodie, 1996; Brodie *et al.*, 1997). Nutrient data, which have been compiled over the last 20 years for the offshore central Great Barrier Reef show no evidence for long-term change in seawater nutrient status of this section of the reef (Furnas and Brodie, 1996; Brodie, 1997; Brodie *et al.*, 1997). However, there is evidence that eutrophication has occurred in some inshore areas of the Great Barrier Reef World Heritage Area. Increases in local and/or regional nutrient levels have led to increased seagrass biomass and distribution at Green Island (Udy *et al.*, 1999) and around Palm Island (Klumpp *et al.*, 1997). At the same time. reductions in coral growth and the relative abundance and composition of corals of nearshore fringing reefs in the Whitsunday region have been linked to elevation in nutrient levels (van Woesik *et al.*, 1999).

While eutrophication is still considered the major threat to the sustainability of the Great Barrier Reef, the management focus on pollutants has shifted somewhat over the last five years as new research has been completed. Recent work by Brunskill *et al.* (1999) concluded that mercury concentrations in surface sediments in Bowling Green Bay in the central section of the Great Barrier Reef World Heritage Area are three times higher than pre-1850 background concentrations. The majority of this trace metal contamination has been attributed to the downstream transport of mercury used as an amalgam in the gold mining industry of northern Queensland at the turn of the century, and through the more recent use of methoxyethylmercuric chloride as a fungicide by the sugarcane industry (Walker and Brunskill, 1997; Brunskill *et al.*, 1999). Similarly, increases in cadmium and arsenic concentrations in marine sediments in the Hinchinbrook region resulting from the use of phosphatic fertilizers naturally enriched in these elements have been noted adjacent to areas with intensive cropping (Tesiram, 1995; Ridd, 1999). Marine sediments collected in the vicinity of urban areas are enriched with a range of metals (Kellaway *et al.*, 1999; Doherty *et al.*, 2000; Haynes unpub. data). This is of particular significance, since it is now recognized that disturbed acid sulphate soils along the Great Barrier Reef World Heritage Area coast pose a significant potential risk to local estuarine and nearshore environments from lowered pH levels which enhance metal mobilization (Cook *et al.*, 2000).

Recently presented data also suggest that pesticide residues and organochlorine contaminants present a greater risk to the Great Barrier Reef and the Queensland marine environment in general, than previously expected. A range of contaminants, including polychlorinated-*p*-dioxins, dieldrin, DDT (and its metabolites) and the herbicides diuron and atrazine have all been detected in nearshore sediments and/or seagrass collected along the Great Barrier Reef World Heritage Area coast (Müller *et al.*, 1998, 1999; Gaus *et al.*, 2000; Haynes *et al.*, 2000a). In particular, the concentrations of diuron found in sediments between Townsville and Cairns are high enough to depress seagrass photosynthetic rates (Ralph, 2000; Haynes *et al.*, 2000b). Dieldrin has been reported to be a ubiquitous contaminant of crabs (*Australoplax tridentata* and *Scylla serrata*) collected between Cairns and Brisbane (Mortimer, 2000). Necropsy sampling of dugong has determined that octachlorinated dibenzo-dioxin (OCDD) congeners are accumulating in Great Barrier Reef dugong to concentrations previously unseen in marine mammals elsewhere in the world (Haynes *et al.*, 1999). These findings are of some concern as accumulation of organochlorine pesticides and polychlorinated biphenyls (PCBs) has been implicated in reproductive and immunological abnormalities observed in terrestrial bird (Kubiak *et al.*, 1989) and marine mammal populations in the northern hemisphere (Kuiken *et al.*, 1994; Johnston *et al.*, 1996).

Great Barrier Reef Pollutant Information Deficiencies

Some 25 major river catchments discharge directly into the Great Barrier Reef World Heritage Area (Moss *et al.*, 1992) and the bulk of their terrigenous inputs are deposited within 10 km of the Queensland coast (Larcombe *et al.*, 1996). This nearshore deposition zone containing mangrove, soft-bottom communities, seagrass and fringing reef environments is most at risk from contaminants (sediments, nutrients and other pollutants) sourced from anthropogenic activity in Queensland coastal catchments. In general, the highest concentrations (and loads) of catchment-sourced pollutants such as sediments (and their associated herbicides and insecticides) are transported from agricultural lands to the nearshore marine environment following the first major rainfalls of the wet season (Cooper and Riley, 1996; Taylor and Devlin, 1997). Apart from nutrient and sediments, no data are available about the concentrations and potential impact of these first-flush loads of pollutants on nearshore Great Barrier Reef biota. Acquisition of this data is particularly important given the potential synergistic impacts of pollutants (particularly herbicides) on corals and seagrass. These are created by a combination of reduced water salinities and high temperatures often experienced by nearshore seagrass beds and reefs during the summer monsoon months (Fabricius, 1999; Berkelmans and Oliver, 1999; Devlin *et al.*, 2000; Michalek-Wagner and Bowden, 2000). The capacity of monsoon river flood plumes to transport entrained nutrients to mid and outer shelf reefs during calm conditions is documented (Devlin *et al.*, 2000), yet no information is available about the offshore transport of other contaminants in the Great Barrier Reef World Heritage Area.

Low level organochlorine (including dioxin) contamination is widespread in northern Queensland agricultural soils (Cavanagh *et al.*, 1999; Gaus *et al.*, 2000; Müller *et al.*, 2000) and adjacent marine sediments (Müller *et al.*, 1999; Gaus *et al.*, 2000; Haynes *et al.*, 2000a). At present, the sources and/or formation mechanisms and environmental cycling of dioxins are unknown. However, a strong positive correlation between their occurrence in marine sediments and agricultural areas in the northern Queensland wet tropics, has been reported (Müller *et al.*, 1999). Given the teratogenic nature of dioxins, their ubiquitous distribution in wet tropics marine sediments and accumulation in dugong (Haynes *et al.*, 1999; Gaus unpub. data), there is an urgent need to assess their role (if any) in Great Barrier Reef ecosystem functioning and in local dugong population decline.

Broad-scale, and intensive, site specific monitoring of Great Barrier Reef sediment metal concentrations has now been completed (Doherty *et al.*, 2000; Haynes unpub. data), although sediment quality guidelines for heavy metals in the Great Barrier Reef World Heritage Area remain to be developed. With the exception of sites associated with urban and industrial activity, metal contamination in the World Heritage Area remains a relatively minor concern. However, given the toxicological relationships between methyl-mercury and butyltin compounds and copper exposure to target organisms, on-going monitoring of sediment concentrations of these metals is still warranted (Goldring, 1992).

Despite recognition that the transport of agricultural (and urban) sourced pollutants to Great Barrier Reef waters represents a potential risk to the ecological integrity of the World Heritage Area, there is little long-term, time-integrated data available to assess temporal change in reef water quality. Most available data on heavy metal and organochlorine concentrations are from 'spot analyses' often collected for a single location, e.g. adjacent to research stations (Smith *et al.*, 1987; Esslemont, 1999), and advances in analytical techniques make direct comparison of modern data sets with results collected prior to the late 1980s difficult.

Catchment Management Strategies

Diffuse source pollutants originating from agricultural land clearly constitute the greatest chronic pollutant source influencing the Great Barrier Reef World Heritage Area, and equally clearly, management of these use sources is essential if the Great Barrier Reef is to protected. A number of land management strategies ve been initiated over the last 10 years. These include Integrated Catchment Management (ICM) pro-amme, which is based on the premise that decision-king processes in management of land and water ources must be coordinated to achieve sustainability hnson and Bramley, 1996). The recognition of eco-mically sustainable development principals at the rm level through the use of property management ans and development of industry codes of practice is ow also emerging (Johnson *et al.*, 1998). Whilst some otable achievements have been made by Queensland ricultural industries and communities (e.g. widespread option of sugarcane trash blanketing to minimize xposure of unvegetated soil to rainfall), the fact remains that appropriate land management in Queensland emains a great challenge (ANAO, 1997; Boulty, 2000). arly approaches to catchment management involved a rge number of independent projects under the Feder-lly funded Landcare programme. Today there is a growing realization that a more strategic approach on a larger scale, backed by adequate resources is required to achieve effective catchment management (ANAO, 1997; Bellamy *et al.*, 1999; Boulty, 2000). Vegetation clearing on Queensland agricultural lands is still being carried out at rates that are up to an order of magnitude higher han any other Australian State, and soil erosion and ssociated nutrient losses continue to be significant roblems on Queensland agricultural properties (Anon, 997, 1999).

The Consequences of Substandard Land Management Practices

Increased sediment and turbidity have been demonstrated to have a range of effects on coral communities (Tomascik and Sander, 1985; Muller-Parker *et al.*, 1994; Ward and Harrison, 1996) and under extreme situa-ions, can result in coral reef community collapse (Smith *et al.*, 1981; Lapointe and O'Connell, 1989). Chronic nutrient stress may also inhibit coral recovery after natural destructive events such as cyclones (Kinsey, 1988). Increased nutrient concentrations and turbidity an also adversely affect seagrass by causing a shading nduced reduction in photosynthesis (Walker and McComb, 1992; Abal and Dennison, 1996). In addition o nutrient stress, chronic herbicide exposure from ag-icultural run-off has the potential to impact seagrasses nd other photo-autotrophic reef organisms (Van-ermeulen *et al.*, 1972). This includes shallow water reef-uilding corals which rely on their symbiotic zooxan-hellae for nutrition (Davies, 1991). While the impact of rganochlorines such as pesticides and dioxins are still nclear for lower invertebrates such as corals, their potential toxicity to immune systems and reproductive processes is of concern.

Future Research Directions: Early Warning of Ecological Stress Methods

Eco-toxicological research on early indicators of ecosystem stress is well established for temperate waters. For example, the induction of biomarkers such as the cytochrome P450 mono-oxygenases (Stegeman *et al.*, 1990; Goksøyr and Forlin, 1992) or the expression of metallothioneins (Price-Haughey *et al.*, 1987; Olsson and Kille, 1997) has been used as a time-integrated analysis tool to assess the exposure of organisms to organic contaminants for decades. Similarly, the formation of DNA-adducts in the presence of carcinogenic compounds (Ericson *et al.*, 1998; Wirgin and Waldman, 1998), and bioassays using cell lines (Tillitt *et al.*, 1991; Michalek 1994) have also been recognized as important tools in the detection of various stresses impacting on aquatic organisms at biochemical, physiological whole organism and ecosystem levels. In tropical regions however, and the Great Barrier Reef region in particular, there is a critical information need with respect to biomarkers and bioassay research.

To date only a limited number of tropical test organisms that relate to keystone species and appropriate test conditions are known (reviewed in Peters *et al.*, 1997). Some of the few exceptions are bioassays based on quantification of coral bleaching (as loss of zooxanthellae) (Jones, 1997) or the reduction in reproductive output in hard corals in response to trace metal exposure (Reichelt-Brushett, 1998). Another promising tool for the assessment of sublethal stress in marine organism is the submersible Pulse-Amplitude-Modulated fluorometer (Diving PAM) (Ralph and Burchett, 1998; Jones *et al.*, 1999). This technique is based on fluorescence yield measurements (as a measure of the efficiency of photosystem II electron transport), which can be made *in situ* in aquatic situations. The degree of electron transport disruption may be directly correlated to the concentration of an assessed pollutant the test organism (seagrass or coral) is exposed to, providing valuable information on the magnitude of the disturbance (Jones *et al.*, 1999). Progress has also been made with the introduction of semi-permeable membrane devices (SPMDs) and diffusive gradients in thin films (DGT) techniques for the analysis of water column lipophilic contaminants as well as heavy metals and nutrient species. These techniques reduce some of the problems inherent in the analyses of water, sediment and biota samples for pollutants (Huckins *et al.*, 1993; Prest *et al.*, 1995; Zhang *et al.*, 1998). SPMDs are devices that consist of a thin film of triolein sealed in a polyethylene tube (Prest *et al.*, 1995). Lipophilic compounds permeate the membrane and partition into the lipid layer where they are concentrated and sequestered according to physico-chemical principals (Huckins *et al.*, 1993). SPMDs have been shown to accurately reflect concentrations present in local bivalves (Prest *et al.*, 1992, 1995; Rantalainen *et al.*, 1998). Similarly, DGT techniques are based on a simple device which accumulates solutes on a binding agent after passage through a hydrogel which acts as a well-defined diffusion layer (Davison and Zhang, 1994; Zhang *et al.*, 1998).

Conclusions

Chemical data derived using innovative techniques can play an early warning role in the assessment of impacts of contaminants on mangrove, seagrass and coral reef organisms of the Great Barrier Reef World Heritage Area. Moreover, the methods could contribute to the understanding of interactions of contaminants with high light and temperature conditions. Without consideration of the subtle impacts of chemical contaminants, managers will fail to fully understand the status of tropical marine ecosystems and the risks associated with anthropogenic impacts. However, if fundamental changes in land-management do not occur, even the most advanced research techniques cannot help in the ultimate protection of the Great Barrier Reef.

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