Developing a macrobenthic monitoring programme for Port Curtis

David R. Currie[1, 2]

[1] Centre for Environmental Management, Central Queensland University, P.O. Box 1319, Gladstone, Qld. 4680, Australia.
[2] *Present Address*: SARDI Aquatic Sciences, P.O. Box 120, Henley Beach, SA 5022, Australia.
Email: currie.david@saugov.sa.gov.au

Abstract. Following responses to perceived increasing pressures on the biological resources of Port Curtis, a steering committee was established in 2001 with the aim of developing a holistic ambient monitoring programme for ecosystem health in Port Curtis. Comprising representatives from Gladstone's principal industries, and representatives of the EPA, CQU and coastal CRC, the committee has focused efforts on the delivery of cost-effective, co-ordinated and objective assessments of environmental health. One prospective indicator of marine ecosystem health for the port, macrobenthic community structure, has been integral in the development of the programme. Most survey techniques allied with this measure involve quantitative sampling of the seafloor at appropriate spatial and temporal scales, and subsequent evaluation of change in the abundance and diversity of bottom-dwelling fauna. In principle, such techniques can provide an unambiguous assessment of whether current or future human activities adversely affect ecosystem health; it is however imperative that the sampling is geared to the spatial and temporal influence of the activity. This paper reviews historical sampling of macrobenthic communities in Port Curtis and highlights inadequacies in established monitoring regimes for ecosystem health. Furthermore, this paper offers a revised sampling strategy for macrobenthos in Port Curtis that should address more comprehensively key stakeholder issues and expectations.

Introduction

Port Curtis is a shallow, semi-enclosed estuarine system situated on the central coast of Queensland approximately 500 kilometres north of the state capital Brisbane (Fig. 1). Bounded by two large offshore islands (Curtis Island and Facing Island), the waters of Port Curtis form a narrow coastal embayment approximately 200 km^2 in area. Freshwater flows to the estuary are seasonally significant and can result in rapid reductions in salinity throughout the marine dominated waterway. Strong tidal currents and a 5m tidal range also have major influences on the area's marine and intertidal ecosystems. The area supports a wide range of marine habitats including mangroves, seagrass beds, salt-marshes, coral reefs, and extensive intertidal mudflats and subtidal soft-sediments.

Several areas of Port Curtis are considered significant in terms of conservation value. The Great Barrier Reef World Heritage Area commences at the low water mark on the mainland side of The Narrows and includes Curtis Island, while the offshore areas east of Curtis Island are included within the Mackay/Capricorn Section of the Great Barrier Reef Marine Park (GBRMPA 1998). Areas in and around Port Curtis also provide feeding grounds for the endangered species *Dugong dugon* and have been declared part of the Rodd's Bay Dugong Sanctuary (GBRMPA 1999).

Industrial growth in the Port Curtis hinterland over the last 40 years has resulted in the development of several foreshore manufacturing, processing and bulk handling facilities. These include major alumina and aluminium processing plants, a coal-fired power station, a cement works, several chemical refineries, and an extensive network of shipping wharves and storage facilities. The Port of Gladstone is now Queensland's largest multi-cargo port and the fifth largest port in Australia, handling more than 50 million tonnes of cargo each year. Other significant industries within the region include mining, agriculture, fishing and tourism.

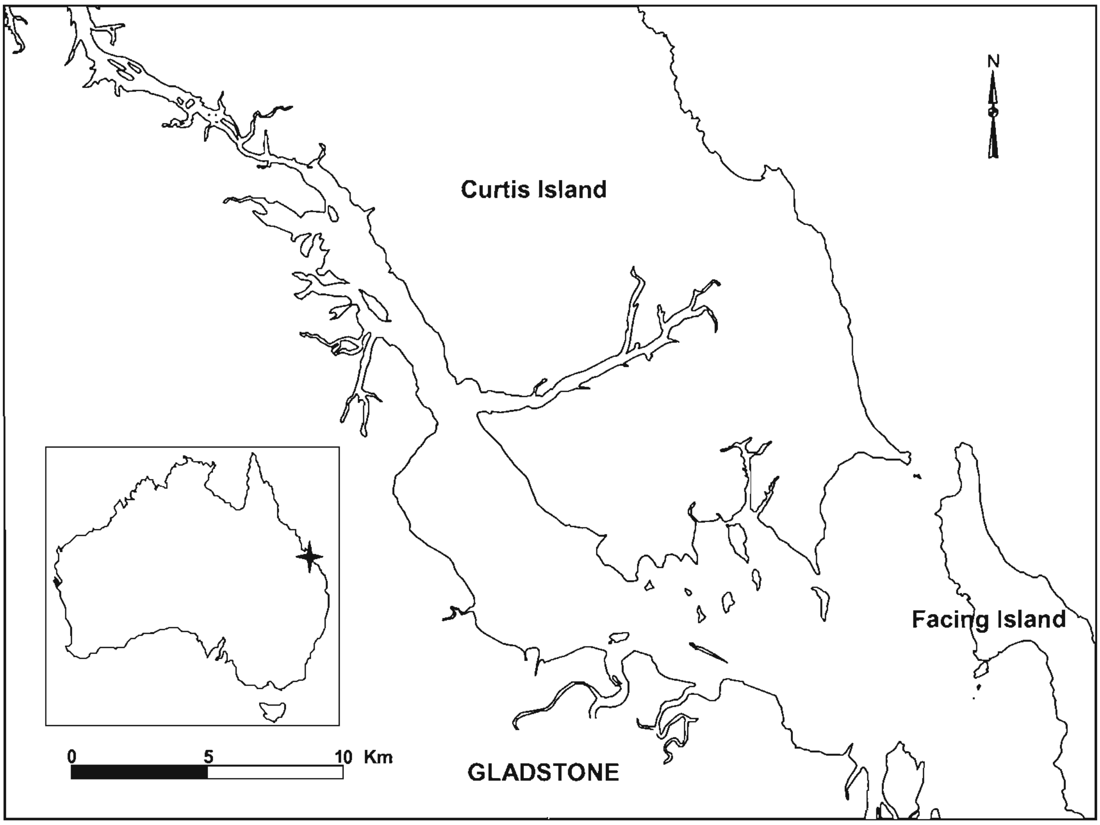

Fig. 1. Location of Port Curtis on the central coast of Queensland.

As the population and industries of the Port Curtis region continue to grow, so to does the potential for environmental degradation. Considerable visible changes to the coastline of Port Curtis have occurred in recent times, with over 650 hectares of mangroves and 990 hectares of saltmarsh being lost due to reclamation or environmental stress since the 1940's (QDEH 1994). Concomitant changes to water quality and subtidal marine habitats remain undetermined due to the absence of any quantitative, historical, baseline data. To ensure that all future developments within the region are implemented in an environmentally responsible manner, it is imperative that the relative environmental values of the ports subtidal marine resources are adequately audited. As part of an effort to address knowledge gaps in biological diversity and ecological processes within Port Curtis, key stakeholders are currently reviewing existing marine survey programmes.

Integrated monitoring programme

Background

The Port Curtis Integrated Monitoring Programme is a collaboration among Gladstone industry, the Queensland Environmental Protection Agency (EPA), Central Queensland University (CQU), and the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (Coastal CRC). The programme was initiated through the National Heritage Trust funded Gladstone Harbour Protection and Enhancement Strategy.

The programme seeks to combine monitoring and research currently undertaken by these parties to provide a holistic ambient monitoring programme for Port Curtis. The programme will describe the current state of, and identify future change in biological communities and environments within the port region. It will also contribute to the overall knowledge of the Port Curtis ecosystem and provide an objective assessment of environmental health. Further, the programme seeks to: a) facilitate cost sharing and cost effective solutions to environmental issues; b) foster coordination of stakeholder activities and cooperation between stakeholders; c) encourage strategic environmental management, to protect and enhance the social, economic and environmental/world heritage values of the port (especially in regard to current and potential developments); and d) promote Gladstone as a sustainable city.

In June 2001, a Steering Committee was established to guide the development and implementation of the programme. The committee includes representatives from Gladstone's main industrial sectors (Boyne Smelters Ltd, Gladstone Area Water Board, Gladstone Port Authority, NRG Operating Services Pty Ltd, ORICA Australia, Queensland Alumina Ltd, Southern Pacific Petroleum, TICOR Chemical Company) and representatives of the EPA, CQU and coastal CRC. All steering committee members are committed to developing the Port Curtis Integrated Monitoring Programme and have agreed to work cooperatively to develop a monitoring framework that will utilise current monitoring resources in a more efficient and scientifically valid manner.

Project Development

As an unambiguous assessment of the ports ecosystem health depends on quantitative measurements of both biotic and abiotic parameters in each of the ports key habitat types, steering committee members considered the range of marine habitats occurring within the confines of Port Curtis. The committee established that the following habitats should be included in any future monitoring process: water column, sandy beaches, sub-tidal soft-sediments, rocky shores, sub-tidal reefs, seagrass beds, mangroves, saltflats, coastal creeks and rivers, and man-made substrates.

While the history and frequency of sampling within these habitats is variable, intensive seasonal monitoring of soft-sediment macrobenthic communities in Port Curtis has been undertaken since 1995. As this research represents the longest continuous monitoring programme for the port, it is the first to be redesigned as part of the Port Curtis Integrated Monitoring Programme. Monitoring programmes assessing other habitats in the port will be sequentially redesigned, although it is anticipated that the spatial organisation of the macrobenthic programme will from the basis for cascading measurements of water quality.

Stakeholder aims and objectives

All key stakeholders in the integrated monitoring steering committee were canvassed for their aims and priorities for any revised macrobenthic monitoring programme. Specific areas of interest to stakeholders were wide-ranging and in no small part reflected the diverse nature of industrial operations within the port. These included the detection of long term adverse impacts associated with: industrial outfalls, discharges and storm-water runoff; altered freshwater flow regimes; contaminant concentrations in water and sediments; dredging and sea dumping; new and existing reclamation sites; maintenance and utilisation of port infrastructure; oil and/or other product spills; and ballast water discharges and hull-fouling.

Understandably many stakeholders were primarily concerned with assessing the likely consequences of impacts associated with current and future developments within their own particular industry, and their respective geographical 'spheres of influence'. Nevertheless central to all submissions were the notions that any future monitoring programme should be capable of: 1) describing the current state of the communities of Port Curtis and providing an assessment of ecosystem health; 2) providing sound, scientific baseline information against which future developments can be assessed; 3) demonstrating that industries are not having unacceptable adverse long term impacts; and 4) providing scientifically valid, acceptable and relevant information to government agencies, industry and the broader community. The extents to which these four central themes are embraced in a revised macrobenthic sampling scheme are discussed in the benefits sub-section below.

Macrobenthic monitoring

Background

Measurements of change in benthic marine communities have for several decades been widely used in identifying and monitoring man-made impacts on the sea (Poore and Kudenov 1978; Gray and Christie 1983; Warwick 1993). This is largely because benthic organisms are relatively non-mobile and integrate effects of pollutants over time. Most importantly, however, macrobenthic organisms are comparatively easy to sample and enumerate to species level. Despite such advantages, macrobenthic monitoring programmes are almost always a compromise between the scientific ideal and political, financial and logistical constraints (Warwick 1993). The costs of biological monitoring are relatively high compared to physical or chemical monitoring (largely because of the labour intensive nature of field sampling and laboratory analysis). But physical/chemical data are only an indirect measure of ecosystem health. Direct monitoring of the biota is the only way in which an unequivocal assessment of ecosystem health can be obtained (QDEH 1993 cited in QDEH 1994).

The use of macrobenthic organisms to assess ecosystem health in Port Curtis is in its infancy. Indeed a recent comprehensive review of marine resources in the Port Curtis region (QDEH 1994) serves to highlight the paucity of information available. The review emphasises the fact that the diversity of aquatic invertebrate fauna and the complexity of their interactions with the marine ecosystem of Port Curtis is not well known. Moreover the review notes that while some species of economic value such as crustaceans and corals have received limited attention, the biology and key habitats for most species is unknown.

Of the few macrobenthic monitoring programmes that have been conducted in Port Curtis to date most, quite understandably, have been directed towards limited geographical regions where assessments of localised effects of specific port developments have been the pre-eminent objective (eg maintenance dredging of berthing pockets at the Clinton Coal wharf, dredge spoil dumping in the outer harbour, land reclamation at Auckland Point, trade waste discharges at Fishermans Landing and industrial developments in the Targinie area of the Narrows) (WBM 1991; WBM 1993a; WBM 1996; SKM 1999; Small *et al.* 2001). Other studies, most notably a survey to determine the status and distribution of exotic marine organisms within the Port, have considered much wider geographical areas (Lewis *et al.* 2001). Unfortunately such studies have been largely qualitative and have principally targeted marine organisms occurring in the immediate vicinity of shipping wharfs, shipping channels and spoil grounds.

Current macrobenthic sampling programme

In 1993, the Gladstone Port Authority (GPA) commissioned the consultants WBM Oceanics to design a long-term macrobenthic monitoring programme for Port Curtis. The aims of this study were to quantitatively assess whether current or future anthropogenic activities significantly impact fauna and the Port Curtis ecosystem (WBM 1993b cited in Small *et al.* 2001). To achieve these aims GPA established 16 sampling stations within the confines of Port Curtis during 1995. A further 14 stations were established by Southern Pacific Petroleum (SPP) between November 1995 and November 2000.

Ten replicate grab samples have been taken from each of the 30 Port Curtis stations on an annual basis (during November) since their establishment. Additional sampling at the

16 GPA stations during April each year has resulted in a total complement of 460 grab samples being collected from Port Curtis in most recent calendar years.

All samples collected were sieved on a 0.1mm mesh, and the fauna retained, sorted, identified and enumerated to the highest taxonomic level (generally species). As of November 2001, more than 2500 grabs had been sorted yielding some 297,049 individuals and 714 macro invertebrate species. The most common species collected were Gastropods (marine snails, 252 species), Polychaetes (marine worms, 132 species), Crustaceans (crabs, prawns etc., 121 species), followed by Bivalves (clams, scallops etc., 118 species) and other smaller taxa (90 species).

Statistical analysis of the faunal data has for the most part been restricted to an assessment of seasonal and inter-annual variations in faunal diversity, richness and abundance. Some effort has also been directed towards assessing the significance of sediment structure in relation to inter-site variations in faunal composition.

Results presented in Small *et al.* (2001) shows that there are strong relationships between sediment structure and faunal composition. Species richness and total species abundances for example increase as sediments change from fine mud to coarse sand. The study also notes that seasonal and inter-annual variations in community composition are small relative to inter-station differences. Unfortunately the study fails to provide any empirical evidence for linkages in community responses to man-induced impacts. Moreover, the speculative conclusions presented reinforce the notion that the combined GPA/SPP survey design, as it currently stands, does not adequately address the key aims of the programme eg 'Differences in richness were detected at both reference and sentinel sites throughout the five years of sampling, suggesting that this is not related to anthropogenic activities at sentinel sites, but to some natural condition (such as climatic variability). Total abundances declined only at one site, possibly as a result of some natural condition (such as climatic variability)'. In other words, it cannot be said with any degree of confidence that apparent temporal changes in macrobenthic community structure are related to anything tangible. Indeed, all that can be said of the current sampling programme is that some key parameters changed over time, and that some site differences were apparent.

One of the main impediments to determining causal links between benthic community structure and man-made impacts within Port Curtis is the absence of any chemical data for sediments from which the samples were taken. Contaminants such as heavy metals and organics are widely documented as having profound effects on benthic infauna and epifauna, yet no sediment assays appear to have been undertaken during the course of these studies. Less serious omissions during data collection include the absence of grab depth and weight records. Both of these parameters can influence sample composition and should be accounted for in any analysis (usually as covariates).

In principle it should be possible to measure the magnitude and persistence of most anthropogenic impacts in coastal waters if enough sampling effort is directed towards the source of the impact. Because the study aims for the current macrobenthic programme are poorly defined there appears to be little justification for the selection of sampling locations, the level of replication or the periodicity of sampling. For whatever reasons, it is apparent that too great an emphasis has been directed towards increasing the precision of the means of diversity indices (ie Shannon-Weiner) at the expense of globally assessing the benthic community structure of Port Curtis. Given the labour intensive nature of this work, it is suggested that effort would be better directed to less frequent collections of data from a much wider range of habitats in Port Curtis. To this end, it is recommended that the established GPA/SPP macrobenthic monitoring design be modified.

Proposed macrobenthic sampling programme

While several options are available in devising a new sampling scheme, the *modus operandi* is that more stations, in addition to those 30 currently surveyed, are sampled over a much wider geographical area. By so doing, the likelihood of sampling a much wider range of habitat types and associated benthic communities is increased. The option detailed in this paper represents the first step towards a refined monitoring strategy. It is principally exploratory in nature, and entails more efficient use of the recurrent sampling cost/effort. In essence it involves fixing an additional 135 stations in a grid array across the port (Fig. 2). Two different spatial resolutions have been utilised in this option in an effort to better direct sampling effort towards the area of principal interest (namely the inner harbour). Sampling stations in the inner harbour have therefore been set at 1.5km intervals, while those in the oceanic outer harbour have been set at 3.0km intervals.

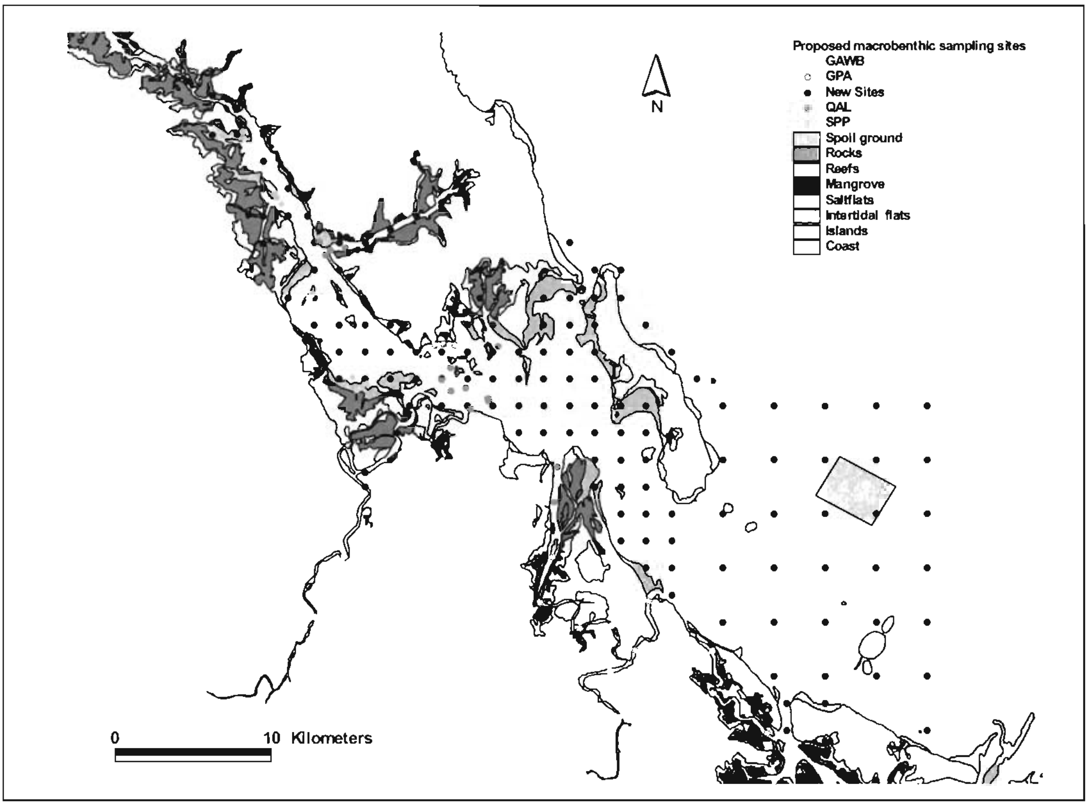

Fig. 2. Map of Port Curtis showing the locations of established and proposed macrobenthic sampling stations.

In the proposed 'snap-shot' survey, three grabs would be taken at each station but only one of these would be sorted and all taxa enumerated - the other two would be archived indefinitely. The archiving of material, while less than optimal, reflects both fiscal constraints and the need to maximise the spatial coverage of Port Curtis. Sediment sub-samples would be retained from each grab and frozen for subsequent physical/chemical analysis. This strategy should ensure some explanation of observed community differences, and where necessary the bank of unsorted samples will provide *post hoc* options for increases in statistical power. As the sampling design involves a reduction in the total number of grabs processed to species level (from 460 to 165), the burden of sorting taxa from the samples may be relaxed, nevertheless the trade-off will probably involve an increase in time spent identifying the many new species that will undoubtedly be collected.

Benefits associated with a revised sampling scheme

The benefits for initiating a wider geographical sampling strategy are considerable and include: 1) the generation of a high resolution (1.5 - 3km) map of benthic community structures in Port Curtis that can be incorporated in GIS layers, 2) a map of chemical contaminant distributions in Port Curtis, potentially identifying "hot spots" of environmental concern, 3) a means of identifying exotic incursions and mapping their spread, 4) a distributional dataset that is essential for determining trophic relationships to demersal fish, and identifying their critical habitats, 5) a base component for developing energy flow (productivity) models within the port, 6) a basis for assessing the distribution and relative abundances of rare threatened and endangered species, and 7) a baseline dataset that will provide pre-impact information in close proximity to any future developments within the port boundaries. Few, if any, of these benefits can be realised if the established sampling design is continued.

While it is practically inconceivable that any one monitoring programme would be capable of addressing the large suite of issues raised by stakeholder groups, there is an extensive research literature that suggests many of the principal areas of concern can be adequately examined using benthic data. Macrobenthic community analyses have proven to be useful in assessing the environmental impacts of coastal discharges (Anderlini and Wear 1992; Ashton and Richardson 1995), chemical contamination of sediments (Coleman 1993; Guns *et al.* 1999), commercial dredging (Jarho *et al.* 1996), sludge dumping (Johnson and Frid 1995) trawling (Currie and Parry 1996; Hill *et al.* 1999; Collie *et al.* 2000), oil exploration (Gray *et al.* 1990; Kingston 1995), and introduced marine pests (Currie *et al.* 1999; Cohen *et al.* 2000). Nevertheless, it cannot be overstated that the proposed pilot survey design is primarily directed towards establishing an ongoing holistic appraisal of benthic community structure and environmental health within the port; endpoints which appear to concur with the broader expectations of stakeholders. The need for complimentary studies will always remain particularly where it is suspected that an impact may be occurring at scales of less than 1.5km in the inner harbour. Of course this issue may be resolved through the application of higher resolution sampling arrays.

Practical considerations

Historical data

Because all 30 established stations would be re-sampled in any revised scheme, the historical data can be incorporated in all subsequent benthic analysis. This will ensure that the accumulated knowledge of benthic community variations at these stations (and associated sampling costs and effort) will not be lost. The integration may involve a randomisation procedure to extract an equal number of grabs/station from both the historical and proposed stations. Alternatively, depending on the number of discrete communities identified in any spatial analysis, data may be pulled across ten of the proposed stations and directly compared with the historical data, therein avoiding any scaling problems. Seasonal and inter-annual variations in community structure at the historical sampling stations should provide a valuable source of reference for assessing the significance of any future changes detected at the proposed sampling stations.

The historical data has the capacity to determine spatial dependency and covariation at the micro-scale fairly well, and some capacity to estimate the broad scale picture, but building a credible picture of the meso-scale spatial variation will require data from more than one grab per proposed station. It is at present very unclear that the proposed 1.5km gap between sample points in the estuary is either too wide or even too close in some parts of the range. Enumeration and analysis of archived samples (2 grabs per station) should provide data necessary for assessing the validity of the spatial resolution.

Analysis

Many marine researchers have enthusiastically adopted multidimensional scaling (MDS) in recent years because of its proven sensitivity in identifying benthic community responses to a wide suite of environmental perturbations (Clarke 1993). One advantage of the technique lays in its robustness for providing consistent ordinations irrespective of the level of taxonomic discrimination or sample replication applied. MDS techniques have also proven useful in investigating linkages between community patterns and environmental data (eg organic loads and heavy metal concentrations). While it is envisaged that MDS techniques will be used to define the spatial extent of benthic communities in Port Curtis, it is likely that several other complimentary techniques will be applied to the exploratory whole-of-port dataset. These may include principal component analysis (PCA), analysis of variance (ANOVA), and a range of spatial interpolation techniques, such as inverse distance weighting and Kriging.

Taxonomic resolution

The identification of all organisms in a community to species level is a major time and cost constraint. Yet many recent studies have suggested that identification of benthic material to taxonomic levels higher than species (e.g. family or phylum) may result in biological data that provides a sensitive test for the presence of environmental impacts (Gray *et al.* 1990; Warwick 1993). Researchers in other habitats have for some years now grouped species into ecologically similar units (functional groups) and some freshwater researchers have demonstrated that higher taxonomic groups have less natural variability and may be more sensitive as ecological indicators (Frost *et al.* 1992).

While there are clearly opportunities to modify the way samples from Port Curtis are processed in the future, it is advised that all samples initially collected in any revised survey are identified to species. This is principally because very little is known about the benthic fauna of the region, and the chances of collecting hitherto undescribed species is high. In the first instance sampling effort should be directed towards mapping the distribution and relative abundances of macrobenthic species in Port Curtis. However the costs and relative benefits of this process should be reviewed on a regular basis. Such reviews could involve assessments of randomised cumulative species curves for sampling effort and or the statistical power to detect future change at different taxonomic levels.

Accidental impacts

The logistics of sampling a pollution event generally require that a series of samples are collected over a time period spanning the course of the event. However many environmental impacts, including oil spills and exotic species introductions, are accidental. By their very nature such accidents are unpredictable in space and time, and it is unusual to have a time series of data prior to the impact. This precludes most 'before-after' assessment designs, which are widely regarded as the most powerful and rigorous means of assessing effects (Green 1979; Stewart-Oaten *et al.* 1986; Underwood 1991). Clearly one of the major benefits of the proposed sampling design will be the provision of before-impact data less than 1.5km from any potential accident within the inner harbour of Port Curtis. The grid design should facilitate unambiguous evaluation of the magnitude, extent and persistence of most catastrophic impacts.

Sampling frequency

Natural temporal changes to ecosystems are essentially unpredictable because of undocumented natural cycles of long or unknown periodicity (Gray and Christie 1983). These cyclical changes and random between-year variation make long-term human change in benthic communities difficult to detect. Unfortunately data is often inadequate to determine whether any particular ecological change is, in fact, directional rather than an unusual random fluctuation or part of a cyclical change. Accumulated knowledge of long-term changes in marine benthic community structure highlights the need for monitoring to occur at appropriate spatial and temporal scales.

Although several significant changes to the Port Curtis coastline have occurred since European settlement the contributions of such changes to benthic community structure are difficult to assess. Like many estuaries with urbanised catchments, Port Curtis receives pollution from a wide range of sources including urban and industrial developments, commercial and recreational shipping and rural agriculture. While some impacts (eg introductions of exotic marine organisms) are probably contributing to irreversible changes to the ecology of the Port, the relative significance of other man-made impacts (eg fishing pressure and the growth of tourism) is unclear. In addition, many natural temporal changes in community structure may be contributing to long-term change, although they remain unmeasured.

Since many natural cycles, including recruitment events, patterns of migration, sea temperature and rainfall, vary annually it is desired that any revised macrobenthic sampling sites in Port Curtis are monitored at least annually. Identification of correlations between these variables and changes in benthic communities should facilitate identification of the likely causes of change. Annual sampling should also ensure that significant changes are identified quickly.

Acknowledgements

A number of staff members at Central Queensland University's Centre for Environmental Management have assisted in the development of this project. In particular I would like to thank Samantha Fox for identifying and synthesising key stakeholder aims and objectives. I am also most grateful to Alistair Melzer for facilitating this research and Kirsty Small for providing technical support. This project funded by the Co-operative Research Centre for Coastal Zone, Estuary and Waterway Management.

References

Anderlini, V.C., and Wear, R.G. (1992). The effects of sewage and natural seasonal disturbances on benthic macrofaunal communities in Fitzroy Bay, Wellington, New Zealand. *Marine Pollution Bulletin* **24**, 21-26.

Ashton, P.H., and Richardson, B.J. (1995). Biological monitoring of the marine ocean outfall at Black Rock, Victoria, Australia. *Marine Pollution Bulletin* **31**, 334-340.

Clarke, K.R. (1993). Non-parametric multivariate analysis of changes in community structure. *Australian Journal of Ecology* **18**, 117-143.

Cohen, B.F., Currie, D.R., and McArthur, M.A. (2000). Epibenthic community structure in Port Phillip Bay, Victoria, Australia. *Marine and Freshwater Research* **51**, 689-702.

Coleman, N. (1993). The macrobenthos of Corio Bay. Environment Protection Authority. SRS 91/010, Melbourne, Australia.

Collie J.S., Hall, S.J., Kaiser, M.J., and Poiner, I.R (2000). A quantitative analysis of fishing impacts on shelf-sea benthos. *Journal of Animal Ecology* **69**, 785-798.

Currie, D.R., and Parry, G.D. (1996). The effects of scallop dredging on a soft-sediment community: a large scale experimental study. *Marine Ecology Progress Series* **134**, 131-150.

Currie, D.R., McArthur, M.A., and Cohen, B.F. (1999). Exotic marine pests in the port of Geelong, Victoria. pp. 227-246. In: Hewitt, C.L., Campbell, M.L., Thresher, R.E. and Martin, R.B. (eds.). Marine Biological Invasions of Port Phillip Bay, Victoria. Centre for Research on Introduced Marine Pests. Technical Report 20. CSIRO Marine Research, Hobart. 344 pp.

Frost, T.M., Carpenter, S.R., and Kratz, T.R. (1992). Choosing ecological indicators: effects of taxonomic aggregation on sensitivity to stress and natural variability. In: D.H. McKenzie, D.E. Hyatt and V.J. McDonald (eds) Ecological Indicators, Vol. 1. Applied Science, 810pp.

GBRMPA (1998). Great Barrier Reef Marine Park – Mackay Capricorn Section zoning information. Great Barrier Reef Marine Park Authority, Townsville, Australia

GBRMPA (1999). Rodds Bay Dugong Sanctuary – 2nd edn. Brochure produced by the Great Barrier Reef Marine Park Authority, Townsville, Australia.

Gray, J.S., and Christie, H. (1983). Predicting long-term changes in marine benthic communities. *Marine Ecology Progress Series* **13**, 87-94.

Gray, J.S., Clarke, K.R., Warwick, R.M., and Hobbs, G. (1990). Detection of initial effects of pollution on marine benthos: an example of the Ekofisk and Eldfisk oilfields, North Sea. *Marine Ecology Progress Series* **66**, 285-299.

Green, R.H. (1997). Sampling design and statistical methods for environmental biologists. Wiley, New York, NY.

Guns, M., Van Hoeyweghen, P., Vyncke, W., and Hillewaert, H. (1999). Trace metals in selected benthic invertebrates from Belgian coastal waters (1981-1996). *Marine Pollution Bulletin* **38**, 1184-1193.

Hill, A.S., Veale, L.O., Pennington, D., Whyte, S.G., Brand, A.R., and Hartnoll, R.G. (1999). Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Estuarine, Coastal and Shelf Science* **48**, 739-750.

Johnson, L.J., and Frid, C.L.J. (1995). The Recovery of benthic communities along the County Durham coast after cessation of colliery spoil dumping. *Marine Pollution Bulletin* **30**, 215-220.

Jarho, P., Urtti, A., Jarvinen, K., Pate, D.W., Jarvinen, T., Kenny, A.J., and Rees H.L. (1996). The effects of marine gravel extraction on the macrobenthos: results 2 years post-dredging. *Marine Pollution Bulletin* **32**, 615-622.

Kingston, P.F., Dixon, I.M.T., Hamilton, S., and Moore, D.C.(1995). The Impact of the Braer oil spill on the macrobenthic infauna of the sediments off the Shetland Islands. *Marine Pollution Bulletin* **7**, 445-459.

Lewis, S., Hewitt, C., and Melzer, A. (2001). Port survey for introduced marine species – Port Curtis. Centre for Environmental Management. Central Queensland University. Gladstone, Australia.

Poore, G. C. B., and Kudenov, J. D., (1978). Benthos around an outfall of the Werribee sewage-treatment farm, Port Phillip Bay, Victoria. *Australian Journal of Marine and Freshwater Research* **29**, 157-67.

QDEH (1993). Gladstone Port Authority Port Curtis monitoring proposal. Queensland Department of Environment and Heritage, Curtis coast study, (unpubl.).

QDEH (1994). Curtis coast study resource report. Queensland Department of Environment and Heritage. Rockhampton, Australia.

SKM (1999). Stuart Oil Shale Project Stage 2. Draft environmental impact statement. Report prepared for Southern Pacific Petroleum by Sinclair Knight Merz. Brisbane, Australia.

Small, K., Johnson, R., Lewis, S., Campbell, J., Shearer, D., Boundy, K., and Melzer, A. (2001). Port Curtis macrobenthic monitoring programme. Report prepared for Gladstone Port Authority by the Centre for Environmental Management. Central Queensland University. Gladstone, Australia.

Stewart-Oaten, A., Murdoch, W.W., and Parker, K.R. (1986). Environmental impact assessment: Pseudoreplication in time? *Ecology* **67**, 929-940.

Underwood, A.J. (1991). Beyond BACI: Experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* **42**, 365-389.

Warwick, R.M. (1993). Environmental impact studies on marine communities: pragmatical considerations. *Australian Journal of Ecology* **18**, 63-80.

WBM (1991). Fishermans Landing, trade waste outfall benthic monitoring report 1990-1991. Draft. Queensland Department of Environment and Heritage. Winders, Barlow and Morrison Oceanics, Spring Hill, Australia.

WBM (1993a). Monitoring of dredge spoil, Gladstone. Report prepared for Gladstone Port Authority by Winders, Barlow and Morrison Oceanics, Spring Hill, Australia.

WBM (1993b). Proposed sample design for benthic monitoring programme of Gladstone Harbour. Report prepared for Gladstone Port Authority by Winders, Barlow and Morrison Oceanics, Spring Hill, Australia.

WBM (1996). Monitoring of Gladstone dredged material placement area. Report prepared for Gladstone Port Authority by Winders, Barlow and Morrison Oceanics, Spring Hill, Australia.