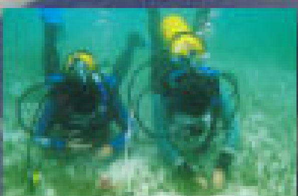
HEALTHY WATERWAYS

Because we're all in the same boat

Moreton Bay Study

A Scientific Basis for the Healthy Waterways Campaign



William C. Dennison and Eva G. Abal

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Preface

The purpose of "Moreton Bay Study: A Scientific Basis for the Healthy Waterways Campaign" is to provide the scientific data, interpretation and rationale for developing the water quality strategy used in the Healthy Waterways Campaign. A companion book, The Crew Members Guide to the Health of our Waterways, provides both an introduction to the Healthy Waterways Campaign and a summary of the strategic initiatives by stakeholders, including councils, state agencies and industry. Scientific data for the Moreton Bay Study was compiled from the 17 component tasks of Stage 2 of the Moreton Bay Study. The final reports for each of these tasks provide a detailed explanation of methods, data obtained, interpretation and conclusions. This book is not designed to replace, rather to augment, the 17 component task reports, and provide an overview of study results using an information-rich, jargon-free, communication-based format with a) text, b) data, c) diagrams, d) maps and e) photos. This approach was pioneered by Karen Holloway in the Stage 2 Interim Scientific Report. The vast majority of the data used in the book has been directly obtained from the Stage 2 final reports. However, some data, appropriately referenced, has been included from other sources to provide a more complete treatment.

The authors would like to thank all those researchers who have contributed their extraordinary efforts to complete the scientific tasks on time and on budget. The enthusiastic contributions from the various post-graduate students and research assistants were essential to the scientific achievements summarised in this book. In particular, the University of Queensland Marine Botany Group spent enough time immersed in the water and then in the data to generate a level of understanding necessary to form the essence of this book. Everyone involved in the Stage 2 tasks of the Moreton Bay Study learned that an incredible amount can be accomplished in a short period of time when a concentrated effort is made by committed individuals working collaboratively.

The book and the study as a whole would not have been possible without the continued support of Prof. Paul Greenfield, Scientific Advisory Group Chair, and the Study Management Team, in particular Barry Ball, Study Director, Trevor Lloyd, Study Manager and Peter McMahon, Water Quality Strategy Coordinator. Each of the task leaders and many of the task participants reviewed and contributed data and assisted with the interpretations included in this book. This report represents the combined efforts of the scientists in the component tasks. The indicated authorship represents the responsibility of representing and interpreting the data from these tasks to provide this comprehensive treatment. A major role in the format used in this report is that of the scientific communicator. This role involved developing the conclusions (section headings), drafting text, identifying and obtaining the 181 photographs (that can say a thousand words each), creating 137 maps, 81 diagrams, 125 figures and 26 tables in standardised formats. Jane Rogers was the scientific communicator, ably assisted by Catherine Collier and Caroline Gaus. Scientific review of specific sections was provided by Simon Bell, Des Connell, Simon Costanzo, Brad Eyre, Cindy Heil, Adrian Jones, Mark O'Donohue, Judy O'Neil, John Parslow, Graham Skyring and Bob You. In addition, editorial assistance was provided by Ros Murrell with help from Joelle Prange and Andrew Watkinson. The staff from Portfolio, in particular Leonie Witten, Myree Tydings, and Alyson Mc Culloch were extremely helpful in achieving our vision of this style of report.

WC Dennison
EG Abal Brisbane 1999

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Foreword

Recognition that Moreton Bay and its rivers - the Brisbane, Logan, Pine and Caboolture Rivers as well as other smaller streams - represent a defining characteristic of south-east Queensland has grown gradually over the past two decades. In this aspect, the region mirrors much of Australia. Australians have traditionally defined themselves by the vast landmass and associated waterways. Water, in all its aspects, is far and away the greatest influence on modern Australia, with around 90% of the population living on or near the coast. However, in south east Queensland the mud-flats of Moreton Bay, the brown colour of the Brisbane River and the lack of amenity or access along the river banks have pushed us to explore the surfing beaches to the north and south of Brisbane - the river and the Bay have been poor cousins.

It is difficult to identify just when a change in attitude took place. Recognition that Moreton and Stradbroke Islands, which form the eastern boundary of the Bay, and the surrounding water were 'special' came early; recognition of the potential of the western foreshore came next; property adjacent to the Brisbane River gained in value once memories of the 1974 flood faded; Brisbanites learned that you could eat out-of-doors without major health problems and this led to inner city river development; the current city administration under Lord Mayor Cr. Jim Soorley provided a rapid transport system on the river. Just as Moreton Bay and its estuaries helped define the indigenous peoples who lived in the region prior to white settlement, the increased recognition of the role and significance of the waterways by today's inhabitants has started, I believe, a process to accord the Bay and its rivers their appropriate place in our thinking.

If interest is increasing why, then, are there concerns?

The concerns result from one basic fact, namely that an increasing number of people wish to live, work and play here. As a result, the waterways are under threat because of the entry of excessive amounts of polluting chemicals and because of physical changes to the river systems. No single cause can explain the deteriorating water quality found in some regions of the Bay and associated rivers. The nutrients, nitrogen and phosphorus, enter from sewage treatment plant discharges and in stormwater runoff from both urban and agricultural areas; sediment is washed into the rivers and Bay also from urban and agricultural areas; storage dams up-stream and dredging downsteam have dramatically changed the flushing and flow regimes in the rivers. There are tell-tale indications, particularly in the western regions of the Bay and in regions of the estuaries that not all is well. In addition, the increased interest in and use of the waterways means that the community expectations are that the quality of the waterways should not just be stabilized but be improved.

In 1994, seven local councils (now six as a result of amalgamation; Brisbane City, Caboolture, Ipswich, Pine River, Redcliffe and Redlands) together with the Queensland Government bid for and were awarded matching funds from the National Landcare program to initiate an integrated study of Moreton Bay and three of its estuaries - the Brisbane, Pine and Caboolture Rivers. The objective was to develop an integrated strategy for improving water quality in the study region, with a particular emphasis on the Bay and estuarine portions of the three rivers and with greater emphasis being directed to the impact of point sources.

The Stage 2 scientific tasks, the results of which provided key inputs to the strategy, are outlined in this book. Stage 1, which has been reported earlier, compiled and assessed available information on the waterways. Stage 3, which is now underway, extends the study into the freshwater regions of the catchment as well as to the immediate north and south of the Bay. In addition, Stage 3 has a much greater focus on non-point sources.

A number of key principles influenced the Stage 2 scientific studies. Firstly, it was agreed by all stakeholders that Stage 2 should focus on developing a system-wide understanding of Moreton Bay and the estuarine regions of the waterways, particularly with respect to nutrients and sediments, rather than focus on specific issues in areas adjoining different councils. Secondly, a conceptual model of the ecosystem was developed at the beginning of the study and regularly modified. This conceptual model, which is depicted at various points in this book, was important in guiding which studies should be undertaken and in conveying technical information to the councils, community groups and other stakeholders. Thirdly, peer review, using both local and remote experts, was employed at key stages of the process. This was important in ensuring both the relevance and quality of the individual tasks. Finally, and most importantly, significant interactions occurred with all stakeholders in ensuring that the studies to be carried out were addressing the agreed priorities, that the level of resourcing of the individual tasks was compatible with both community perceptions and scientific rigour, and so that progress could be regularly reported.

Resource and time constraints limited the scope of the Stage 2 tasks. With the stakeholders having agreed that the primary goal was to gain an overall system understanding of the sources, fate and role of nutrients and sediments, the priority tasks were identified. This meant that studies on issues such as the role of dams, environmental flows and fish/fauna populations had to be deferred to a later date. Some of these have been picked up in Stage 3. In addition, the geographic focus of Stage 2 was restricted to the estuarine regions of the rivers and the bay itself. Stage 3 extends coverage to the whole catchment.

The most encouraging outcome from the Stage 2 scientific tasks has been the willingness of councils to make investments and to take other actions on the basis of the results found from the study. This was facilitated by the on-going involvement of all stakeholders throughout the scientific tasks.

There are many people and groups who have contributed to Stage 2 of the study and to this book - too many to name. I would like to pay tribute to the six councils who, in a leap of faith, agreed that an overall approach was required (rather than a focus on their own special issues) and that high quality but relevant scientific investigations were required. Finally, I would like to acknowledge the financial support from the Queensland Government and from the National Landcare and Rivercare programs.

I hope you enjoy reading this book. It does not answer every question about Moreton Bay and its rivers. For the first time, however, we have an understanding of how the overall system works, how an action in one part of a river may impact activities elsewhere in the river or in the Bay itself. There is much more to be done, but at least we have made a beginning.

Paul F Greenfield
Chair, Scientific Advisory Group

Table of Conclusions

CHAPTER 1

Conclusions and Recommendations

Overall Conclusion:

Environmental degradation evident in river estuaries and western portions of Moreton Bay: Rich and diverse ecosystems of eastern and northern Moreton Bay are essentially intact.

Overall Recommendations:

RESTORE degraded areas and PROTECT intact areas.

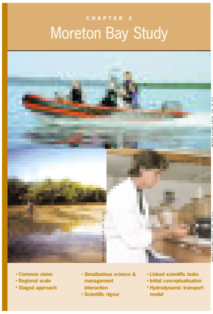
Strategy: Reduce nutrient loads (particularly nitrogen) by sewage treatment upgrades. Reduce sediment and nutrient loads with stormwater controls, riparian revegetation, and catchment management.

Research: Investigate causes and nature of environmental degradation, as well as investigating restoration techniques.

Monitoring: Assess ecological outcomes of nutrient removal from sewage, stormwater controls and other management actions.

This book starts with the overall Conclusions and Recommendations (Chapter 1), with the supporting information provided in the subsequent chapters (Chapters 2-16). The conclusions express the current understanding of Moreton Bay and estuarine processes and are provided as the section headings within each chapter. Each section contains an elaboration of the conclusion (heading), using text, data, diagrams, maps and photos to establish the scientific basis for the conclusion. The actual message to be conveyed within the chapters is stated unequivocally as section headings to minimise ambiguity.

Recommendations for actions required for ongoing scientific and management practices are provided for each chapter, and these recommendations are based directly on the conclusions. An overall recommendation for each chapter is given in an active form, hence the use of verbs that begin each recommendation. In addition, specific recommendations are provided that relate to the overall management strategy required to achieve the Healthy Waterways vision, additional research required to further elucidate key issues, and future monitoring to determine the effectiveness of various management practices to maintain ecological health. Many of the recommendations have already been incorporated into various actions, but an explicit expression of these recommendations, with the conclusions upon which they are based is an important aspect of documenting the scientific basis for the Healthy Waterways campaign.



The **Moreton Bay Study** had several features that distinguish it from previous Moreton Bay research and studies conducted elsewhere. The study participants had a common or shared vision represented by the Healthy Waterways logo. The scale of the study was regional with all of Moreton Bay and its principal tributaries included, necessitating a multi-council, multi-agency, community and industry consortium. The staged or step-wise approach in the study allowed the scope of Stage 2, reported here, to be focused on Moreton Bay and its estuaries, with Stage 3 to be focused on the catchments of the whole south east Queensland region, including freshwater reaches of the rivers. The simultaneous science and management interaction provided constant feedback and allowed for outcomes to be obtained prior to the end of Stage 2. Scientific rigour was maintained through a peer review process which included expertise from all around Australia. Scientific tasks were linked both conceptually and through an ongoing scientific core group. A hydrodynamic transport model was developed as a tool to help define research questions and to simulate movement of water and particles. We will need to maintain these essential features and BUILD on this strong program for Stage 3.

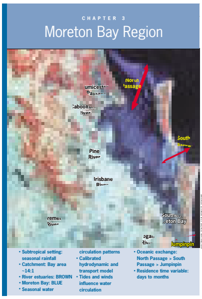
Recommendations

BUILD on strong science and management interactions using staged approach.

Strategy: Expand regional coverage to entire south east Queensland region by incorporating more local councils and relevant state government agencies to insure a comprehensive approach.

Research: Develop diverse and consistent funding sources and foster collaborative on-going research programs.

Monitoring: Incorporate Stage 2 outcomes into monitoring program.



There are several aspects of the **Moreton Bay Region** that are important in providing the contextual basis for the scientific studies. Moreton Bay has a subtropical climate with variable runoff due to seasonal, monsoonal rainfall patterns and an offshore current that reduces likelihood of upwelling events. The catchment area is roughly fourteen-fold more extensive than the area of Moreton Bay. The water colour of the river estuaries (brown) and Moreton Bay (blue) provide acronyms of characteristics of each region to help EDUCATE people about the important and unique features of the region. Water circulation patterns in Moreton Bay were predicted by the hydrodynamic model, which was calibrated by dye release studies, water drogue movements and direct measurements of water velocities at the entrances. The hydrodynamic model allowed for calculation of the contributions of each of the 3 entrances to overall flushing and provided estimates of water residence times to be made for each portion of the bay, ranging from days near the entrances to months in Bramble Bay.

Recommendations

EDUCATE community about important and unique features of SE Queensland waterways (via Healthy Waterways campaign), while insuring management actions and scientific tasks are commensurate with the strong temporal and spatial gradients in the region.

Strategy: Establish environmentally sensitive areas using water residence time estimates and flow/circulation data to predict where environmental degradation is likely to occur.

Research: Investigate factors influencing residence times, including inlet configuration, shoreline development, dredging, and environmental flows of freshwater.

Monitoring: Develop stratified monitoring program to focus on environmentally sensitive areas.

Historical Perspective provides an understanding of how we have reached the current ecological status and also provides a benchmark goal to FORMULATE management strategies. Historical data and anecdotal evidence indicates that in the past, Moreton Bay and the river estuaries were healthy ecosystems. Increased population and intensified land use has led to declines in water quality and significant ecological degradation in some portions of the Moreton Bay region. People once swam in the Brisbane River and they could see the river bottom, but now high turbidity restricts visibility. Turbidity is particularly high in the Brisbane River estuary due to tidal resuspension of fine grained sediments that enter the river from a variety of sources. The historical perspective of turbidity and overall ecological health provides a long term view that can be incorporated into our vision and planning for the future scenarios of the region.

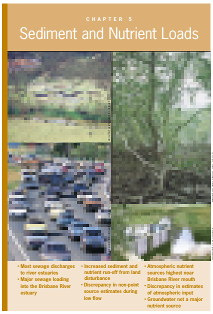
Recommendations

FORMULATE ecological health benchmarks using historical conditions in ongoing comparisons with current conditions.

Strategy: Record environmental history of Moreton Bay and waterways (as in Gregory, H, 1996 The Brisbane River Story).

Research: Investigate degradation and recovery processes to better understand causes and potential recourses to degraded conditions using various techniques to infer historical patterns (e.g. coral banding, sediment core analyses, stable isotope analysis).

Monitoring: Incorporate long view time scale in monitoring program; use of consistent techniques and sampling sites, comparisons with historical ecological health, and the development of temporally integrating ecological health indicators.



It is important to quantify the **Sediment and Nutrient Loads** that enter the waterways of the Moreton Bay region in order to FOCUS on regions of high inputs. Most sewage discharges are into the river estuaries, particularly into the Brisbane River estuary. Runoff of sediments and nutrients from catchments are increased by various land disturbances, particularly by urban development. The total amount of runoff in low flow periods was difficult to quantify due to unresolved catchment processes, but high flow estimates were relatively consistent. Atmospheric nutrient inputs were modelled, predicting a strong west-east gradient, but model estimates are appreciably lower than measurements from other regions in the world, requiring further resolution. Nutrient inputs from groundwater do not appear to be significant in the Moreton Bay region compared with the other nutrient loads.

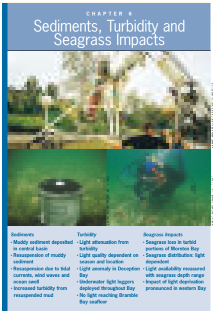
Recommendations

FOCUS on regions of known high sediment and nutrient inputs, incorporating changes in loading factors (e.g. population density changes, sewage treatment upgrades, land use changes).

Strategy: Target major sediment and nutrient inputs for load reductions; e.g. sewage treatment upgrades, urban stormwater controls.

Research: Resolve discrepancies in non point source and atmospheric loads; initiate data collection to test model predictions from diffuse sources.

Monitoring: Incorporate load monitoring into overall monitoring program; obtain data on loads, particularly before/after strategy actions undertaken.



Sediment, Turbidity and Seagrass Impacts delineates the fate and consequences of sediment loads. Fine grained particles that enter the Bay form a large region of muddy sediments with high nutrient content in the central-western Bay. In Stage 3, we need to IDENTIFY the source(s) of this mud to determine the origin of the dirt, fertiliser and sewage that comprise these fine grained sediments. Resuspension of muddy sediments due to tidal currents, wind waves and ocean swell occurs throughout the Bay, accounting for high turbidity which results in high attenuation of light. Light attenuation from resuspended mud is the major cause of reduced light availability to seagrasses, although light attenuation in Deception Bay is anomalous. Seagrasses require light for photosynthesis and light reductions reduce their depth penetration and eventually causes complete seagrass loss in some regions. Underwater light loggers confirm that Bramble Bay can no longer support seagrasses due to turbidity. Seagrass depth range can be used to infer chronic changes in light availability, and experiments indicate Moreton Bay seagrasses could also be susceptible to light deprivation events from high runoff. The link established between sediments, turbidity and associated seagrass losses is one of the key findings of the study.

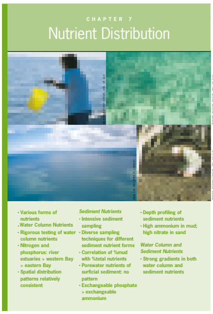
Recommendations

IDENTIFY sources and ages of sediments causing increased turbidity and associated seagrass loss so that appropriate control measures can be initiated.

Strategy: Reduce sediment runoff from urban stormwater and various catchment land uses; particularly focusing on fine-grained sediments.

Research: Resolve Deception Bay light anamoly.

Monitoring: Assess changes in turbidity using seagrass distribution and depth ranges.



In the Moreton Bay region, **Nutrient Distribution**, which includes both water column and sediment nutrients, appeared to be highly dependent on location. Concentrations of both nitrogen (N) and phosphorus (P) in the water column were much higher in the river estuaries than the western Bay, which in turn were higher than the eastern Bay. These spatial gradients were consistent in both intensive surveys conducted. Concentrations of sediment nutrients, measured with a variety of techniques, were also location dependent. The muddy sediments contained high concentrations of total N and P as well as high organic carbon and dissolved silica. In contrast, the dissolved N and P in sediment porewaters did not demonstrate large scale patterns. The exchangeable nutrients, attached to sediment particles but easily converted to dissolved porewater nutrients, were much higher for P than N. Dissolved nutrients deep within sediments were measured in sandy and muddy sediments using sediment cores. Muddy sediments contained N largely as reduced ammonium and sandy sediments contained N largely as oxidised nitrate. The strong gradients observed in both water column and sediment nutrients allow us to PRIORITISE nutrient reductions in the river estuaries and western embayments.

Recommendations

PRIORITISE nutrient reductions using the observed strong spatial and temporal gradients of nutrient distributions.

Strategy: Target nutrient reductions in river estuaries and western embayments where high water column and sediment concentrations were observed.

Research: Discern origin and fate of nutrients in sediments, particularly in muddy sediments, and investigate the interactions between sediment characteristics and nutrient content.

Monitoring: Stratify sampling efforts (higher sampling density and more frequent sampling in places/times of high variability) using Stage 2 results in order to maximise interpretative power of data collected.

Several key **Nutrient Processes** are crucial in Moreton Bay, in particular, the transformations of nitrogen (N). The conversion of dissolved N compounds to N gas by bacteria (denitrification) was measured by two techniques (acetylene blockage and sediment flux chambers) and inferred by mixing plots and flushing time relationships. These approaches indicate that the natural removal of N via denitrification is a major feature of sediments in some of the river estuaries and in portions of the Bay. The availability of nitrate appears to be the major controlling factor for denitrification. The conversion of N gas to organic N by bacteria (N fixation) measured in sediments (acetylene reduction technique) indicated particularly high rates associated with seagrasses. These high N fixation rates may sustain the continued grazing of seagrasses by dugongs and turtles in the eastern Bay. The recommendation to REDUCE nutrient loads is based on the observations from sediment flux chambers that the release of nutrients from sediments to the overlying water column appears to be 'poised' in muddy sediments. Slight changes in oxygen concentrations led to large changes in denitrification efficiency, and associated nutrient release. Any additional of organic matter loading to muddy sediments could result in higher sediment nutrient release rates.

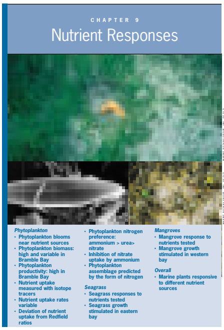
Recommendations

REDUCE nutrient loading, particularly into areas with muddy sediments, to avoid a breakdown in efficiency of ambient denitrification rates. Muddy sediments of river estuaries and western Bay 'poised' in terms of nutrient fluxes into overlying water; slight changes in nutrient loadings could result in large changes in nutrient fluxes, leading to further water quality degradation.

Strategy: Upgrade sewage treatment and stormwater controls in western Moreton Bay and river estuaries.

Research: Investigate controls of sediment nutrient fluxes; especially seasonality of denitrification; fate of fixed N in the seagrass and turtle/dugong food web.

Monitoring: Develop ecological health indicators for sediment processes; particularly sediment nutrient fluxes or other proxies for sediment denitrification efficiency.



Nutrient Responses by the major marine plant groups, phytoplankton, seagrasses and mangroves, were investigated to establish the form and amount of nutrients that had the greatest effects. Phytoplankton responded to water column nutrients. The highest phytoplankton biomass values were located in the river estuaries and western Moreton Bay. Within Moreton Bay, the highest and most variable phytoplankton biomass and also the highest productivity was in Bramble Bay. Phytoplankton nitrogen (N) uptake, measured using isotopic tracers, was influenced by the form of N: ammonium was the most preferred form of N, followed by urea, then nitrate. The phytoplankton assemblage appeared to be affected by the principal form of N: high urea availability related to high dinoflagellate abundance and high ammonium availability related to high diatom abundance. Seagrass and mangrove responses to sediment nutrients were tested with in situ fertilisation experiments. Seagrass growth was stimulated in eastern Moreton Bay, but mangrove growth was stimulated in western Moreton Bay. These results indicate that in order to LIMIT impacted zones, nutrient loading, in particular nitrogen, needs to be controlled.

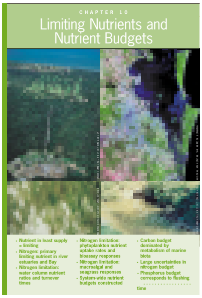
Recommendations

LIMIT impacted zones in the river estuaries and Bay by avoiding nutrient stimulation of phytoplankton growth. While there are a variety of factors controlling phytoplankton growth that have been elucidated in Stage 2 (e.g. temperature, grazing, light), nutrient loading is the factor most applicable for control.

Strategy: Oxidise reduced nitrogen in sewage treatment (e.g. nitrification) to reduce urea and ammonium discharges.

Research: Investigate phytoplankton bloom/crash cycles in western embayments; test dinoflagellate and diatom preference for various forms of dissolved nitrogen.

Monitoring: Incorporate urea assessment in water quality testing; assess Bramble Bay phytoplankton dynamics at rapid time scales.



Limiting Nutrients were investigated and **Nutrient Budgets** were constructed to identify the key processes and transformations in the cycling of elements which are important in biological systems. The delineation of nitrogen (N), rather than phosphorus (P), as the primary limiting nutrient in the river estuaries and Moreton Bay was made by comparing dissolved nutrient ratios and turnover times, phytoplankton uptake rates and bioassay responses, and macroalgal and seagrass responses. System-wide nutrient budgets identified the key role of marine biota in the budgets, particularly the carbon budget. Phosphorus export from Moreton Bay as estimated in the budget (70% of inputs) compared favourably to the amount predicted from the flushing time of the Bay, based on other studies. Large uncertainties remain unsolved in the N budget, thus the recommendation to RESOLVE discrepancies is a matter of priority.

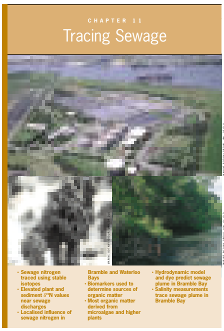
Recommendations

RESOLVE nutrient budget discrepancies as a matter of priority so that appropriate strategic and research decisions can be made.

Strategy: Target nitrogen reductions in sewage treatment upgrades, but phosphorus reductions that accompany nitrogen removal are beneficial.

Research: Determine limiting nutrient(s) in freshwater (dams and streams/rivers); test nitrogen versus phosphorus limitation in benthic microalgae.

Monitoring: Assess at regular intervals the nitrogen versus phosphorus responses of phytoplankton and benthic microalgae throughout river estuaries and Bay, particularly as nitrogen reduction strategies come on line.



Various approaches for **Tracing Sewage** were employed, including a novel stable isotope tracer method developed as a component of the study. The stable isotope tracer method provided a measure of the biological assimilation of sewage derived nitrogen using marine plants as biological indicators. This technique produced sewage plume maps that delineated consistent and separate Brisbane River versus Pine Rivers/Hays Inlet plumes in Bramble Bay. In addition, variable sewage plumes into Waterloo Bay were observed. In contrast, appreciable sewage plumes were not detected in Deception Bay or southern Moreton Bay. Biomarkers, specific compounds contained in sediment organic matter, were used to infer that little sewage organic matter was contained in Moreton Bay sediments. The restricted extent of the Brisbane River sewage plume into Moreton Bay was supported by the hydrodynamic modelling of a previous dye tracer study and by salinity measurements. The delineation of sewage plumes allows us to TARGET major nutrient sources and the regions where sewage nutrients are important.

Recommendations

TARGET efforts in clearly delineated sewage plumes and on sources contributing to sewage plumes. Clear delineation of sewage plumes established, allowing identification of sewage sources.

Strategy: Remove nitrogen from all Bramble and Waterloo Bay discharges to reduce sewage nitrogen plumes.

Research: Investigate environmental factors that control sewage plume distributions.

Monitoring: Map sewage plumes in Waterloo Bay at regular intervals to establish temporal variability patterns.

While the purpose of Stage 2 scientific tasks was not to resolve human health issues, there were several **Human Health Implications** of the various studies conducted. The high turbidity in western Moreton Bay and faecal coliform levels in the Brisbane River exceed limits for swimming. A broad scale survey of toxicants in water, sediments and biota was conducted. Water sampling in the Brisbane River identified high concentrations of dieldrin, a pesticide that was used historically. Sediment sampling also established that dieldrin levels exceeded guidelines in some sites. Strongest contamination levels were consistently found in Brisbane River sediments and biota. A bloom of a marine cyanobacterium (blue-green algae) in Deception Bay was identified as *Lyngbya*. The bloom led to severe human skin rashes as well as having ecological impacts. The cause of the *Lyngbya* bloom was hypothesised to be a result of dissolved iron derived from hydric (acid sulfate) soils. Bacterial levels and productivity were high in the Bremer River which could have implications for human health. These disparate results indicate that there is significant need to INCORPORATE toxicant, *Lyngbya* and coliform studies into Stage 3.

Recommendations

INCORPORATE toxicant, *Lyngbya* and faecal coliform issues into Stage 3, as they are issues which have arisen as a major concern in the region.

Strategy: Reduce toxicant inputs, particularly in Brisbane River. Avoid discharge from hydric soils that may stimulate *Lyngbya* blooms. Designate areas unsuitable for swimming based on turbidity and faecal coliform levels and take action to minimise these areas.

Research: Investigate a) detoxification processes by biota, particularly in contaminated areas, b) cause(s) of *Lyngbya* blooms and c) fate of infective agents derived from sewage.

Monitoring: Assess application of toxicant sampling in ecological health monitoring. Establish patterns of *Lyngbya* biomass & toxicology. Report turbidity and faecal coliform results for swimming areas.

Moreton Bay supports a rich and diverse array of plants and animals. **Moreton Bay Biota** includes plankton, benthic microalgae, macroalgae, seagrasses, mangroves and corals which provide food and habitat for many animals and it is of paramount importance to MAINTAIN this biodiversity. Phytoplankton were usually dominated by diatoms but sometimes by dinoflagellates, and zooplankton were usually dominated by copepods. The smaller forms of zooplankton, microzooplankton, appear to be the most significant grazers of phytoplankton. Microscopic plants were also found living on or near the sediment surface, and these plants (benthic microalgae) were ubiquitous throughout the Bay and common on the river banks. Moreton Bay has a diverse assemblege of macroalgae, attached to rocks, mangroves and seagrasses. Nuisance green algae were observed in both western Moreton Bay (*Ulva*) and eastern Moreton Bay (*Caulerpa*). Widespread seagrass meadows in eastern Moreton Bay are intensively grazed by dugong and turtles. Remote sensing can detect seagrass distributional patterns and revealed worm digging disturbances. The Moreton Bay shoreline and river estuaries are inhabited by mangroves, which provide an important habitat and nursery. Moreton Bay has unique coral assemblages which contain historical record of floods within the growth rings.

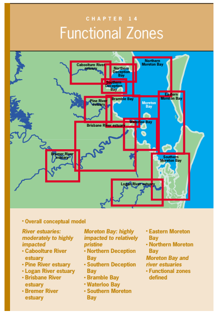
Recommendations

MAINTAIN biodiversity, critical habitats (e.g. corals, seagrasses, mangroves) and component productivity patterns (e.g. avoid proliferation of undesirable species to exclusion of diverse native biota).

Strategy: Recognise important features of Moreton Bay biota; sensitivity to perturbation, long term changes, and habitat/nursery values.

Research: Investigate effects of sediments, nutrients and toxicants on higher trophic levels; specifically, sea bird contribution to nutrient cycling, macroinvertebrate interactions with sediment processes, causes of turtle tumours & mortality, and fisheries catch & river flow relationships.

Monitoring: Repeat and revise habitat mapping at regular intervals; assess relative abundance and diversity of various biota.



The study region can be subdivided into **Functional Zones**, geographical entities with common structural and functional characteristics. A functional zone was created for each of the river estuaries, which were moderately to highly impacted. Moreton Bay was subdivided into seven functional zones; four in the subembayments. The Moreton Bay functional zones ranged from highly impacted to relatively pristine. The conceptual diagrams of these functional zones attempt to SYNTHESISE the scientific understanding of the key inputs and processes, impacts and biotic features.

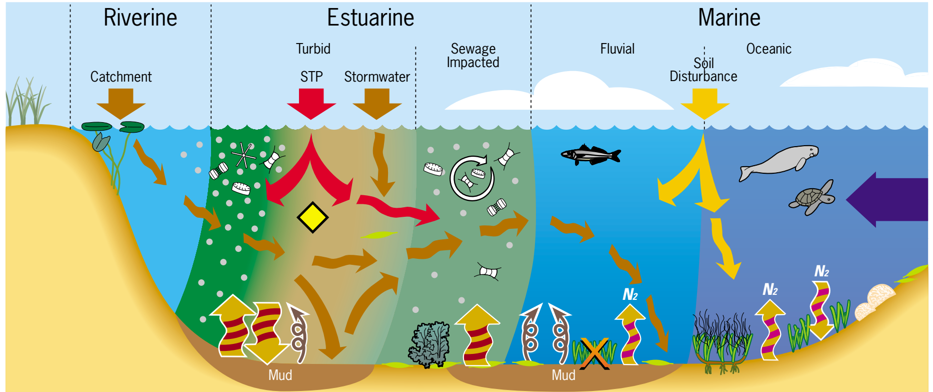
Recommendations

SYNTHESISE scientific results and community-derived environmental values into conceptualisations that depict major functional zones of the region.

Strategy: Standardise report card process using functional zone and make annual presentations of report card (e.g. River Festival Symposium).

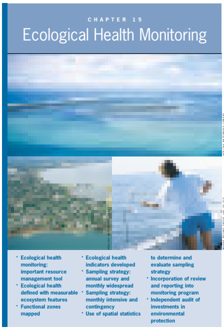
Research: Develop quantification techniques for functional zone mapping using spatial statistical approaches and techniques.

Monitoring: Focus monitoring efforts at boundaries of functional zones to determine whether zones are contracting or expanding.



Conceptual model for Moreton region depicting the major processes and impacts on the riverine, estuarine and marine functional zones. Refer to Symbol Glossary for definition of process, imput and biota symbols.

Three dimensional conceptual model for the river estuaries and Moreton Bay depicting major processes and impacts. Refer to Symbol Glossary for definition of process, input and biota symbols.



In order to assess the effectiveness of management efforts in environmental protection, a **Monitoring** program that targets ecosystem responses to natural and anthropogenic inputs has been established. This ecological health monitoring program is an important resource for independent audit of the investments in environmental protection. Measurable ecosystem features are defined in terms of key processes, zones of anthropogenic impact and critical habitats. Functional zones are mapped using ecological health indicators, which include water quality, phytoplankton bioassays, seagrass depth range and sewage plume mapping. The sampling strategy developed includes variable time and space scales, using spatial statistics to determine and assess the effectiveness of the sampling strategy. Review and reporting was incorporated into the monitoring program so that results are rigorously scrutinised and delivered in clear and informative accounts to the stakeholders and the community. The ecological health monitoring program will be used to EVALUATE the effectiveness of the substantial stakeholder investment in sewage treatment upgrades and stormwater controls—management actions arising from Stage 2 of the Moreton Bay Study.

Recommendations

EVALUATE effectiveness of various management actions by establishing an Ecological Health Monitoring Program.

Strategy: Expand monitoring to include broader Stage 3 study area and freshwater monitoring components.

Research: Develop new ecological health indicators that will provide cost-effective and ecologically meaningful information.

Monitoring: Initiate river estuary and Moreton Bay monitoring and liase with community and catchment groups in order to incorporate stream and tributary monitoring in the future.

Putting the **Moreton Bay Study in Perspective** allows results from previous studies in other parts of the world to be compared and contrasted. Australian estuaries have some fundamental differences from Northern Hemisphere estuaries, largely due to the low and/or variable rainfall patterns in Australia. Australian estuaries are relatively poorly studied, with less than 50 of the 700+ receiving any research or monitoring attention. The Australian embayment intensively studied just prior to the Moreton Bay Study is Port Phillip Bay, near another major population centre (Melbourne). Hervey Bay, a similar ecosystem to Moreton Bay has significant ecological issues, but without the large adjacent urban population. A brief comparison with Chesapeake Bay in the U.S. is made, since Chesapeake Bay represents a benchmark estuary due to its unique catchment area to bay volume ratio and its well studied, but degraded condition. Stage 3 of the Moreton Bay Study will BROADEN its scope and membership, with a catchment focus, rather than the Bay & estuary focus presented here. The Moreton Bay Study is attempting to respond to the coastal management challenge of learning to cope with increasing population pressures without irreversibly damaging the rivers, estuaries and coastal oceans. It is hoped that this book will provide some insights useful in other areas (e.g., inshore Great Barrier Reef) in how to respond to the coastal management challenge.

Recommendations

BROADEN scope of Moreton Bay Study by developing linkages with other regions, comparing results, techniques, approaches and outcomes. Explore potential widespread application of the various approaches and techniques developed in the Moreton Bay Study.

Strategy: Invest in environmental protection NOW; as other studies demonstrate that delays in funding for environmental protection ultimately end up with higher economic and ecological costs.

Research: Foster a sustained research program involving post-graduate education, to address unresolved issues, build necessary research infrastructure, and train the next generation of resource managers and scientists.

Monitoring: Compare status and trends of ecological health in response to management actions in Moreton Bay to the status and trends of ecological health in response to various alternative management actions in other regions.

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CHAPTER 2

Moreton Bay Study

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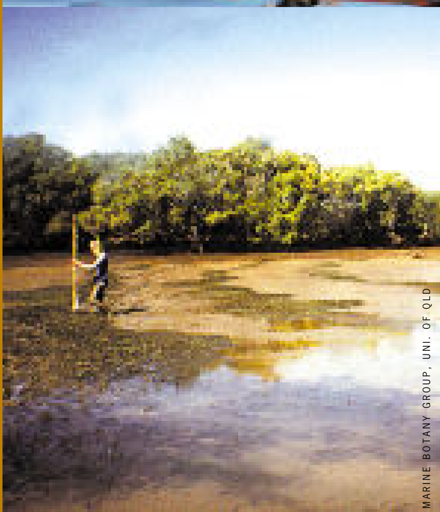

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- Common vision
- Regional scale
- Staged approach
- Simultaneous science and management
- Scientific rigour
- Linked scientific tasks
- Initial conceptualisation
- Hydrodynamic transport model

Common vision

The most crucial element in developing a successful strategy and integrated research/management program is the shared or common vision. This common vision in the development of an integrated strategy used the best possible scientific knowledge in order to achieve a sustainable commitment to improving water quality and ecological health. The partnership between local councils and state government agencies was established early in the Study. The Study was initiated in 1994 by six local councils - Brisbane City, Pine Rivers Shire, Caboolture Shire, Ipswich City, Redlands Shire and Redcliffe City, in association with Queensland State Department of Environment and Heritage (now Queensland Environmental Protection Agency) and Queensland Department of Natural Resources. The National Landcare Program (Natural Heritage Trust) also provided funding. This Study is the first integrated approach to the issues of Moreton Bay and its catchments.

Features of the study:

- has **multiple jurisdictional partners**: six local councils, state departments, federal government, industry and community;
- began with **no single issue**: nutrients, sediments and toxicants were all recognised as possible issues;
- intended to **pre-empt and proactively manage** potential major impacts of nutrients, sediments and toxicants;
- contracted scientific tasks simultaneously with water quality strategy development and public involvement. This provided **parallel streams** of science, strategy and communication;
- was **action-oriented**, with recommendations and implementation directly resulting from scientific findings.

Prior to the finalisation of the various scientific tasks and in fact prior to publication of this book, commitments were made by state and local governments, industry and community in order to achieve the vision of healthy waterways:

The Vision:

"Moreton Bay and its waterways will, by 2020, be a healthy ecosystem supporting the livelihoods and lifestyles of residents and visitors."

This vision has been adopted by all the major stakeholders of the Study. ***Healthy Waterways*** refers to both ecological and human health and requires effective management strategies. To achieve the subtitle - ***"because we're all in the same boat"***- reflects the necessary combined efforts of all sectors of the community to achieve this common vision.

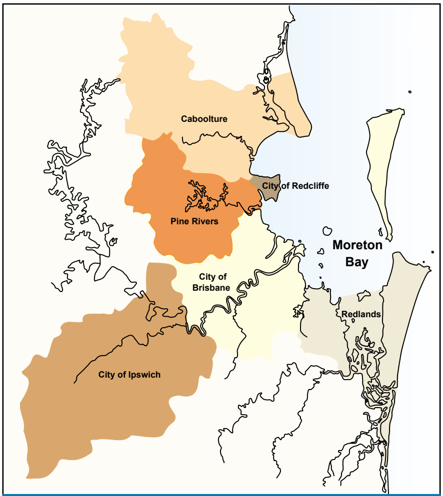
HEALTHY WATERWAYS

Because we're all in the same boat

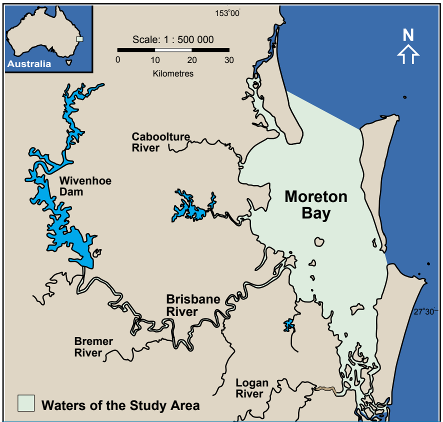
Healthy Waterways logo designed during Stage 2 to represent the cultural and ecological aspects of the vision

Regional scale

The Study was conducted over a large geographic scale that transcended local council boundaries. This regional scale was necessary for an effective linking of processes and development of consistent management strategies. Having a regional scale has led to an appropriate scale for scientific investigation. It was crucial that the six local councils and state government agencies formed an equitable partnership which pooled resources and ensured a consistent overall strategy. The Study incorporated Moreton Bay from the ocean inlets to the western shores, including Pumicestone Passage and the major rivers of the region: Caboolture River, Pine Rivers, Brisbane and Bremer Rivers and the Logan River. The Study initially concentrated in the lower reaches of the rivers and Moreton Bay. The entire watershed of Moreton Bay was not a focus of this stage of the Study, and the various local councils upstream of the lower reaches were not in the original composition of the Study.



Jurisdictions for the six local councils involved in Stage 2 of the Study



The Study area for Stage 2 incorporating Moreton Bay, Pumicestone Passage and the tidal/estuarine regions of the major rivers of the region

The Study has a crucial national and international significance.

- Moreton Bay is included in the international Ramsar Agreement for the protection of wetland habitats for migratory birds
- Moreton Bay Marine Park was recently established and zoned
- South-east Queensland has experienced a rapid population growth, largely from interstate migration to Moreton Bay and its catchment.

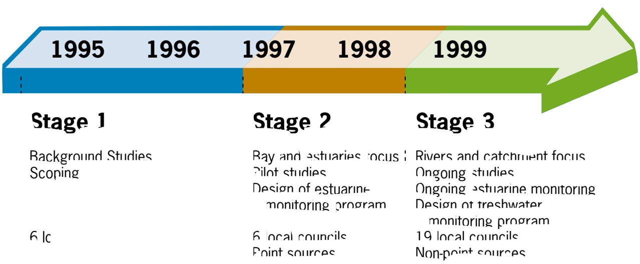
Staged approach

The Study applied a staged approach; each stage with a different scope and objectives interspersed with a review period in order to develop, re-evaluate and re-assess objectives and achievements. While consultation with stakeholders was conducted throughout each of the stages, the initiation of each new stage was carefully planned and reviewed. Stage 1 focused on background studies and initial scoping of the terms of reference for the scientific tasks. The background studies collated previous research results and produced some preliminary models which identified major issues that required further investigation. The Stage 1 scoping was conducted by a team of engineers and scientists from a local consortium of consultants (Sinclair Knight Mertz/WBM Oceanics). Stage 1 also involved the formation of a Scientific Advisory Group to ensure quality control and rigorous peer review. The staged approach promoted simultaneous scientific investigations, stimulating a synergy that produced a more integrated final product.

The development and application of a hydrodynamic transport model based on PhD research (J. McEwan) and the formation of a Modelling Advisory Group was also accomplished in Stage 1. An early version of the hydrodynamic transport model was used to aid in the initial scoping of the tasks for Stage 2. In Stage 1, a conference on Moreton Bay and Catchment was organised by the University of Queensland School of Marine Science. This conference brought together scientists from throughout the region and produced a symposium volume summarising the various research activities that had been accomplished in Moreton Bay and its catchment (Moreton Bay and Catchment).

Stage 2 focused on the river estuaries and Moreton Bay, and the agreed outcome of Stage 2 activities was the Water Quality Strategy and monitoring program for Moreton Bay and the river estuaries. The specific focus on river estuaries and Moreton Bay in Stage 2 resulted from the immediate need by water quality engineers from local councils to plan and implement sewage treatment upgrades. This focus on point sources and their impact in Stage 2 was designed to serve as a pilot study for more thorough, longer-term studies in Stage 3. Stage 2 was completed over a short time frame, 18 months, so that implementation could be based on the best possible scientific understanding.

The focus of Stage 3 is designed to be much broader than Stage 2, incorporating regional catchment issues and the rivers above the estuaries. Thus the non-point source or diffuse sources of sediments, nutrients and toxicants will be investigated. Another reason for employing a staged approach was to allow the development of effective teams of scientists as well as linkages between the public involvement, Water Quality Strategy and scientific investigations.



A staged approach was adopted by the Study, with each stage having a different focus and set of objectives.

Simultaneous science and management

The key attribute of the Moreton Bay Study was the strong interaction between the scientific research and development of a Water Quality Strategy. Participation of community, local council and state government in the process ensured that the scientific recommendations were implemented and also ensured that the scientific tasks appropriately focused and targeted the major issues. Science and management interaction was facilitated by simultaneous scientific investigations and strategy development. The public involvement component was also a crucial aspect to the Study. Some of the scientific efforts were directly focussed around issues raised by the community. For example, the *Lyngbya* bloom in Deception Bay was initially identified by commercial fishermen, communicated to the catchment co-ordinator and then involved the scientific team. The outcomes of Stage 2 include:

- Water Quality Management Strategy, initially addressing best practice standards and management actions for point source discharges
- Receiving Water Quality Model (numerical) for the analyses of management scenarios
- Ecological Health Monitoring Program which provides a design for monitoring the health of our waterways using ecological health indicators
- Information Management System which manages all data generated
- Public Involvement/Consultation Program which raises awareness of the issues and management actions
- Better understanding of our waterways from the 17 scientific tasks
- Cooperative network of governmental and non-governmental bodies working to improve the state of aquatic ecosystems
- Recommendations which led to a saving of $200 million expenditure on sewage treatment

Interactions between elements of the Moreton Bay Study-scientific research, water quality strategy development and public involvement- were crucial to the success of the study. A number of publications have come out of the Study, including the highly successful 'Crew Members Guide'.

Scientific rigour

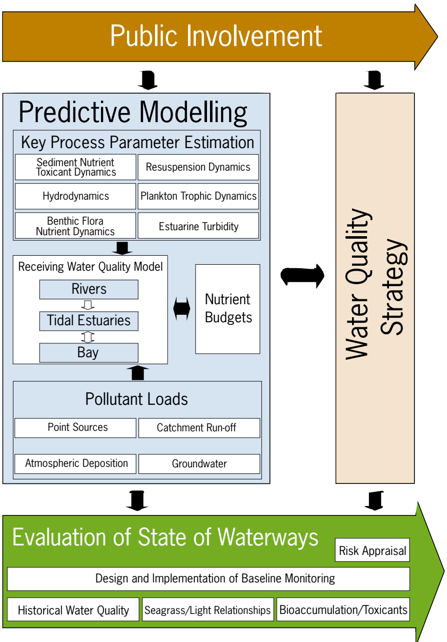
The provision of Scientific Management Services for the Study called for the formation of the Scientific Advisory Group (SAG), which ensured that the scientific components of the Study were designed, conducted, co-ordinated, integrated and reviewed in accordance with the best practice in the scientific community. In addition, the structure ensured that the scientific investigations were directed towards the development of the Water Quality Strategy.

The SAG consisted of an Executive Panel to oversee the Modelling Advisory Group (MAG), Stage 2 Round 2 Core Group and other core groups (such as the Freshwater Core Group) and draws on a broader Scientific Expert Panel on an as-needs basis for the over-all scientific direction of the Study. An External Review Panel provides an independent peer review of the scientific direction and program.

Structure and membership of the Scientific Advisory Group. The inclusion of an external review panel and the advisory groups of the study ensured the scientific components were conducted and reviewed with community input and in line with best practise in the scientific community.

Linked scientific tasks

The main objective of Stage 2 was the formulation of a Water Quality Management Strategy for the waterways. It was recognised that no previous integrated study of Moreton Bay and/or catchments had been done and much of the required information was lacking. To address these deficiencies in the current state of knowledge of water quality processes in the Study Area, a set of key tasks were defined by the Scientific Advisory Group, a group of scientific experts from the various universities, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Queensland Department of Environment & Heritage (now Queensland Environmental Protection Agency), in conjunction with the stakeholders. The 17 Stage 2 tasks aimed to provide the necessary data and information to quantify and verify the relative importance of the various processes in the conceptual model. The integration of the different tasks is illustrated in a task architecture, which has a numerical receiving water quality model as the central core.



Architecture for the scientific tasks in Stage 2, showing the integration and linkages. The numerical receiving water quality model was the central core, but all tasks had input to the Water Quality Strategy.

The following questions highlighted the gaps in the understanding of water quality processes in the Bay and waterways, and provided a focus for the intensive scientific effort in Stage 2.

- Are Moreton Bay and its rivers ecologically healthy?
- How has water quality changed since pre-European settlement?
- What are the flushing patterns in Moreton Bay?
- Where does the sewage effluent end up?
- Can we predict water quality patterns?
- Why is the Brisbane River turbid?
- What is the importance of critical habitats in terms of nutrient cycling?
- What are the environmental factors controlling phytoplankton and other marine plants?
- How does sediment resuspension affect seagrass distribution?
- What are the sediment and nutrient loads into the waterways?
- How do sediment processes influence nutrient cycling?
- Are toxicants important?
- Are there additional issues affecting the waterways?

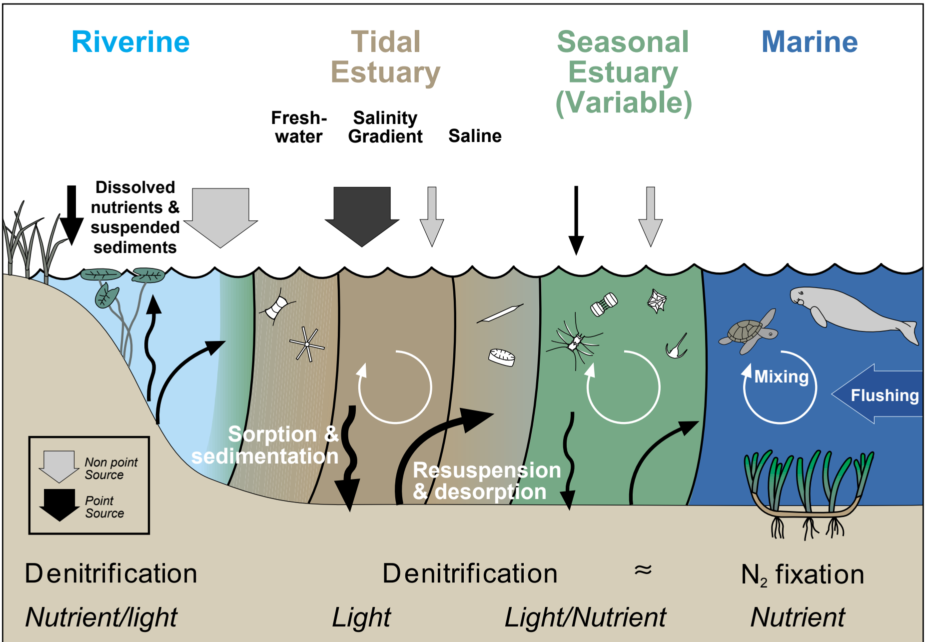
Initial conceptualisation

The initial conceptualisation served to prioritise, link and inter-relate scientific efforts. A sound understanding of the key processes of the system relative to the priority issues and pollutants identified is necessary for the development of an effective water quality management strategy. To illustrate the preliminary understanding of the waterways, a conceptual model which describes the Study area as four main functional zones (riverine, tidal estuary, seasonal estuary and marine), was developed in early 1996. The model was a result of the conceptualisation of data from scientific investigations conducted in the Study area and a series of discussions among the Scientific Advisory Group members, as well as background knowledge on other systems.

The **riverine section** represents non-tidal freshwater streams and rivers characterised by large non-point sources of suspended sediments and nutrients with riparian and floating-leaf vegetation reducing available light. Nutrients and light are major limiting factors for aquatic primary productivity.

Riverine section of the Study region, surrounded by farmlands.

ENVIRONMENTAL PROTECTION AGENCY



Initial conceptualisation for the Study region, indicating the preliminary understanding, including impacts and processes, of the waterways.

The **tidal estuary** can be subdivided into three sections: tidal freshwater, salinity gradient, and saline. Tidal mixing throughout the three sections reduces water column stratification and enhances sediment resuspension, resulting in high turbidity and low phytoplankton concentrations in spite of high nutrient concentrations. Nutrients from significant point sources, as well as from non-point source run-off, are sorbed to suspended sediments and some nitrogen removal is effected by denitrification, but the bulk of the nutrients are transported into Moreton Bay. Light is the major limiting factor for aquatic productivity.

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Tidal estuary of the Brisbane River, characterised by high turbidity and low phytoplankton concentrations despite high nutrient sources.

The **seasonal estuary** is the variable portion of Moreton Bay affected by river discharges. Turbidity reduces seagrass distribution but provides sufficient light penetration for phytoplankton growth.

The **marine portion** of Moreton Bay is characterised by tidal flushing, extensive seagrass beds grazed by green sea turtles and dugong, and high rates of benthic nitrogen fixation. The major limiting factor is nitrogen availability

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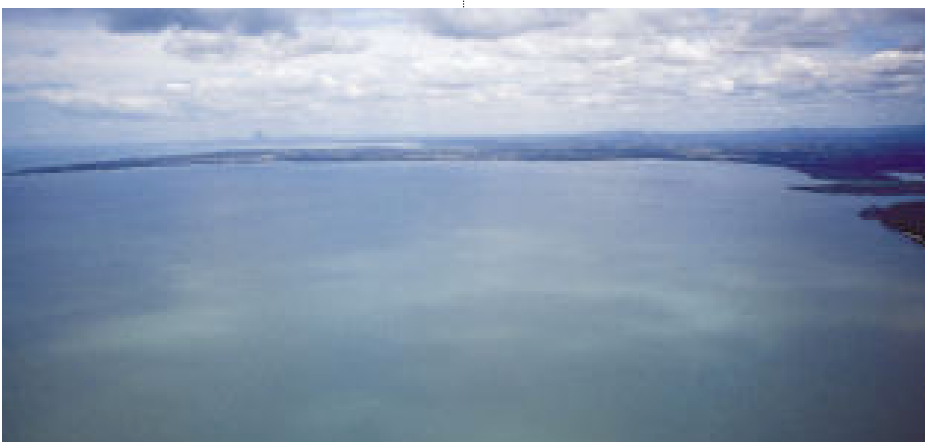
Marine portion of Moreton Bay on the western side of Stradbroke Island



HEALTHY WATERWAYS LIBRARY

Seasonal estuaries are variably affected by river discharges, including southern Deception Bay shown in this image.

Hydrodynamic transport model

In order to ensure the long-term environmental integrity of complex systems like Moreton Bay and its river estuaries, a sound understanding of the different processes is necessary. The usefulness of models, both conceptual and numerical, as tools in the development of a sound understanding of the system, and ultimately in the development of the Water Quality Strategy, was recognised at the start by the Study.

The Study initially used a modified version of the US EPA WASP modelling package (Ambrose, R.A. et al., 1993 WASP5, A Hydrodynamic and Water Quality Model), which is a dynamic compartment modelling suite incorporating time-varying advection, dispersion, point/diffuse mass loading and eutrophication kinetics in both the water column and benthos. Since then, the model has been upgraded to the RMA platform (King, I.P., Resource Management Association).

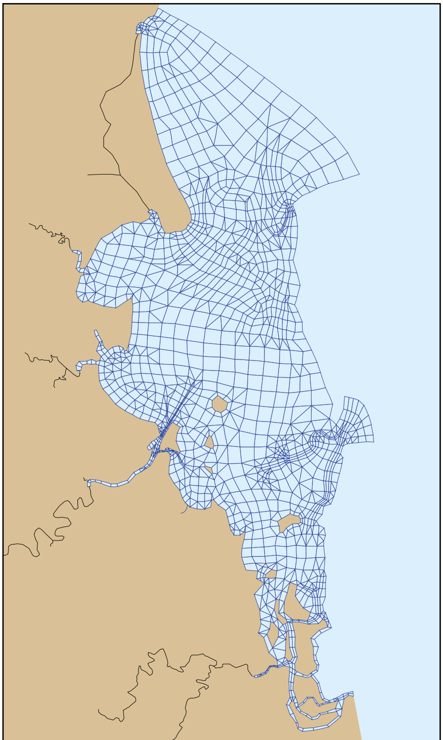
The overall structure of the numerical hydrodynamic-transport model, includes hydrodynamic, transport and water quality components.

The hydrodynamic module determines the basic model identity in terms of spatial extent and degree of segmentation and simulates the movement of water. Output from the hydrodynamic module is coupled with the transport module to simulate the movement of pollutants. Lastly, the addition of kinetic routines to the transport module simulates the biological and chemical processes controlling the interactions between the system variables.

The hydrodynamic model forms the basis of the subsequent transport and water quality models. The physical configuration of the water body to be modelled is represented as a network of one-dimensional and two-dimensional elements. The hydrodynamic model geometry consists of a mesh with 2125 'elements' with a spatial resolution ranging from 330 m - 2000 m.

The northern boundary of the model extends from Caloundra to Cape Moreton. The southern boundary is formed by Jumpinpin Bar. River systems included are Brisbane and Bremer, North and South Pine, Caboolture, and Logan and Albert. The upstream boundary of all rivers extends to the limit of tidal influence.

A key feature of the hydrodynamic-transport model is the ability (and necessity) for it to be continually refined and enhanced in response to new information from process and field studies.



Hydrodynamic model geometry. The model mesh consists of 2125 'elements'.

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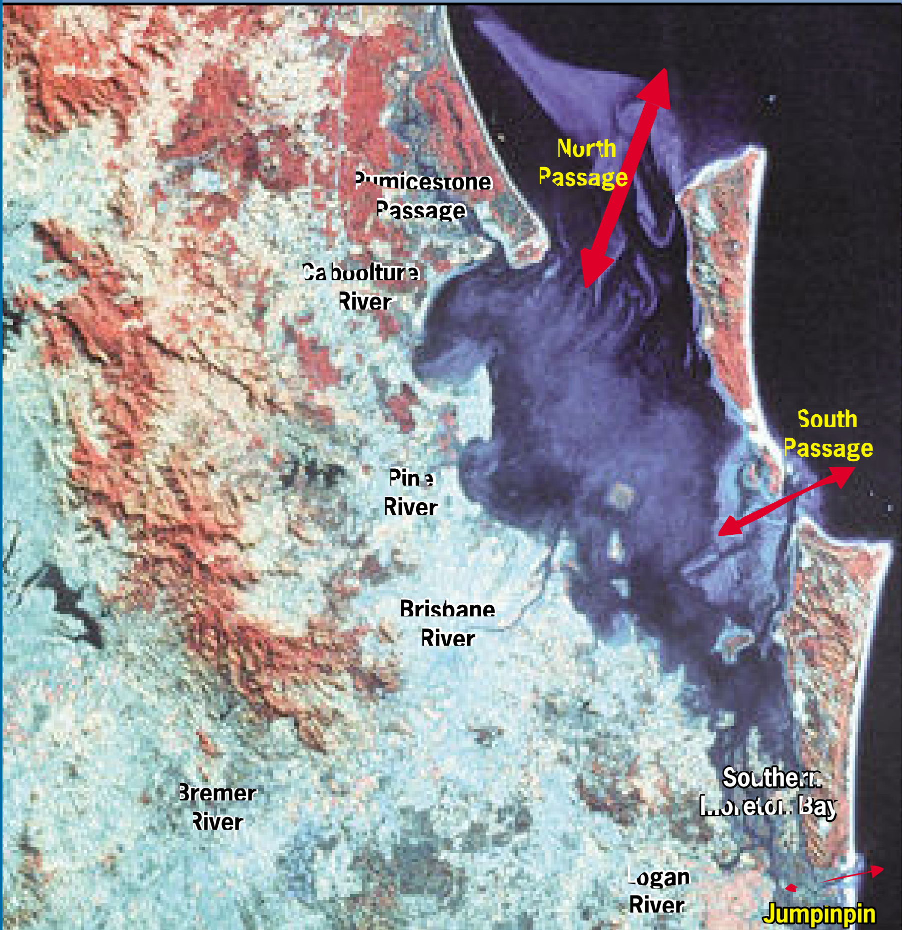
CHAPTER 3

Moreton Bay Region



AUSTRALIAN CENTRE FOR REMOTE SENSING

- Subtropical setting: seasonal rainfall
- Catchment: Bay area ~14:1
- River estuaries: BROWN
- Moreton Bay: BLUE
- Seasonal water circulation patterns
- Calibrated hydrodynamic and transport model
- Tides and winds influence water circulation
- Oceanic exchange: North Passage > South Passage > Jumpinpin
- Residence time variable: days to months

Subtropical setting: seasonal rainfall

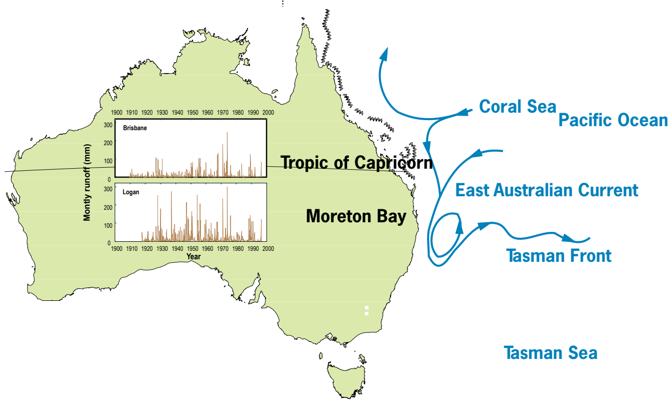
The Moreton Bay region is at 27° S latitude, ~400km south of the Tropic of Capricorn. In summer, prevailing winds are from the north-east and south-west. In winter, weather fronts moving west to east bring periods of cool, dry westerly winds. Monsoonal low pressure systems bring rain to the region, particularly in the summer and early autumn. The seasonal rainfall leads to periods of high runoff, and occasional floods. Large scale floods are typically generated from degraded cyclones that remain in the region for some days. The long term hydrographs of the Brisbane and Logan Rivers reveal the variable runoff patterns, with considerable year-to-year variability. There appear to be long periods of low runoff interspersed with periods of high runoff, and the 1974 flood event is clearly evident on both hydrographs.

East Australia Current (EAC)

The offshore water currents are dominated by the EAC, a rapid south-flowing current. This current is a 'western boundary current' providing the poleward leg of a large subtropical 'gyre'. The subtropical gyre is an anti-clockwise circulation of water across the entire south Pacific Ocean. Due to the effect of the earth's rotation on water circulation, the subtropical gyres have intense currents in the western portion of the ocean (e.g. EAC, Gulf Stream, Kuroshio, Bengela Current). Subtropical gyres have important consequences for the transport of biota and biogeographical patterns. The EAC has its origins in the equatorial Coral Sea, thus being a warm water, low nutrient current. It is relatively fast flowing (up to 4 knots) and turns east near Cape Byron (south of Moreton Bay), to form the Tasman Front which separates the Coral and Tasman Seas. The presence of the EAC offshore of Moreton Bay has the following implications: transport of tropical larvae into Moreton Bay, relatively consistent water temperature and low frequency of upwelling events in which cool, deep ocean water, rich in nutrients, are brought to the surface, stimulating plant growth.

Brisbane suburbs under water during the 1974 flood, a 1 in 100 year flood event.

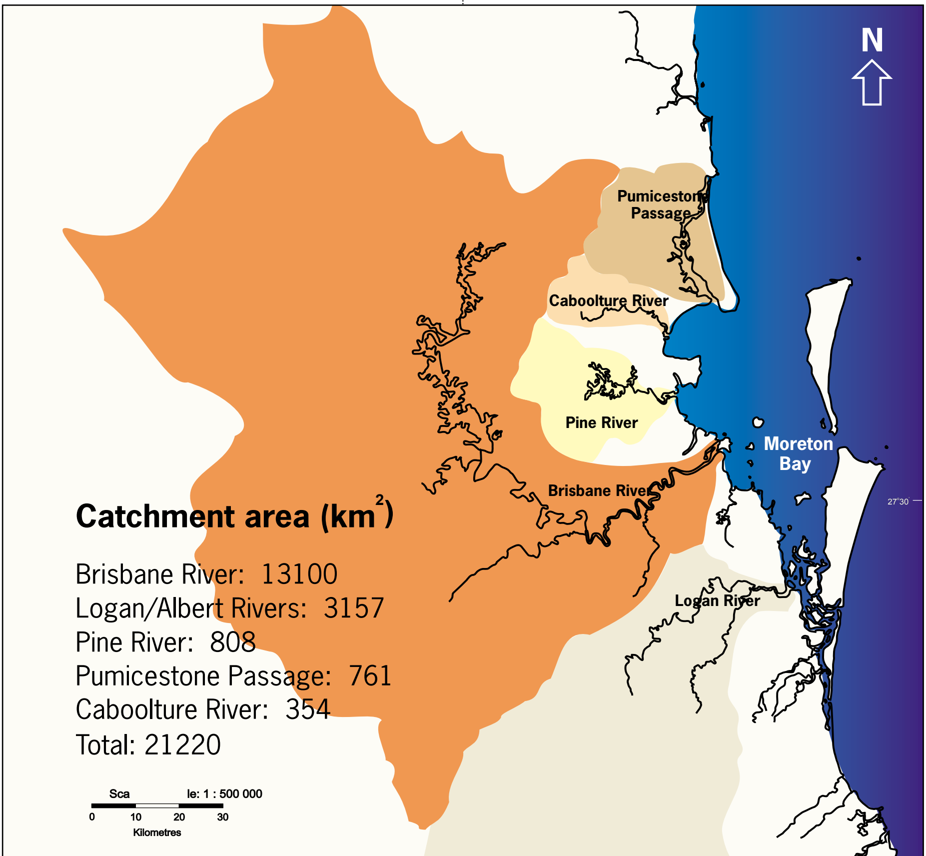
ENVIRONMENTAL PROTECTION AGENCY



The predominant offshore water currents which influence Moreton Bay. Rainfall data for the Brisbane and Logan regions (inset) show considerable annual and year-to-year variability.

Catchment: Bay area ~14:1

The catchment area of Moreton Bay is dominated by the large catchment of the Brisbane River (13100 km^2), which extends west to the Great Dividing Range. This catchment includes the subcatchments of the Upper Brisbane, Stanley, Lockyer, and Bremer Rivers. Several large streams or creeks also enter the tidal reaches of the Brisbane River: Bulimba, Breakfast, Norman, Oxley, and Mogill Creeks. The next largest catchment is the Logan/Albert catchment (3157 km^2) extending west to the Great Dividing Range and south to the Lamington Plateau. The Pine Rivers catchment (808 km^2), includes the North and South Pine Rivers. The Pumicestone Passage catchment (761 km^2) consists of several small creeks, discharging throughout the passage. The Caboolture River catchment (354 km^2) is small, as are the myriad of small coastal creeks that discharge directly into Moreton Bay. The combined catchment area of creeks and rivers discharging into Moreton Bay is 21220 km^2, and compared to the area of the Bay itself (1523 km^2), represents roughly 14:1 ratio of catchment to Bay area.



The main river catchments of Moreton Bay. The Moreton Bay catchment is dominated by the Brisbane River catchment with an area of 13000 km^2

River estuaries: BROWN

The river estuaries of south-east Queensland are distinctly brown in colour, especially after rain. They have low biological diversity, with a limited number of organisms that can survive the high turbidity, highly variable runoff and salinity, and shifting substrate. Resuspension of fine-grained sediments occurs, with wind and tides providing the water mixing that promotes resuspension. The population pressure on these river estuaries is intense, consequently they tend to be over-loaded with sediments, nutrients and toxicants. The principal wastewater discharges are into the river estuaries, rather than into the Bay directly. The river estuaries are nutrient-laden, with extremely high nitrogen concentrations, in particular, nitrate.

River estuary definition: 'river' refers to a flowing stream of water moving in a defined course; 'estuary' refers to junction between freshwater and oceanic seawater. The term 'river estuary' is used to define the lower tidal portions of the south-east Queensland rivers.

Biological diversity =low

Resuspension

Over-loaded

Wastewater

Nutrient laden

Bremer River estuary

HEALTHY WATERWAYS LIBRARY

Brisbane River estuary

MARINE BOTANY GROUP, UNI. OF QLD

Caboolture River estuary

HEALTHY WATERWAYS LIBRARY

Moreton Bay: BLUE

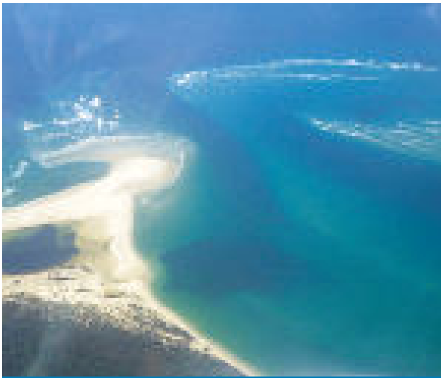
Moreton Bay is generally blue in colour, particularly in the northern and eastern Bay. Western portions of the Bay are occasionally green (algae), brown (suspended sediments) or yellow-brown (humic runoff). The biological diversity in the Bay is high, with a variety of habitat types: soft muddy sediments to hard packed sandy sediments, seagrass meadows, mangrove forests, coral communities, rocky intertidal and subtidal outcrops, and a variety of species in each habitat type (Davie, P.J.F., Hooper, J.N.A., 1998, Moreton Bay and Catchment). The Bay is lagoonal in nature; a shallow water mass separated from the ocean by a series of barrier islands (Moreton, North and South Stradbroke Islands), leading to a restricted exchange of oceanic water. Vertical stratification in the Bay is rare, as tides, wind and ocean swell in the generally shallow water (6.8 m average depth) serve to break down any layers of fresh, warm water overlying saline, cool water. The Bay is energetic, with a moderate tidal range (1.5-2.0 m), frequent onshore breezes and ocean swell acting on the system. Lack of cloud cover results in high light intensities, and marine plants throughout the Bay photosynthesise and support a diverse and rich fauna.

Biological diversity = high

Lagoonal

Unstratified

Energetic



Jumpinpin Bar

HEALTHY WATERWAYS LIBRARY

North Stradbroke Island

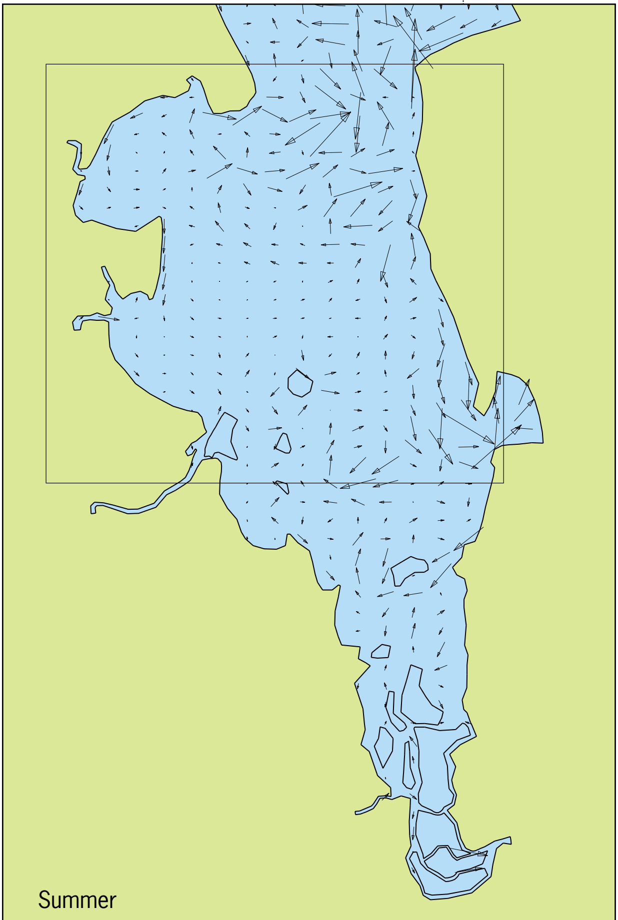
HEALTHY WATERWAYS LIBRARY

Eastern Bay

HEALTHY WATERWAYS LIBRARY

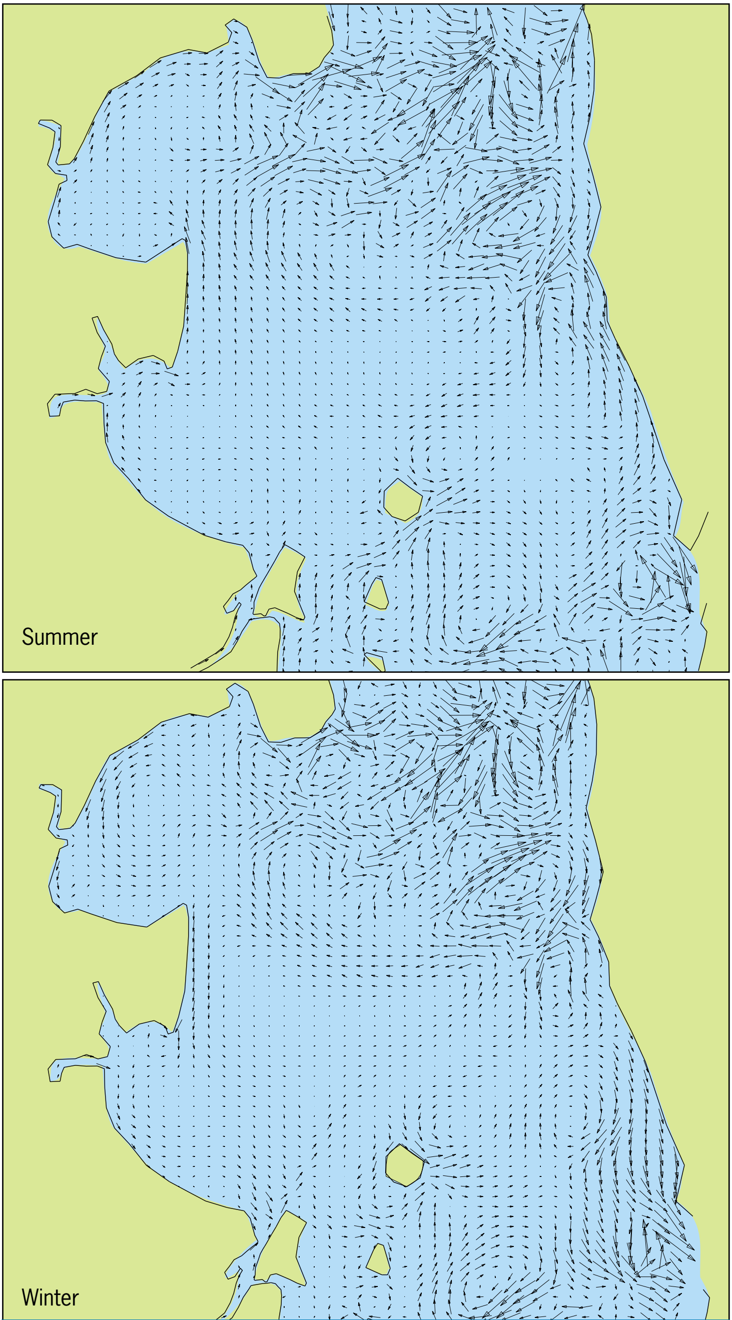
Seasonal water circulation patterns

The shallow depth of Moreton Bay combined with the tidal range, enables significant exchange of the Bay's water with the ocean, on each tide. However, the flood tide that brings seawater into the Bay does not exactly match the ebb tide that removes water from the Bay and into the ocean. This asymmetry in tides leads to 'residual circulation', a net gradual movement of water. The net movement of water due to tides over a Spring-Neap cycle (~14 days) creates a pattern of northward water movement on the western side of the Bay and a generally southward water movement on the eastern side. This sets up an overall clockwise pattern of water circulation in the Bay. The residual circulation is highest near the openings and lowest in the western embayments.



Residual circulation patterns in Moreton Bay in summer as predicted by the hydrodynamic model. There is a general northward water movement in the western Bay and a southward movement in the eastern Bay driven by tidal asymmetry.

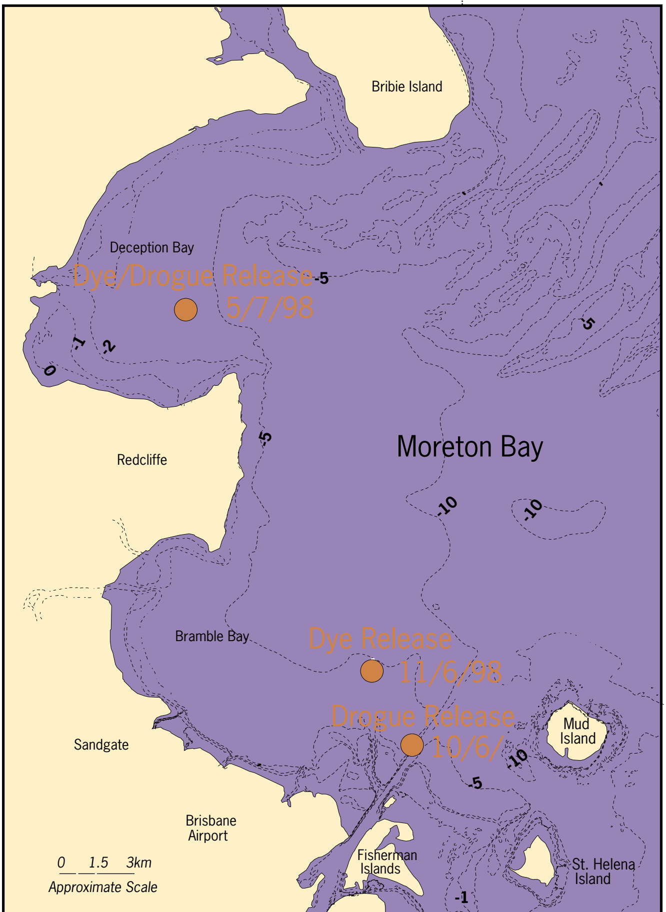
There is a seasonality to the pattern of residual circulation due mostly to seasonal changes in wind patterns. For summer, modelling predicts a net clockwise circulation in both Deception and Bramble Bays. In winter, this reverses and there is a net anti-clockwise circulation in these western embayments. Neither of these seasonal residual circulation patterns result in substantial water flows, as indicated by the small vectors, however, the net movement is important in dispersing sewage or other runoff.



Circulation patterns for Deception and Bramble Bays in summer and winter as predicted by the hydrodynamic model. Circulation patterns within these embayments show seasonal differences.

Calibrated hydrodynamic and transport model

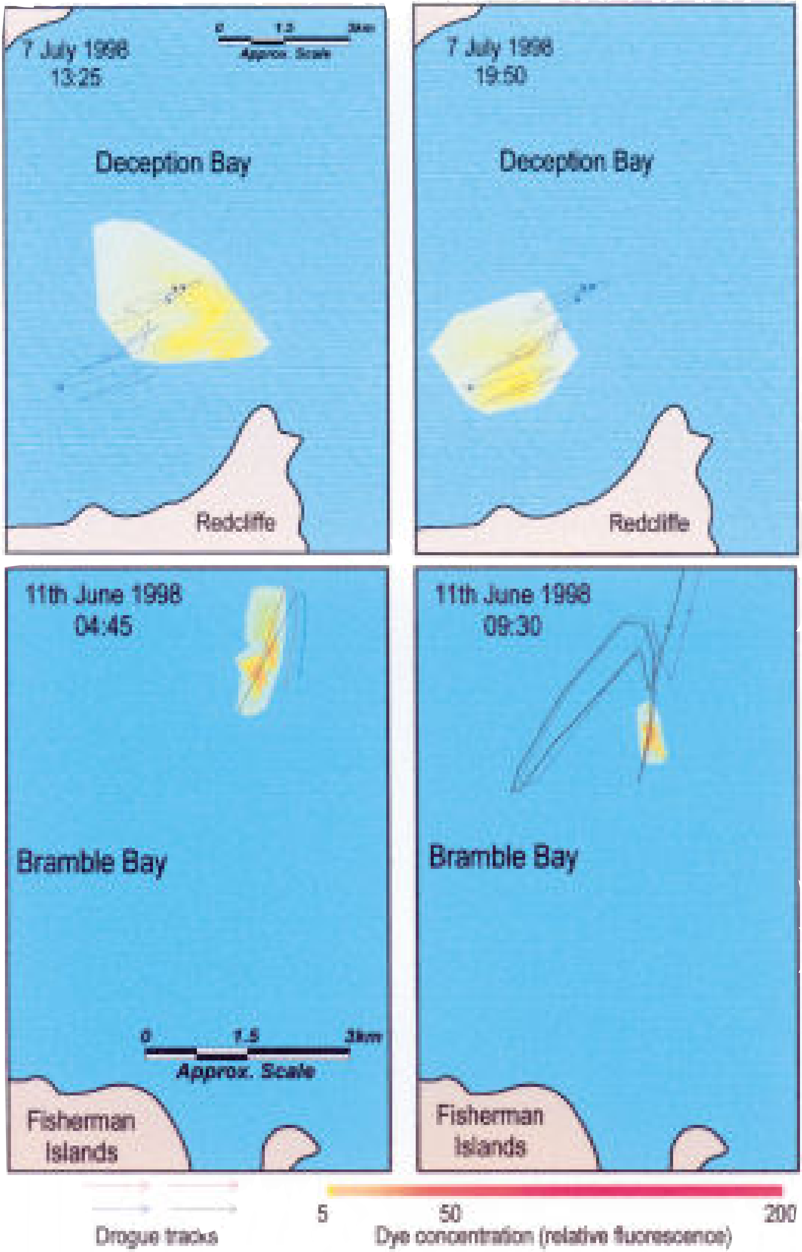
A hydrodynamic model was created to simulate the movement of water in the Bay. This model was calibrated using three techniques: tracer dye release and tracking, drogue release and tracking and saline recovery of the Bay after the May 1996 1:20 year flood event. These techniques provide a measure of the dispersal of a simulated pollutant in the water (tracer dye) and a measure of net water mass movement (drogue). The tracer dye is a soluble pigment released in a concentrated form that slowly disperses in the water. A pigment was chosen (rhodomine) to be essentially inert and to be detectable at relatively low concentrations (via fluorescence). The drogue is a float attached to a weight with a large submerged 'sail'. The float (with radar reflector) remains visible, but the movement of the drogue device is due to the effect of water currents on the submerged "sail", rather than the effect of the wind on the float.



Site map for dye and drogue release in Bramble and Deception Bays.

Three sites were chosen for dye and/or drogue studies: Deception Bay, Bramble Bay and the mouth of the Brisbane River. The Bramble Bay and Deception Bay dye and drogue results illustrate the significant tidal excursions and the extent of dispersion that occurs in the first 24 hours.

Tides and winds influence water circulation



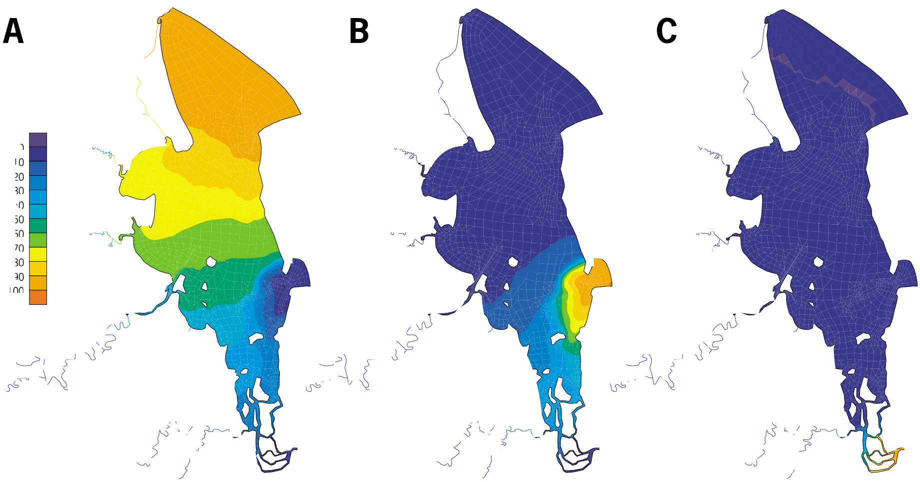
Dye and drogue release results in Deception Bay (top) and Bramble Bay (bottom).

Oceanic exchange: North Passage > South

Tidal exchange between the Bay and the ocean plays a major role in the transport and fate of sediments, nutrients and toxicants. The position of the three openings of the Bay into the ocean, the width of the openings, the tidal deltas that restrict water exchange through the openings, and the bathymetry of the Bay, interact to produce complex patterns of oceanic exchange. All of the openings have ebb tide sand deltas that build up outside the Bay proper where the water flow from the ebbing tide slows sufficiently for the sand to deposit. However, the flood tide deltas are the largest, with extensive sand banks stretching across the northern portion of the Bay and Moreton and Amity Banks near South Passage. These sand deltas are dynamic (e.g. the shift in flow from the east-west Rous Channel to the north-south Rainbow Channel that occurred ca. 100 years ago) and the openings themselves are dynamic (e.g. the creation of Jumpinpin in 1897).

Most of the oceanic exchange occurs via the North Passage, with oceanic water from this passage dominating the entire northern half of the Bay, including Deception and Bramble Bays. The exchange through South Passage is more restricted and influences flushing in the southern bay, via Rainbow Channel. Waterloo Bay is affected by both North and South Passages, which could account for the relatively oceanic water quality conditions that were observed (refer to Chapter 6). Jumpinpin has a narrow opening with a shallow bar, and thus has the least oceanic exchange. The return coefficients are calculated as the percentage of water going out with the ebb tide that returns on the subsequent flood tide. North Passage has the highest return coefficient (95%), with 50% for South Passage, and only 10% for Jumpinpin.

Since water current velocities at the oceanic boundaries were so crucial to the development of the hydrodynamic model, a series of measurements were made along North and South Passages. A shipboard acoustic doppler technique was employed. This device transmits sound waves and measures the reflection of the



The relative percentage contributions to the flushing of Moreton Bay by the three oceanic boundaries for generic summer conditions A) North Passage, B) South Passage and C) Jumpinpin Bar. The greatest degree of flushing is via the North Passage.

Passage > Jumpinpin

transmitted sound off small particles in the water. The speed of the particle causes a slight deflection of the sound wave (Doppler shift) which can be detected. Water current speed can be inferred from the speed of the particles.

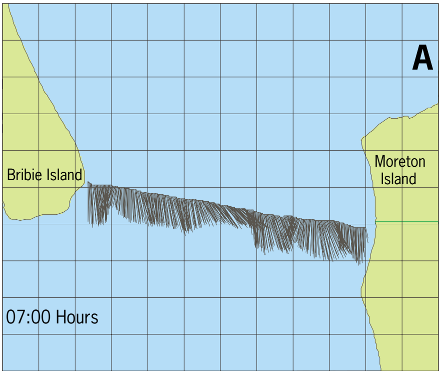
The North and South Passage transects have rapid water currents with the flood tide (100-150 cm s^{-1}; 2-3 knots), and slightly slower currents with the ebb tide (<100 cm s^{-1}). The effect of bathymetry can be seen, with faster currents in the deeper channels.

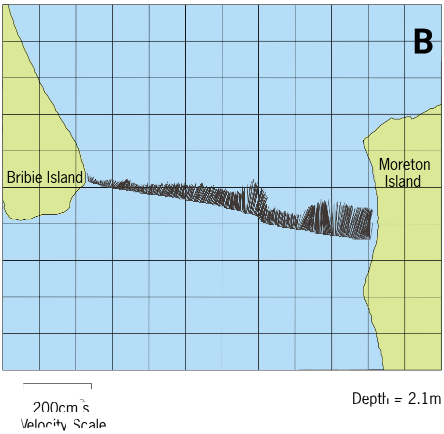
Water current speeds

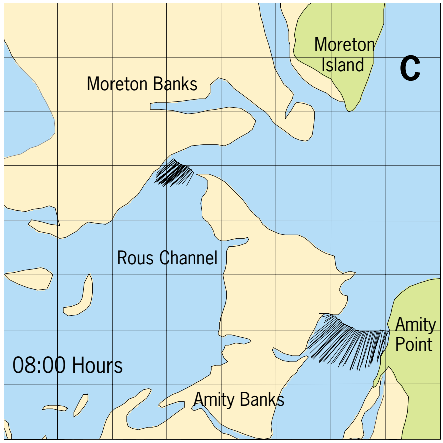
1 knot = 1 nautical mile per hour ~ 45 cm s^{-1}

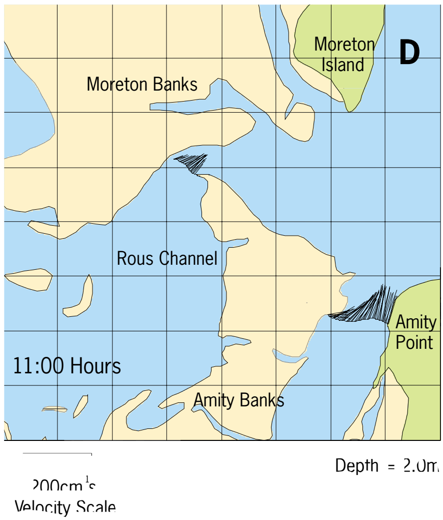
1 nautical mile = 1.85 km

The fastest oceanic water currents are roughly 10 knots









Water current velocities and flow data at the northern (A, B) and eastern (C, D) boundaries for calibration and verification of the model. Measurements were taken over flood (A, C) and ebb (B, D) tides.

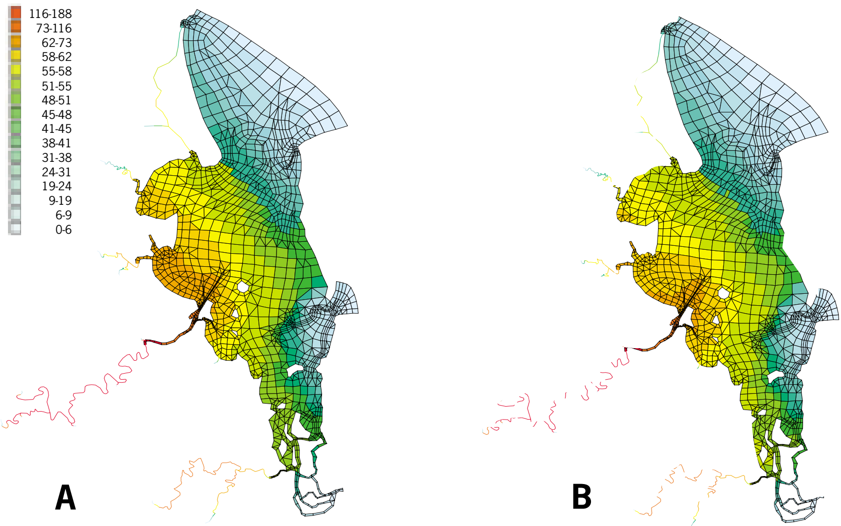
Residence time variable: days to months

The hydrodynamic transport model can be used for predictions of water movement. One of the more useful predictions is that of residence time. Residence time refers to the length of time that a parcel of water remains at a certain location. Viewed from the perspective of a pollutant that is added to the water, the residence time is the time for a mass of pollutant in a given volume of water to reduce to approximately ⅓ of its value if no biological or chemical factors affected the pollutant.

The gradient in residence times are from the shortest residence times at or near the oceanic boundaries (several days) to the longest residence times in the western embayments and river estuaries (months). The overall residence time for the whole of Moreton Bay can be calculated from the tidal prism, volume of the Bay, and return coefficients. The model predicts an overall residence time of about 45 days. There are seasonal patterns of residence times due to change in wind speed and direction, as noted in the water ciculation patterns . Bramble Bay consistently has the longest residence time in the Bay, followed by Waterloo and Deception Bays. Unfortunately, the major sewage and river discharges are into the greatest residence time portions of the Bay.

Flushing times in days for key sites around the bay

Sites	Residence Time (d)
Ocean boundaries	3-5
Central Bay	50-55
Mouth of Brisbane River	63-68
Lower Brisbane River	110-120
Middle Brisbane River	154-162
Bremer/Brisbane junction	187-189
Bramble Bay	59-62
Deception Bay	54-57
Pumicestone Passage	43-53
Pine River	55-62
Caboolture River	53-57
Logan River	66-75



Residence times throughout the bay under two wind regimes A) no wind and B) mean annual wind based on 1997 wind data. Residence times decrease with increased wind, particularly in Bramble Bay.

CHAPTER 4

Historical Perspective

QUEENSLAND MUSEUM

COURIER MAIL

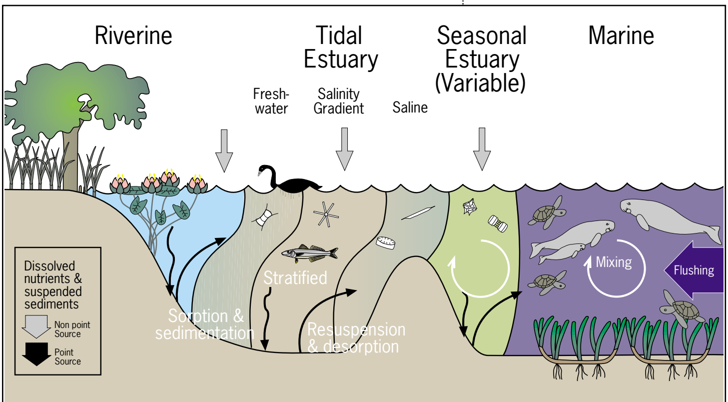
QUEENSLAND MUSEUM

- Historically healthy ecosystem
- Increasing population
- Increasing land use
- Degrading water quality: Brisbane River estuary
- Degrading water quality: Logan River estuary
- Degrading water quality: Moreton Bay
- Turbid river estuaries
- Particularly turbid Brisbane River estuary
- Multiple turbidity sources: Brisbane River
- Turbidity maintenance by tidal resuspension
- Turbidity influenced by river flow

Historically healthy ecosystem

The Moreton region ecosystem has undergone significant changes over time. The geologic history of the region is strongly influenced by relative sea levels. Formation of the large barrier islands (Moreton and North Stradbroke Islands) was a result of accumulation of wind-blown sand around large rock outcrops (Cape Moreton and Point Lookout) at previous low sea level stands. The river courses and the Bay itself have changed dramatically as a function of sea level. The original inhabitants of the region used the sand islands and the waterways as a source of food and shelter (Crowther, G. et al., 1998, Minjerribah, An Indigenous Story of North Stradbroke Island). In order to establish the environmental conditions before European settlement, reports from early European settlers have been compiled (Gregory, H., 1997, Brisbane River Story: Meanders Through Time). These early reports all indicate that the historical ecosystem was quite different from the current situation. Inputs of sewage and catchment runoff were much reduced historically. Extensive riparian vegetation along the waterways was present throughout the catchment and included patches of rainforest, abundant water lilies and overhanging trees. The water clarity in the Brisbane River was much better than exists today as indicated by reports of swimmers in the lower and upper reaches of the river. The abundance of large fish, including cod, in the river as recently as the mid-20th Century indicate a much healthier ecosystem than currently exists. Black swans, a strong indication of submersed aquatic vegetation, were abundant in the Brisbane River. The bar at the mouth of the Brisbane River, due to sandbanks, was one of the reasons that the original European explorers, including Matthew Flinders, were not able to discover the mouth of the Brisbane River. The early accounts of crossing the bar at the mouth of the river indicate that only a couple of metres of water depth were present in dry, low-flow periods. The intact bar at the mouth of the river reduced the tidal energy propagating upriver thereby increasing the likelihood of vertical stratification of river water. Moreton Bay was also quite different historically. For example, the abundance of dugong, turtles and seagrasses in the western embayments was reported by early European settlers.

One of the initiatives of Stage 2 was to quantify some of the changes that have been qualitatively indicated through anecdotal reports. Historical trends in population and land use of increasing human pressures on the Moreton region. The historical water quality provides definitive evidence of degradation and allows some insight into the processes driving this degradation.



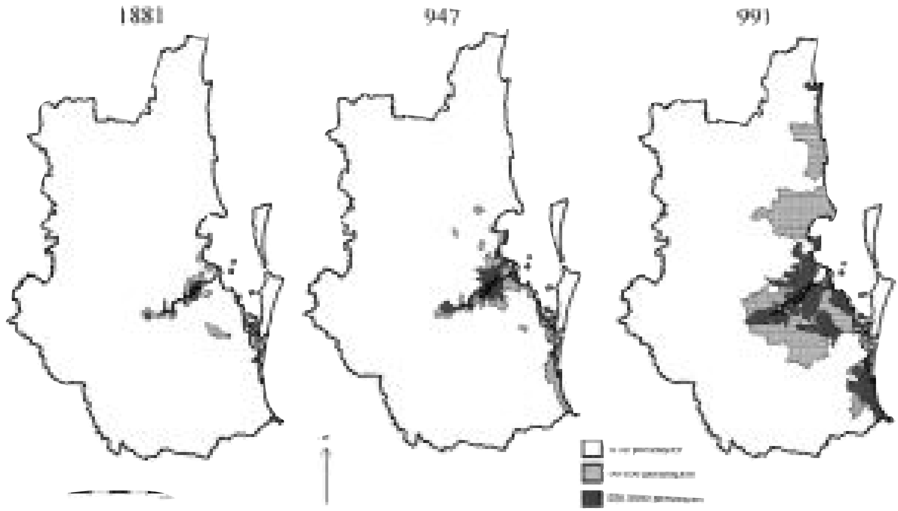
Conceptual model depicting historical water quality and ecosystem zonation in the Moreton Region extending from the riverine to the tidal estuary and into the marine system. Historically, this was a healthy ecosystem.

Increasing population

South-east Queensland has an expanding population which originally centred around the Brisbane River. Early settlement of the region included several coastal communities and a large community centred in the current Brisbane City area. The availability of reliable fresh water was a major consideration in early settlement patterns. The population expansion in the Brisbane region has been primarily to the south (Gold Coast) and to the north (Sunshine Coast) providing a dense population throughout most of the coastal regions of Moreton Bay.

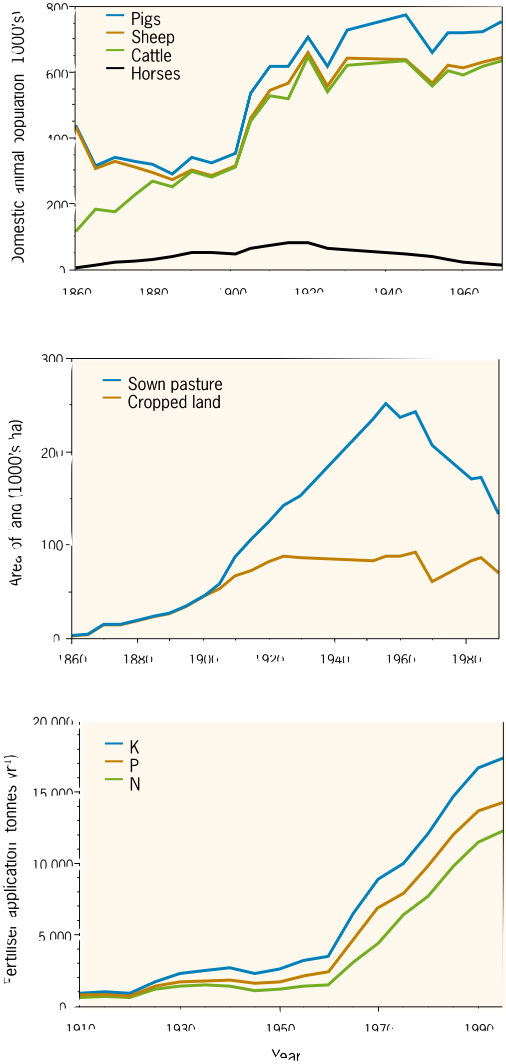
South-east Queensland has been the fastest growing region in Australia over the past decade, and this region has been one of the most rapidly growing regions in the world over the past half century (Skinner, J.L., et al., 1998, Moreton Bay and Catchment). In fact, south-east Queensland is uniquely consistent in population growth. While many regions in the world have experienced rapid growth, typically these patterns are not sustained. This pattern of sustained population growth in south-east Queensland provides a fairly reliable prediction of continued future population growth.

Population growth provides one of the major pressures in the region. An increasing population means more sewage, more intensive land use and more demands on waterways for commercial and recreational use. Most of the population growth is in the coastal floodplain and along the river estuaries. An expanding population means that increased environmental controls must be instituted simply to maintain the *status quo* and that remediation of existing degraded areas will require considerable efforts.



Population density in the Moreton region, 1881 - 1991. Population density has increased dramatically in the south east Queensland region over the past 120 years (Skinner, J.L., et al., 1998, Moreton Bay and Catchment).

Increasing land use



Land use patterns in the Moreton catchment, 1860 - 1995, A) livestock numbers B) sown pasture and C) fertiliser application to crops. Increasing human population has been accompanied by increases in livestock, land used for crops and fertiliser use (Neil, D., 1998, Moreton Bay and Catchment).

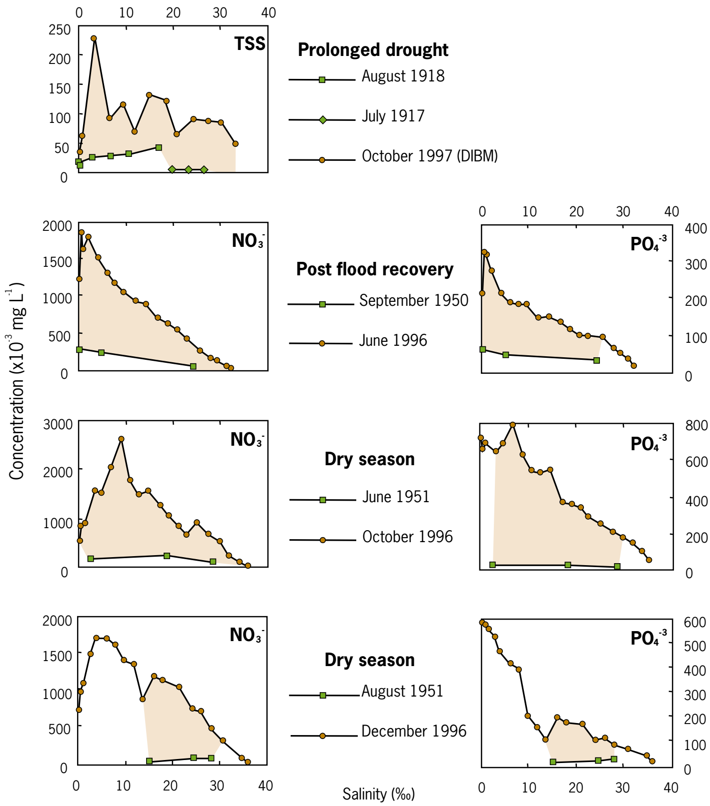
Population increases have resulted in more sewage discharges and also have been accompanied by more intensified land-use. The number of livestock in the region increased dramatically 100 years ago and a combination of more pigs, sheep and cattle has resulted in more intensive grazing. The increasing population of humans, and domestic animals, and increasing fertiliser application, have resulted in environmental degradation in the region.

The amount of nutrient runoff from the waste of the 1.5+ million animals in the region combined with sewage from the 1.5+ million people results in potential nutrient impacts. The amount of land that is being converted to pasture or more intensive agricultural use for crops has increased, most dramatically in the mid 20th Century. This trend has begun to decrease as pastures are being converted to rural/residential and urban developments.

Even though the amount of agricultural land has not increased over the past decades, what has increased is the intensity of agriculture. This can be seen in the increased amount of fertiliser applied, particularly in the period from 1960 to the present. The ramification of this is that more nutrients are entering the waterways. Only about one third of fertiliser applied to agricultural crops is typically assimilated by the crop itself and the remaining two thirds is a potential source of runoff nutrients into the waterways through groundwater, volatilisation into the atmosphere and subsequent precipitation and direct runoff (Neil, D., 1998, Moreton Bay and Catchment).

Degrading water quality: Brisbane River estuary

Water quality has declined in the Brisbane River over the past 80 years. Mixing plots, constructed from data as early as 1917-18 for total suspended solids (TSS) and 1950-51 for dissolved inorganic nutrients, demonstrate a quantitative increase in the amount of suspended sediments and nutrients in the Brisbane River. Since the 1950's nitrate (NO_3^-) concentrations have increased 22-fold, while phosphate (PO_4^{-3}) concentrations have increased 11-fold. TSS concentrations have also increased 4-fold. These increases in nutrients and sediments were persistent over different hydrographic cycles. Both wet and dry season values are currently higher than they were historically. This provides the first quantitative evidence supporting the multiple anecdotal reports which indicate increased turbidity in the Brisbane River.

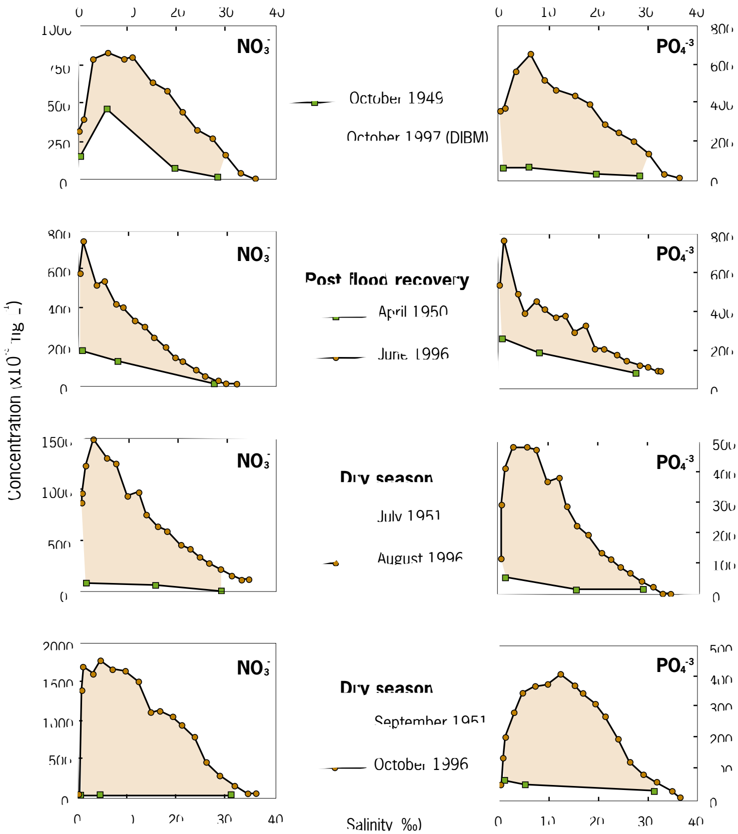


Historical and present mixing plots for total suspended solids (TSS) and dissolved inorgainc nurients (NO_3^- and PO_4^{-3}) in the Brisbane River. TSS and nutrient concentration have increased since the first recorded sampling was carried out, particularly in the lower salinities of the upper estuary.

Degrading water quality: Logan River estuary

In the Logan River, increased concentrations of nitrate (NO_3^-) and phosphate (PO_4^{-3})observed since 1949-51 are similar to those observed in the Brisbane River. The Logan River catchment is much less urbanised than the Brisbane River catchment which indicates that these increased nutrient concentrations are the result of a variety of catchment land uses other than just urbanisation. Like the Brisbane River data, these Logan River comparisons were consistent in different hydrographic cycles. During both the dry and wet seasons, nitrate concentrations have increased by 200-400% over those of 1950.

The similarity of the historical versus current water quality comparisons of the Brisbane and Logan Rivers suggest that similar water quality degradation has occurred in river estuaries and smaller creeks for which historical water quality data are not available.



Mixing plots of historical and present nutrient (NO_3^- and PO_4^{-3}) concerntrations in the Logan River estuary. TSS and nutrient concentration have increased since the first recorded sampling particularly in the lower salinities of the upper estuary.

Degrading water quality: Moreton Bay

Historical data for Moreton Bay show there has been a statistically significant increase in nutrient concentrations (nitrate, NO_3^- and phosphate, PO_4^{-3}) within some regions. The greatest degree of change was for nitrate concentrations from 1950-84 in the seasonal estuary (38x) and marine (17x) portions of the Bay. However, both nutrients decreased in concentration after 1984 and the effect is more pronounced for nitrate. A possible cause of this dramatic increase in nutrient concentrations from 1950-84 and the dramatic decrease from 1984-97 is a sampling bias. Sampling of Moreton Bay during the 1970's to the 1980's was concentrated in western regions (particularly in Bramble Bay). The sparse sampling before and after this period were scattered all across the Bay. The western Bay is subject to greater influences of terrestrial run-off from point and non-point sources and typically has higher nutrient concentrations than other areas of the Bay that are more influenced by marine flushing. Apart from this spatial sampling bias, samples taken during the dry season may have resulted in some temporal bias.

The 1984 samplings were conducted generally during the wet season (December-May) in a given year. Because it has been suggested that the initial data (1950) generated by CSIR (CSIRO precursor) may also have provided an underestimate of nitrate concentrations for the region (zero values recorded may be related to limits of detection at that time). Because of these uncertainties, in terms of the accuracy of the historical data, and therefore, the precision of the magnitude of increases over time, the magnitude of changes needs to be viewed with caution.

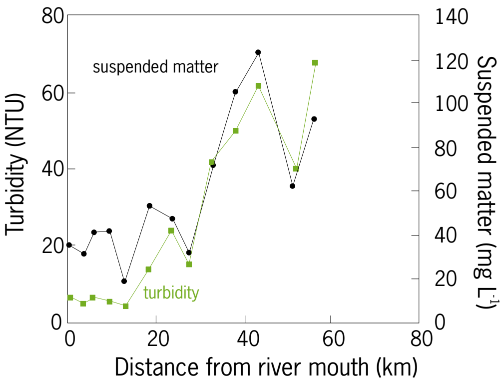
However, when considered together with historical and current data from the Logan and Brisbane Rivers, there is clear quantitative evidence of a significant decline in water quality (increase in nitrate concentrations particularly) in our waterways. Changed land use patterns, and the associated increases in sewage effluent and catchment and stormwater runoff, have resulted in increases in nutrient and sediment runoff to Moreton Bay, and contributed to a significant degradation of water quality.

Summary of changes in water quality in the tidal, seasonal and marine zones relative to 1950. Increases are rounded to whole numbers and are relative to 1950.

	1950 $\mu g\ L^{-1}$	1984 $\mu g\ L^{-1}$	1950-84 Increase	1997 $\mu g\ L^{-1}$	1950-97 Increase
Phosphates					
Tidal	12.2	44.6	4x	42.3	3x
Seasonal	6.7	17.4	3x	20.1	3x
Marine	5.9	9.3	2x	11.2	2x
Nitrates					
Tidal	2.7	25.4	9x	8.1	3x
Seasonal	0.6	22.9	38x	4.9	8x
Marine	0.6	9.9	17x	2.6	4x

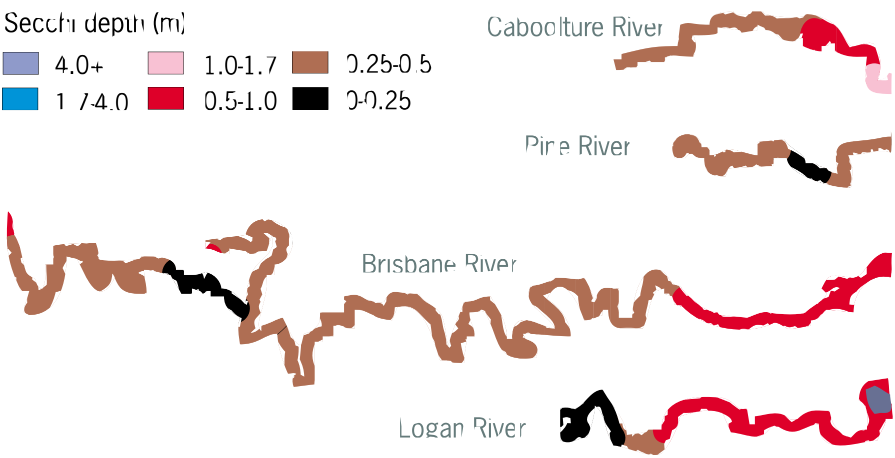
Turbid river estuaries

River estuaries in the Moreton Region are typically turbid, as indicated by measurements of total suspended solids, turbidity (Nephelometric Turbidity Units, NTU) and secchi depth. High turbidity in these sections of our waterways result in low phytoplankton abundance and strong light limitation of these communities. This high turbidity prevents the occurrence of algal blooms usually brought about by high nutrient loads into the system. The turbid nature of the river estuaries has been concluded to be caused by the excessive production of organic and inorganic suspended sediments from rural and urban sources, and continued resuspension by processes such as tidal action and dredging (Stock, E. and Neller, R., 1990, The Brisbane River, A Source-book for the Future). Increased turbidity has also been associated with high rainfall and associated run-off events. Strong tidal currents keep the particles in the river estuaries in suspension. River estuaries also have long residence times (up to 120 days, refer to Chapter 3), which contribute to their turbid nature.



Suspended sediment load and turbidity profiles along the Brisbane River. Highest levels of suspended matter and thus highest turbidity occurred 40-60km upstream (Cox, M., 1998, Moreton Bay and Catchment).

Turbidity is also related to the sediment trapping capacities of our rivers. Dredging and upstream retention of flood water (through the dams) has increased the sediment trapping capacity of the river estuaries.



Secchi depth along the four major river estuaries flowing to Moreton Bay. Highest turbidity occurred in the Brisbane River.

Particularly turbid Brisbane River estuary

Satellite image of the Brisbane River estuary. The turbidity region which correlates with low secchi depth, high total suspended solids and turbidity is clearly visible in the satellite image.

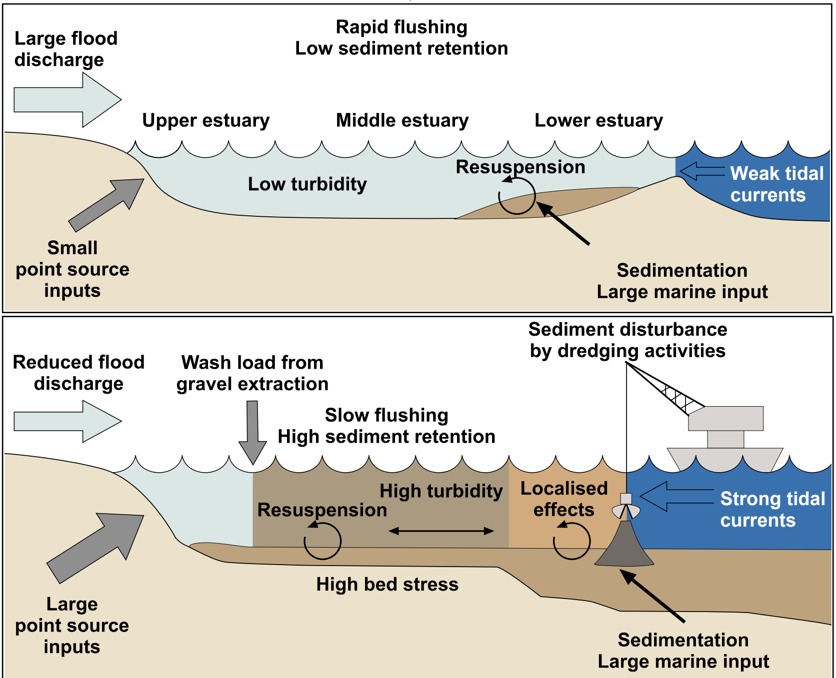
SATELLITE IMAGE PROVIDED BY THE AUSTRALIAN CENTRE FOR REMOTE SENSING

Multiple turbidity sources: Brisbane River

Brisbane River turbidity is largely a result of suspended sediments in the water column. Sediments can be derived from a number of sources including catchment runoff, gravel washing, urban runoff and input from Moreton Bay. A major sediment input into the Brisbane River is the input of sediments from Moreton Bay. Water depths in Brisbane River are maintained deeper than Moreton Bay through navigational dredging. This allows the deposition of sediments from Moreton Bay into the lower reaches of the Brisbane River.

Sediment deposited in the lower Brisbane River may not contribute significantly to the tidally-induced turbidity maximum. During the dry season, mass-balance calculations suggest that urban runoff and the wash load from gravel extraction could account for most of the suspended sediment concentrations (turbidity) in the water column.

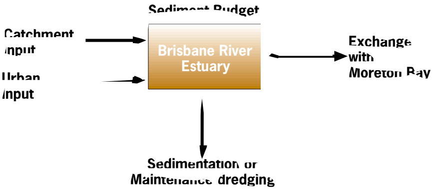
Today, the Brisbane River requires a flood discharge of about 2x10^9 m^3 to flush fresh to the mouth. In 1962 the amount required was 0.8x10^9 m^3. This 2.5 fold difference results in a change in the sediment transport capacity of the river. Dredging and upstream retention of flood water (through the dams) have increased the sediment trapping capacity of the estuary. The river can trap a greater proportion of flood-borne sediment. Extractive dredging in the Brisbane River ceased in December, 1998, however, on-going navigational dredging in the lower reaches continues.



Conceptual models depicting the historical and present factors causing changes to sediment inputs and turbidity. Historically, small point source inputs and weak tidal flushing maintained low riverine turbidity while currently, large point source inputs of sediment, strong tidal currents and upstream resuspension leads to high turbidity in the Brisbane River.

Turbidity maintenance by tidal resuspension

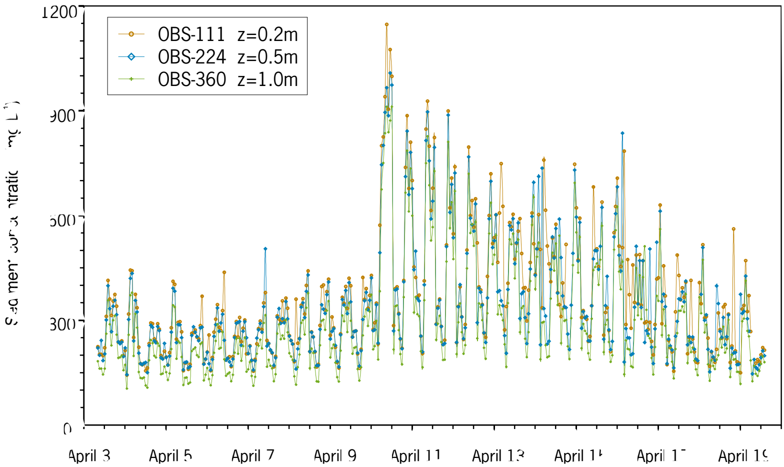
Using a data-logging instrument array deployed in the Brisbane River, turbidity was measured near the river bottom. Little variation occurred between suspended sediment concentrations 20, 50 and 100 cm above the bottom of the river. This lack of vertical stratification of turbidity within a metre above the bottom matches a lack of vertical stratification measured throughout the water column. The tidal energy effectively serves to completely mix the water column in the Brisbane River. The tidal signal of turbidity is pronounced within the river, and every 6 hours a peak of suspended sediment concentration occurs. These 6 hour periods of high and low suspended sediment concentrations match periods of flooding and ebbing tidal currents in the river. As each tidal wave propagates upriver the energy associated with that wave resuspends sediments, particularly the fine-grained sediments resulting in higher suspended sediment concentrations. Extractive dredging, which removes primarily sand and gravel sized particles, would have little influence on the availability of fine-particles for resuspension, however washing of fine particles back into the river increases turbidity. The propagation of tidal energy into the estuary is accentuated by the navigational dredging which removed the sand bar barrier at the mouth.



Conceptualisation of the sediment budget for the Brisbane River.

Sediment budget for the Brisbane River estuary (tonnes yr^{-1})

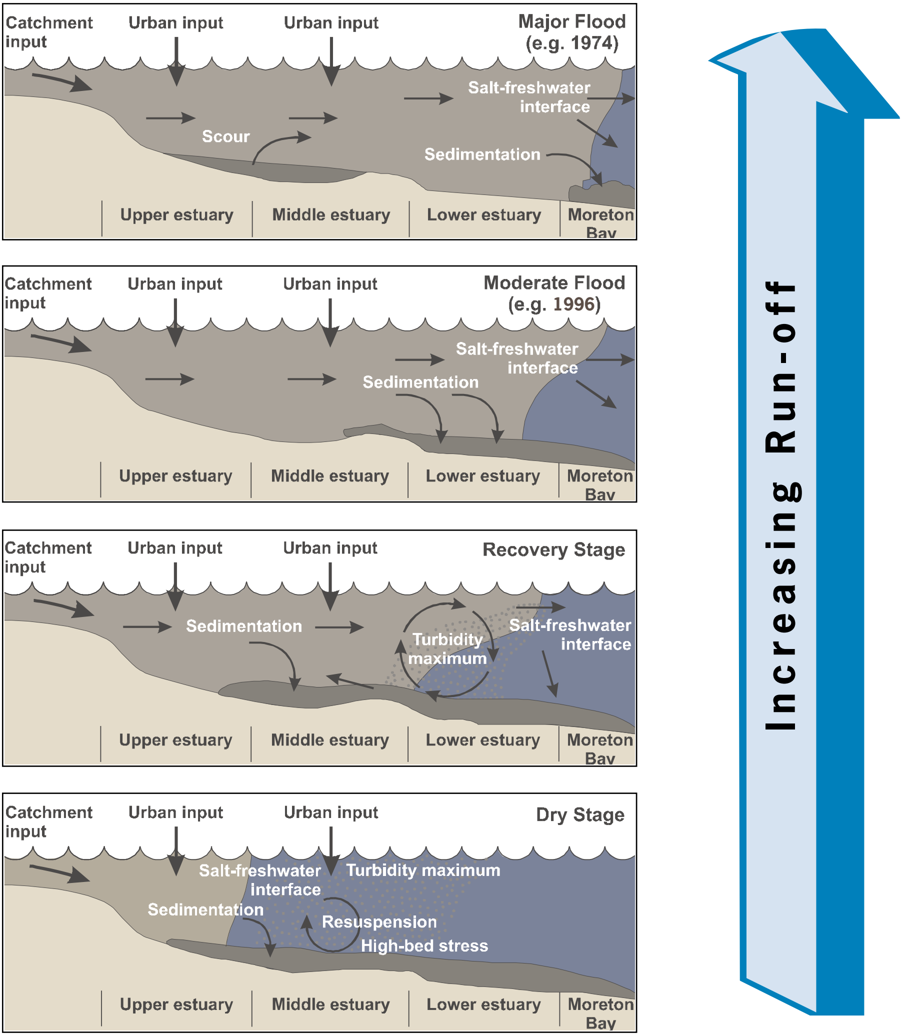
	Average year	1996 flood
Catchment input	178 321	599 854
Urban input	112 190	152 369
Export to Moreton Bay	92 801	495 137
Fluvial deposition	197 711	257 086
Marine deposition	456 133	456 133
Net deposition	653 844	713 219



Turbidity for water near the sediment surface of the Brisbane River. There is a pronounced tidal signal of turbidity within the River, with 6-hour periods of high and low suspended sediment concentrations associated with periods of flooding and ebbing tidal currents, respectively.

Turbidity influenced by river flow

The Brisbane River is more turbid than other sub-tropical Australian estuaries. The turbidity is largely a result of suspended sediments in the water column. Sediments can be derived from a number of sources including catchment run-off, gravel washing, urban run-off and input from Moreton Bay, and maintained by, for example, scouring and resuspension processes.



Conceptual models of processes maintaining suspended sediment in the Brisbane River estuary. Turbidity maximums are maintained by the development of a gravitational (recovery stage) and dry stage where sedimentation and resuspension occur in the lower and middle reaches of the estuary at the salt-freshwater interface.

Next section ▶

CHAPTER 5

Sediment and Nutrient Loads

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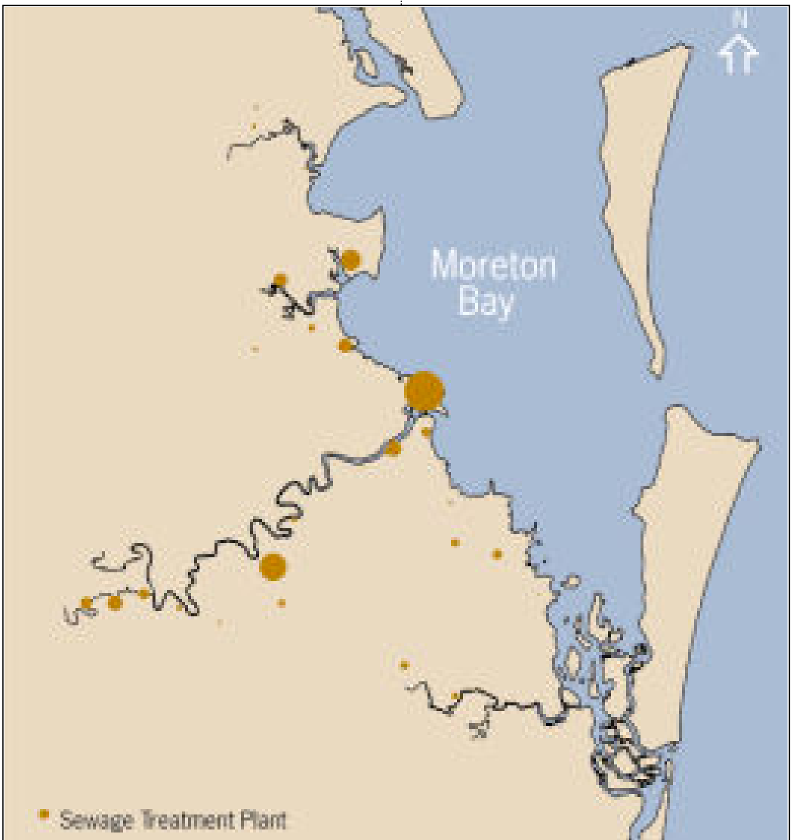
BRISBANE CITY COUNCIL

- Most sewage discharges into river estuaries
- Major sewage loading into Brisbane River estuary
- Increased sediment and nutrient run-off from land disturbance
- Discrepancy in non-point source estimates during low flow
- Atmospheric nutrient sources highest near Brisbane River mouth
- Discrepancy in estimates of atmospheric input
- Groundwater not a major nutrient source

Most sewage discharges into river estuaries

Sewage treatment plants (STP) are point source inputs to the river estuaries. Other point source inputs into the waterways include discharges from petroleum refineries, paper manufacturers, meat and food processors, landfills, dredging and gravel extraction operations, petroleum storage, water treatment plants, aquaculture operations, boating operations and other industries with small loadings. Major point sources are those that discharge more than 0.5 megalitres of effluent per day on a regular basis; in the study region this includes a total of 30 sewage treatment plants and 7 industrial wastewater treatment plants. Most of these treatment plants discharge their effluent into the river estuaries.

Effluent discharges into the waterways comply with specific Queensland Environmental Protection Agency licensing requirements. The majority of STPs remove solids and most organic matter, however, the effluent still contains some nutrients (mainly nitrogen and phosphorus), bacteria, and may contain metals and organic compounds.



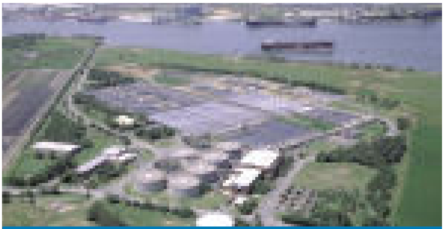
Relative nitrogen loading (expressed as relative dot sizes) from the sewage treatment plants. The greatest sewage nitrogen inputs are from the Luggage Point STP discharging 2.5t N d^{-1} into the mouth of the Brisbane River .

Major sewage loading into Brisbane River estuary

Most of the sewage and industrial point source discharges are into the Brisbane River estuary. Approximately 70-75% of the total point source load to Moreton Bay is via the Brisbane River estuary. Luggage Point and Oxley Creek sewage treatment plants are the two largest point source discharges in the region. The Luggage Point sewage treatment plant (STP) alone provides approximately one half of the total point source nutrient load into the Brisbane River and a third of the total point source nutrient loading to Moreton Bay.

In a 'do nothing' scenario where no new management actions are implemented and population continues to grow over the next 70 years, it is expected that by the year 2037 up to 45% of the total nutrient load to the Bay will come from Luggage Point STP.

Sustainable point source nitrogen (N) loads have been determined for various waterways including Deception, Bramble and Waterloo Bays. Best Practice Environmental Management will be achieved at almost all STPs and major industrial discharges. This includes an average total N concentration of 5 mg L^{-1} in treated effluent from Redcliffe STP by 2005 and 10 mg L^{-1} from Luggage Point STP by December 1999. Further improvements at Luggage Point are proposed by 2005.



Sewage treatment plant discharging into the Brisbane River

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Sewage treatment plant discharging into the Bremer River

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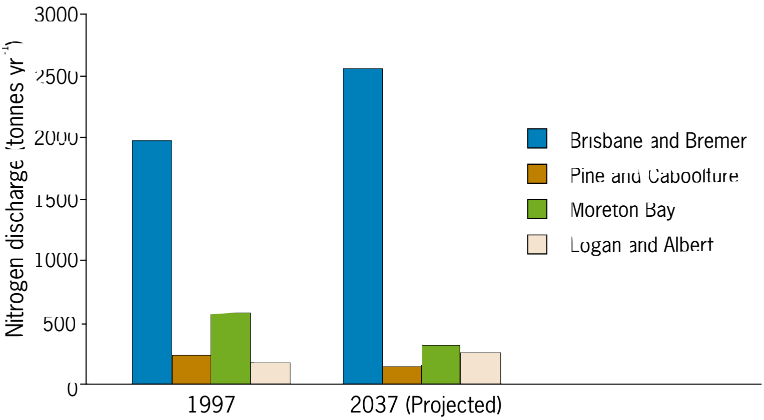
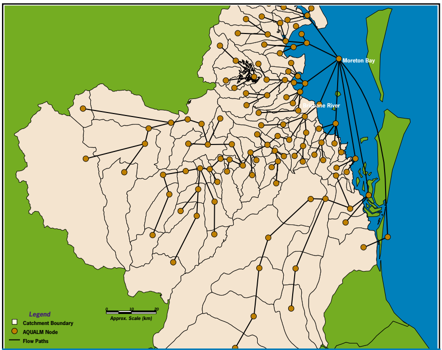


1997 and 2037 (projected) nitrogen discharge from major sewage treatment plants. The greatest contribution is and will remain from the combined discharge of the Brisbane and Bremer STPs

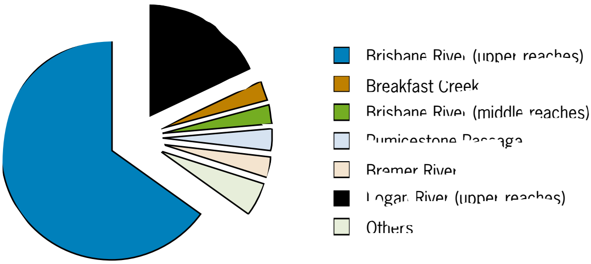
Increased sediment and nutrient run-off from land disturbance

Catchment runoff, estimated from limited data sets and a catchment runoff model (AQUALM), is largely affected by land disturbance. The model predictions indicate increased runoff of sediments and nutrients due to various types of land disturbance. The most extreme enhancement of sediment and nutrient runoff is via urbanisation.



Catchment run-off model (AQUALM) nodal network

The AQUALM model is a suite of programs used to model catchment run-off water quality and includes modules for estimating runoff and pollutant export and routing. The catchment was divided into 95 subcatchments and six land use categories (urban unsurfaced, urban surfaced, rural residential, cultivated, pasture and undisturbed). The model was then developed as a series of nodes and channels, including several outflow nodes into Moreton Bay. A hydrodynamic simulation of the May 1996 flood estimated that a total of 1.1 million tonnes of sediment was loaded into Moreton Bay during the period 27 April to 8 June 1996. The upper Brisbane River catchment contributed 65% of this 1.1 million tonnes, and the second largest contributor was the upper Logan catchment.



Hydrodynamic model simulation of sediment loads from the major river systems during the May 1996 flood event (in tonnes). The upper Brisbane River catchment contributed 65% of a total of 1.1 million tonnes of sediments.

Land use areal loading rates (kg ha^{-1} yr^{-1}) into Moreton Bay

	Total N	Total P	Total suspended solids
Undisturbed	0.99	0.10	100
Pasture	1.80	0.22	110
Pasture (Laidley)	2.10	0.28	85
Cultivated	4.40	0.55	200
Cultivated (Laidley)	5.60	0.56	240
Rural Residential	4.10	0.68	150
Urban unsurfaced	3.90	0.71	530
Urban surfaced	9.00	2.00	770

Discrepancy in non-point source estimates during low flow

Estimates of catchment nitrogen loads (tonnes yr^{-1}) into Moreton Bay

	Low Flow (average year)			High Flow (1996 flood)	
	AQUALM model estimates	Predicted[1]	Measured data[2]	AQUALM model estimates	Measured data[3]
Logan River	550	807	51	1400	777
Brisbane River	1100	1092		4500	2220
Caboolture River	100			190	348
Other	650	588		1610	
Total	2400	2487		7700	3345

Estimates of catchment phosphorus loads (tonnes yr^{-1}) into Moreton Bay

	Low Flow (average year)			High Flow (1996 flood)	
	AQUALM model estimates	Predicted[1]	Measured data[2]	AQUALM model estimates	Measured data[3]
Logan River	79	118	20	140	203
Brisbane River	160	152		620	342
Caboolture River	15			20	24
Other	86	220		181	
Total	340	490		970	569

1 Sinclair Knight Merz, 1995, Review of Brisbane River and Moreton Bay scientific data for Brisbane City Council.

2 Logan River data collected by Southern Cross University, Centre for Coastal Management 1997/1998

3 Eyre, B. and Davies, P., 1996, Flood impact monitoring Study Report.

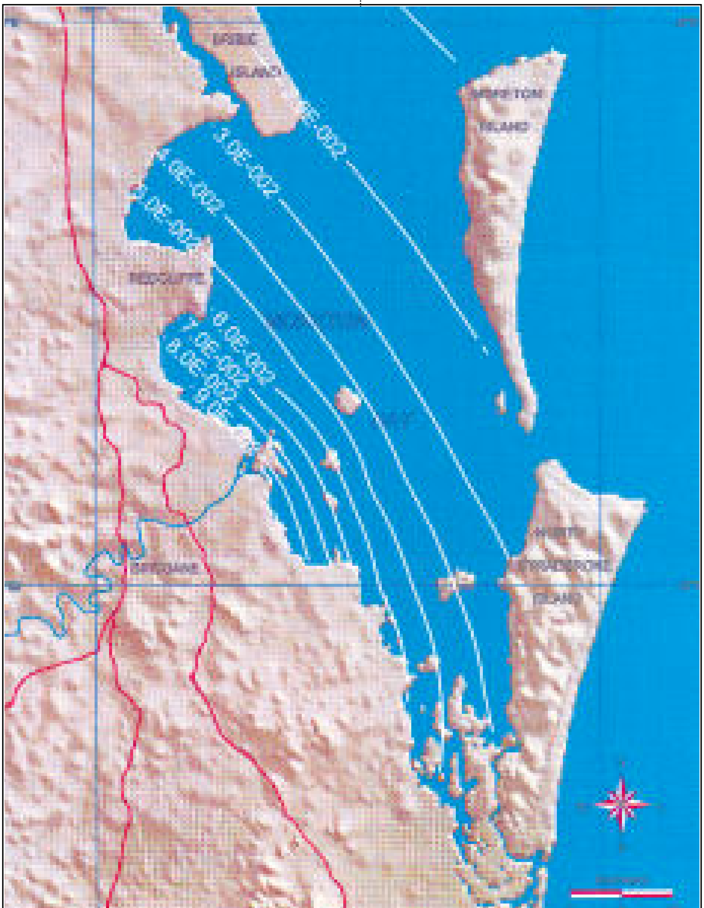
Output from the catchment runoff model (AQUALM) predicts that in low flow years, an average of 2400 tonnes of nitrogen (N) and 340 tonnes of phosphorus (P) are delivered to Moreton Bay from catchment sources. These estimates were similar to the loads predicted by a previous desktop study for an average year (Sinclair Knight Merz, 1995, Review of Brisbane River and Moreton Bay Scientific Data). However, comparison of model predictions and outputs calculated from flow weighted data for Logan River indicate a large discrepancy in load estimates. The model predicts 10 times higher total N and 4 times higher total P than flow weighted data.

This discrepancy between model outputs and measured values is not as much for a flood year (e.g. 1996). N loads from model outputs were 1.8 times higher than measured values and modeled P loads were 1.4 times higher than measured values.

This discrepancy could be attributed to errors in the characterisation of catchment processes such as flood plain storage and in-stream assimilation which reduce exports out of a catchment. Catchment processes are likely to be less important during flood years due to shorter residence times, which would account for the better agreement in high flow load estimates from model outputs and measured values.

Atmospheric nutrient sources highest near Brisbane River mouth

Atmospheric nutrient deposition loads were estimated using two models: a meteorological model (AUSMET) in conjunction with a plume dispersion model (AUSPUFF). The meteorological model (AUSMET) includes wind, terrain and boundary layer effects, and the plume dispersion model (AUSPUFF) includes parameters such as terrain effects, over-water transport, coastal effects, wet and dry precipitation, and chemical transformations. Model results predict an average of 69 tonnes of nitrogen per year and 25 tonnes of phosphorus per year are delivered to Moreton Bay. The general distribution pattern was highest atmospheric deposition near the Brisbane River mouth, and decreasing deposition away from the mouth.



Estimates of atmospheric deposition of total nitrogen based on outputs from a meteorological model (AUSMET) in conjunction with a dispersion model (AUSPUFF). Greatest deposition was near the Brisbane River mouth, with decreasing deposition moving further out into the Bay.

Discrepancy in estimates of atmospheric input

Model estimates for atmospheric deposition of nitrogen (N) appear to be quite low compared to measured loads from other locations. For example, measurements of atmospheric N deposition in coastal northern New South Wales (Richmond River Catchment) applied to the surface area of Moreton Bay results in an estimated N load of 1410 tonnes N per year. Estimates of phosphorus (P) deposition, on the other hand, were similar for both AUSMET/AUSPUFF model outputs and estimates using world literature concentrations of rainfall (i.e. 25 tonnes P per year and 18 tonnes P per year, respectively).

In spite of the large variability in the estimates of atmospheric N input, atmospheric inputs may potentially be important and should be monitored for the following reasons:

1 the input is more widespread throughout the Bay

2 reductions in sewage nutrient discharges and stormwater controls that are being instituted as part of the Water Quality Strategy are NOT accompanied by reductions in atmospheric inputs

3 atmospheric inputs may be increasing due to NOx from automobile emissions.

Estimates of atmospheric deposition of nitrogen and phosphorus (tonnes yr^{-1}) to Moreton Bay

	Year of collection	Nitrogen			Phosphorus		
		Mean	Min	Max	Mean	Min	Max
Model Estimate	[1]1981	69	48	90	28	2	250
North Stradbroke Island[2]	1978	9600	7040	12160	25		
Richmond River Catchment[2]	1996	1410	104	5465	95	10	528
World Literature[4]	-	1118	550	2983	18	5	154

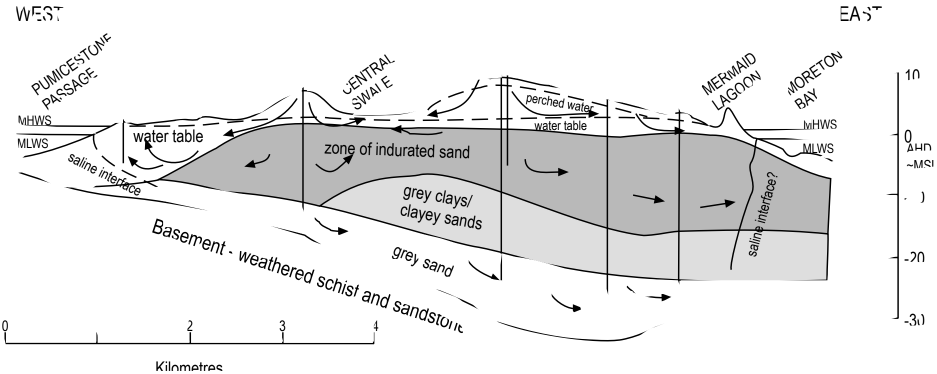
1 'Typical' weather year for the Moreton Bay region

2 Extrapolation based on data collected on North Stradbroke Island, the mean annual rainfall for Brisbane Airport (1177 mm) and the area of Moreton Bay

3 Calculations based on data collected in the coastal areas of the Richmond River Catchment in northern New South Wales, the mean annual rainfall for Brisbane Airport (1177 mm) and the area of Moreton Bay

4 Calculations based on data contained within Meybeck, 1982, for total dissolved nitrogen and total dissolved phosphorus, the mean annual rainfall for Brisbane Airport (1177 mm) and the area of Moreton Bay

Groundwater not a major nutrient source

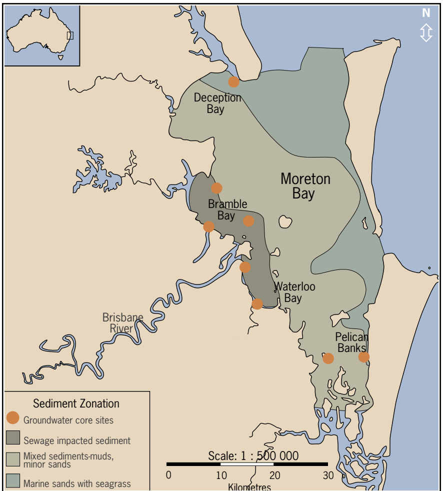


Groundwater flow through the central transect of Bribie Island. Groundwater flow in coastal regions is influenced by a number of factors, including the elevation of the seawater boundary above mean sea level (Harbison, J.E and Cox, M.E., 1998, Moreton Bay and Catchment).

Groundwater nutrient loads to Moreton Bay were estimated for a two-kilometre wide strip around the Bay and river estuaries. Groundwater discharges were calculated, taking into consideration geological materials/aquifer type, field permeability, likely depth of the water table, hydraulic gradient and the saturated thickness for each segment and then applying Darcy's Law of groundwater flow. Nutrient concentrations were then assigned to each discharge based on landuse, rainfall and aquifer type. Nutrient loads, of 120 tonnes nitrogen and 2.3 tonnes phosphorus per year associated with groundwater adjacent to Moreton Bay, represent a small component of the nutrient budget.

In coastal areas, the elevation of the seawater boundary above mean sea level, the degree of semi-confinement of the regional aquifer by horizons of indurated sand ('coffee rock'), and the extent of other low permeability layers, are among the critical factors affecting the behaviour of the groundwater system (Harbison, J.E. and Cox, M.E., 1998, Moreton Bay and Catchment).

Compared to the other pollutant loads (i.e. point sources, catchment run-off, atmospheric loads) into Moreton Bay and the river estuaries, the nutrient loads from groundwater sources were not highly significant.



Groundwater core sites and sediment zonation patterns in Moreton Bay

Next section ▶

CHAPTER 6

Sediments, Turbidity and Seagrass Impacts

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Sediments

- Muddy sediment deposited in central basin
- Resuspension of muddy sediment
- Resuspension due to tidal currents, wind waves and ocean swell
- Increased turbidity from resuspended mud

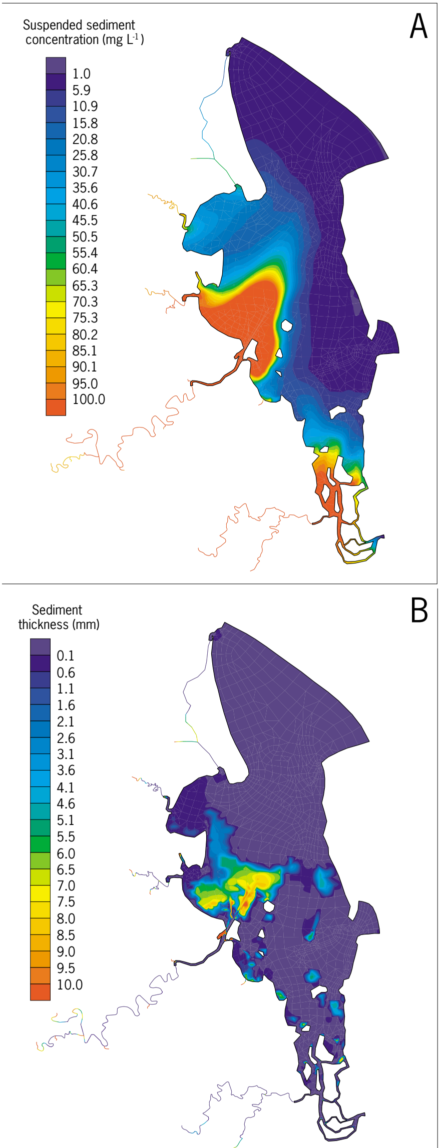
Turbidity

- Light attenuation from turbidity
- Light quality dependent on season and location
- Light anomaly in Deception Bay
- Underwater light loggers deployed throughout Bay
- No light reaching Bramble Bay seafloor

Seagrass Impacts

- Seagrass loss in turbid portions of Moreton Bay
- Seagrass distribution: light dependent
- Light availability measured with seagrass depth range
- Impact of light deprivation pronounced in western Bay

Muddy sediment deposited in central basin



Hydrodynamic transport model estimates of suspended sediment concentrations of A during a peak flood (May, 1996) and B the subsequent sediment deposition zones. Suspended sediment delivery to Bay resulted in a plume and deposition through Bramble and central Moreton Bay.

Using the hydrodynamic transport model, the distribution of suspended sediment and deposited sediments can be discerned. A large plume of suspended sediments enters Moreton Bay primarily from the Brisbane River but also from the Caboolture, Pine and Logan Rivers. As observed in the May 1996 flood event, extensive turbidity plumes are manifested throughout the Bay following a large runoff event. The fate of this suspended sediment material is ultimately either a) transport out of the Bay and into coastal waters or b) deposition on the Moreton Bay sea floor. This deposition onto the Moreton Bay sea floor can be predicted by simulating the effect of tides, wind and resulting water circulation on resuspension and deposition. Using the hydrodynamic transport model the simulated turbidity runoff event results in an accumulation of sediment. This pattern of sediment deposition is in a roughly triangular shape – with the bottom of the triangle extending from Bramble Bay to Mud Island and the top of the triangle at the northern tip of Redcliffe Peninsula – matching quite closely the sediment distributional patterns observed in Moreton Bay.

Sediment distribution patterns were mapped using diver collected samples at approximately 50 stations throughout the bay. The top 2 cm of sediment was collected by hand and analysed for sediment grain sizes and nutrients. Sediment grain size patterns can be grouped into two major categories: percent mud and percent sand. The sediment size criteria for mud was less than 0.0625 mm diameter and for sand between 2 and 0.0625 mm. The high percent mud content in the Bay is concentrated in the same triangular pattern of Bramble Bay to Mud Island to the tip of Redcliffe Peninsula as was predicted by the hydrodynamic transport model. In addition to the large mud pool in the western-central Moreton Bay, there were small regions in the Bay with high mud content: Deception Bay, Waterloo Bay and southern

Sediments

Muddy sediment in western Bay.

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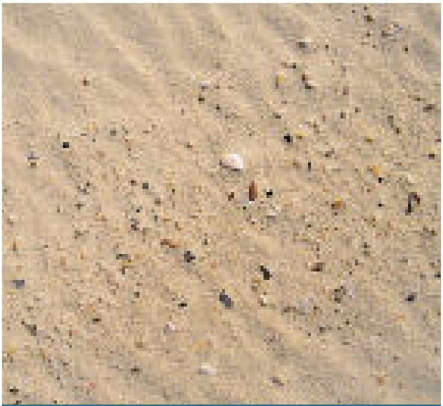

Sandy sediments predominate in the western and northern Bay regions

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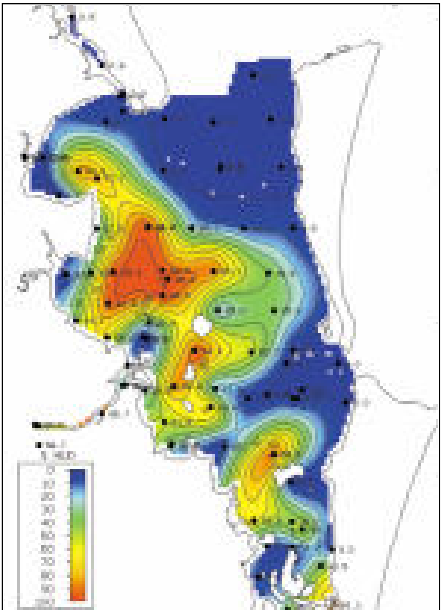
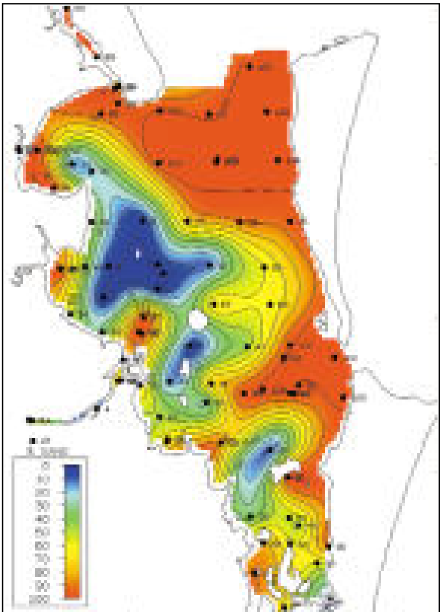
Moreton Bay near Peel Island. Sandy sediments occur at the river mouths, in Pumicestone Passage, on the Amity and Moreton Banks and throughout the tidal delta of the North Passage. The muddy sediments are largely terrigenous in origin, however sandy sediments have either a marine origin (near the passages) or terrigenous in origin (river mouths). Fine-grained sediment particles i.e. mud, are more easily resuspended due to waves, tides or ocean swell than large-grained sediment particles. Thus, the distribution of the muddy sediments in Moreton Bay with their terrigenous origin are of concern regarding resuspension processes.



Distribution of mud in Moreton Bay. Bramble Bay and central Moreton Bay sediments are dominated by mud.



Distribution of sand in Moreton Bay. North, eastern and southern Moreton Bay sediments are dominated by sand.

Sediments

Resuspension of muddy sediment

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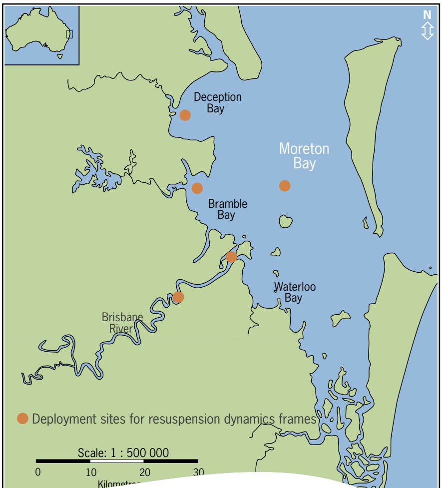
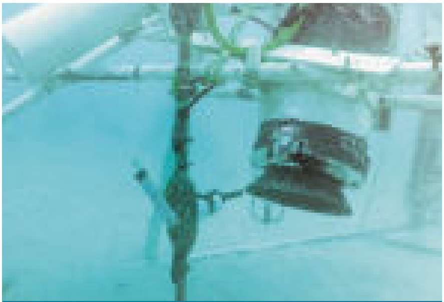
Resuspension dynamics frame with instrument array

Resuspension dynamics were measured with a set of instruments deployed on a tripod that rested on the sea floor. The submersible instrument array was deployed successively at several locations. This approach allowed data collection during strong wind events when research vessels would not be available. Data logging turbidity sensors as well as wave, water current and tidal-stage sensors were used. In addition, sediment traps at various distances above the sea floor were deployed to measure sedimentation rates.



Deployment sites for resuspension dynamics frames



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Underwater video camera to observe sediment resuspension

Resuspension of muddy sediments in the western/central Moreton Bay occurred via a) tidal currents, b) wind waves and c) ocean swell. The combination of these processes results in virtually all of the muddy sediments being available for resuspension on a daily basis. Even in the deeper portions of the central basin, tidal currents are sufficient to resuspend mud. Due to the shallow nature of the Bay and the various energy forces impacting upon the water, there is essentially nowhere in the study region in which deposited sediments are free from resuspension forces.

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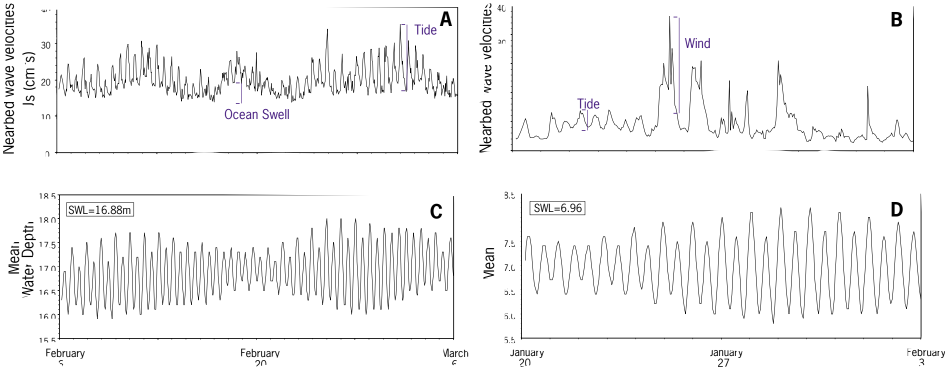
Frame with sediment traps to measure sediment deposition rates

Resuspension due to tidal currents, wind waves and ocean swell

Time course plots of current speed reveal the interactions of the various forcing functions influencing resuspension dynamics, with the different time-scales of tidal currents (6 hour intervals), wind waves (days) and ocean swells (days). The relative importance of tidal currents, wind waves and ocean swells varies throughout the Bay. Ocean swells and tidal currents are particularly relevant near the inlets. Tidal currents are important in the river estuaries. Wind waves are particularly important in shallow water where effects of the short wave-length wind waves are manifested. Western portions of Moreton Bay, in particular Deception and Bramble Bays, are particularly affected by wind waves due to the prevailing north-easterly and south-easterly winds and the shallow water depths.

The water depths recorded by the underwater data logging apparatus clearly show the tidal influence. Both the 6 hourly change of high to low tide and the fortnightly change between spring tides (higher high and lower low tides) and neap tides (moderate high and low tides). These fortnightly changes in tide height also result in changes in tidal currents and resuspension. For example, periods of spring tides result in greater tidal currents and tidal resuspension.



Wave velocities at the seabed during tidal cycles measured at (A) North Passage and (B) Bramble Bay and mean water depths at (C) North Passage and (D) Bramble Bay. Oceanic swells, tidal fluctuations and wind events leads to fluctuating water levels and current speeds.

Current meters on the resuspension dynamics frame

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Sediments

Increased turbidity from resuspended mud

Scientist filtering water for analysis of total suspended solid concentrations.

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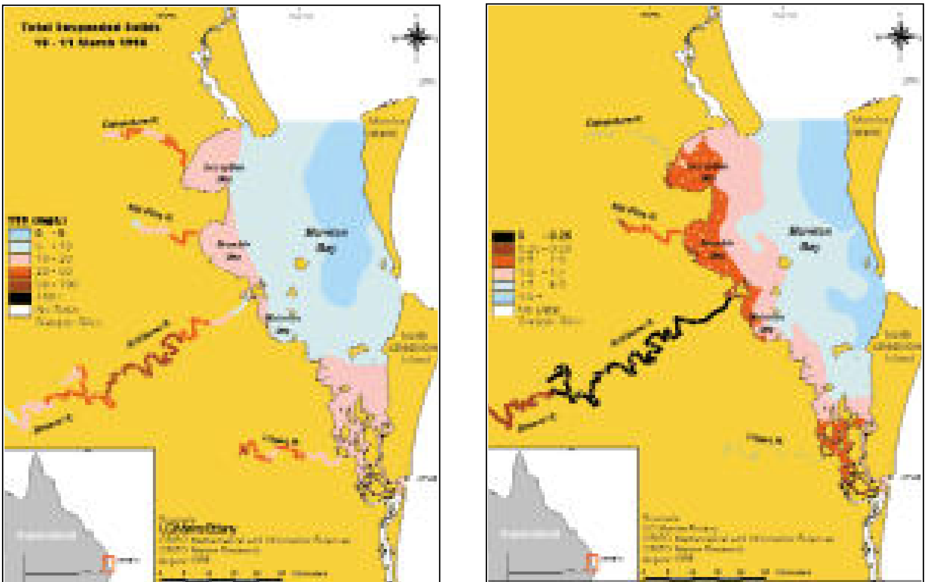
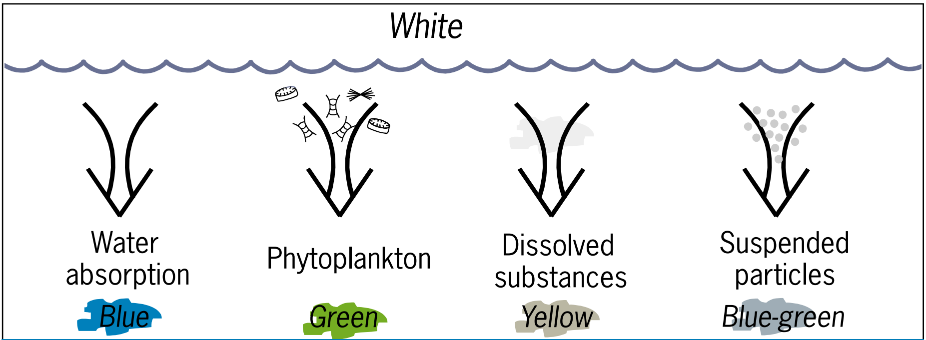
High turbidity levels, measured as total suspended solids (TSS), were observed in the western embayments (Deception and Bramble Bay), portions of Waterloo Bay and throughout southern Moreton Bay. These high levels of total suspended solids in the western and southern Bay are consistent with previous surveys in the region (Moss, A.J., et al., 1992, Moreton Bay in the Balance; Abal, E.G. and Dennison, W.C., 1996; Mar. Freshw. Res. 47, O'Donohue, M.J.H. and Dennison, W.C., 1997; Estuaries 20). Associated with high TSS loads is a reduction in light penetration into the water as manifested by reductions in secchi depth. The secchi disc is a round dinner-plate sized disc which is lowered over the side of the boat until it is no longer visible. The secchi depths in the western embayments and southern Moreton Bay are generally less than half a metre and in the rivers they are generally tens of centimetres. In contrast, low TSS and very deep secchi depths are observed in the eastern and northern portions of Moreton Bay, and secchi depths often reach the sea floor in these regions.



Total suspended solid (TSS) concentration in the water column and secchi depth of Moreton Bay and rivers. High turbidity from resuspension of the fine muds in the western Bay portions results in high TSS loads and shallow secchi depths.

Light attenuation from turbidity



Light attenuation properties of the water column and materials suspended in the water. As white light passes through the water column, wavelengths of light are selectively absorbed leading to variously 'coloured' water

A variety of factors attenuate light in water. The different attenuating factors result in the water colour that is visible to the human eye. Water itself absorbs light, particularly in the red wavelengths, leaving only blue wavelengths. Phytoplankton (microscopic plant life) floating in the water also absorb light, primarily due to the photosynthetic pigments in the phytoplankton cells. Chlorophyll is a photosynthetic pigment of all phytoplankton, and chlorophyll molecules absorb red and blue light leaving green light (this is why plants generally appear green). Dissolved substances within water also absorb light. These dissolved substances are often humic and tannic acids from mangrove or melaleuca swamps, and they absorb blue light resulting in a yellowish-brown water colour. Another contribution to light attenuation is due to suspended particles such as sediments or organic matter. These particles reflect light, effectively increasing the path length for light in water and the absorption of red light, resulting in blue or blue-green water colour.

Any particular water mass contains some level of phytoplankton, dissolved substances and suspended particles. The contribution of these factors result in a water colour associated with a particular water mass. The brown water colour of the river estuaries is mostly due to suspended particles. The green water colour both upstream and downstream of the turbidity region in the river estuaries is due to phytoplankton. Following runoff events, especially in the Pumicestone Passage region, dissolved substances in the water darkly stain the water yellowish-brown. The blue water of eastern and northern Moreton Bay is a result of low concentrations or dissolved substances in the water.

One of the efforts in Stage 2 of the study was to quantify the different light attenuating processes in water, as well as determine the overall light attenuation characteristics of each water body, to be able to discern how much light reached the sea floor.

Spectroradiometer used to measure spectral properties of the water

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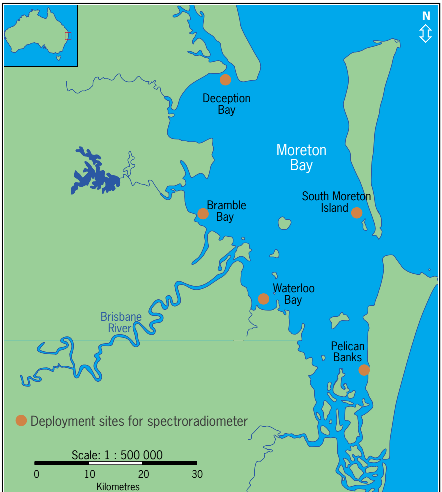
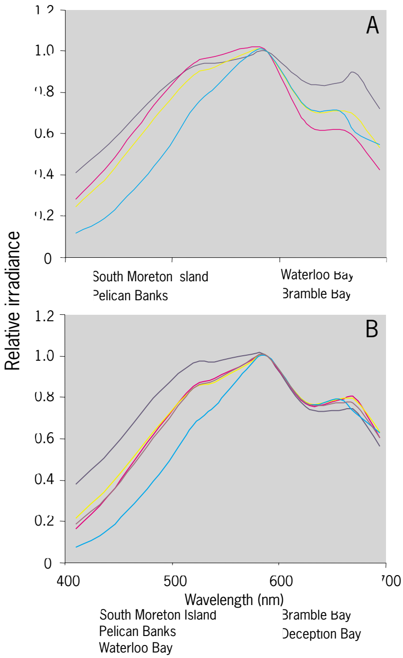
Light quality dependent on season and location

A spectroradiometer was used to measure the different wavelengths of light resulting from the combined light attenuating processes: water, phytoplankton, dissolved substances and suspended particles. The spectroradiometer was deployed twice: September, 1997 and January, 1998. Light absorption characteristics differed throughout Moreton Bay. In particular, the absorption of blue light was variable between water masses and red light absorption was also variable in September. The site with consistently the most blue light penetration was the eastern bay (south Moreton Island) site. The turbid water of Bramble Bay was consistently lower in blue light penetration. Absorption curves were generated in low water flow periods. There was a small rain event prior to the September sampling, but none prior to the January sampling period. Deception Bay was not sampled in September following the small runoff event due to logistical constraints. This was unfortunate in that a light anomaly in Deception Bay is evident by comparison with the light data from other Moreton Bay sites. Comparing light attenuation measured by a submersible light sensor and a secchi disc, a strong relationship exists between these two, among the sites of Moreton Bay – with the exception of Deception Bay. The comparison of light attenuation or secchi depth with another measure of light, seagrass depth range, provides support for a consistent anomaly of Deception Bay light data.

The spectroradiometer measurements made in Deception Bay in January do not reveal divergence of light quality from the other sites. However, visual observation of water colour in Deception Bay and southern Pumicestone Passage immediately following rain events, indicates a change in light quality due to the large humic and tannic acid runoff. Time course spectroradiometer measurements will be required to resolve this anomaly.

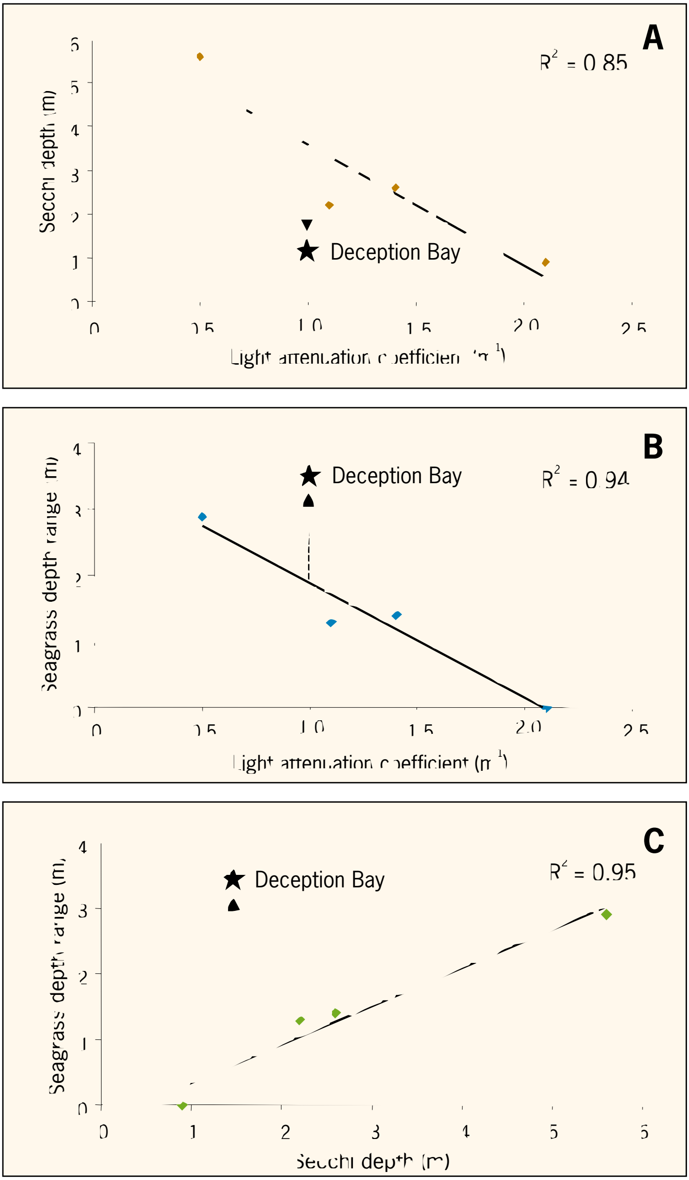


Deployment sites for the spectroradiometer.



Spectral irradiance at the seagrass monitoring sites A) September 1997 and B) January 1998. Bramble Bay had consistently lower blue light penetration.

Light anomaly in Deception Bay



Correlations of secchi depth, seagrass depth range and light attenuation at the 5 seagrass sites. Consistent light anomalies occurred in Deception Bay where A) shallow secchi depth accompanied low light attenuation coefficient B) seagrass depth range remained the greatest despite higher light attenuation coefficient and C) seagrass depth range remained high with low secchi depth.

Turbidity

Underwater light loggers deployed throughout Bay

Underwater light loggers with an automated 'cleaner' deployed in Moreton Bay.

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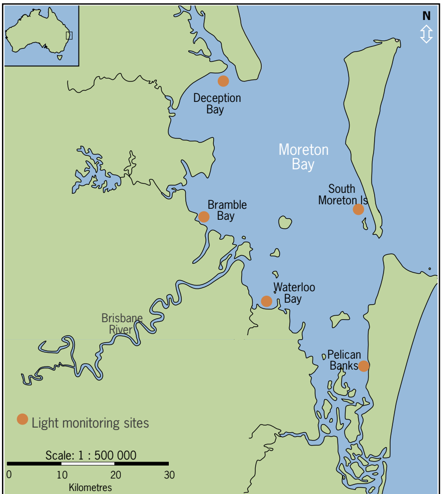
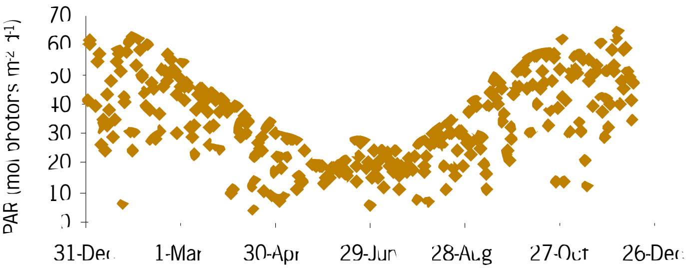
In order to accurately assess the relevant amount of light available for plant growth, photosynthetically active radiation (PAR = 400-700 nm) light loggers were deployed throughout the Bay. These submersible light loggers were accompanied by submersible motorised toothbrushes that swept the sensor surface every 15 minutes to avoid fouling. The sensors were collected every several weeks, the data downloaded and the sensors redeployed. Underwater light was monitored for approximately one year. Two sensors were deployed at each site, one in shallow water and one in deeper water equivalent to the deepest penetration of seagrass. By comparing the shallow and deep light sensor data, the light attenuation coefficient (previous page) of the water mass could be calculated. In addition to the pair of submersible sensors at each location in the Bay, a single sensor was placed on the roof of a building at the University of Queensland. The results from this ambient light sensor were used to calculate attenuation of surface light at each site, assuming a consistent light field across the geographic region. Viewing this surface light data, a seasonal trend of diminished light in winter is evident due to shorter day lengths and lower sun angle, as well as day-to-day variability due to cloud cover and atmospheric haze. The submersible light sensors at the deep extent of the seagrass beds showed a dampened seasonal variation compared with surface light intensity.



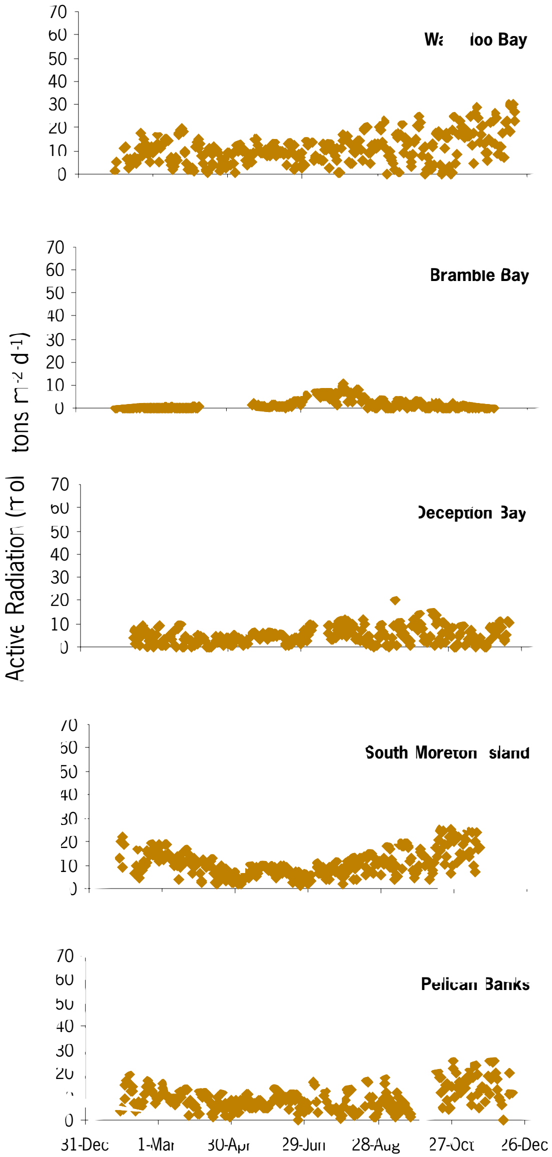
Deployment sites for underwater light loggers.



Surface photosynthetically active radiation (PAR) over one year. Light availability is greatly reduced in the winter months

No light reaching Bramble Bay seafloor

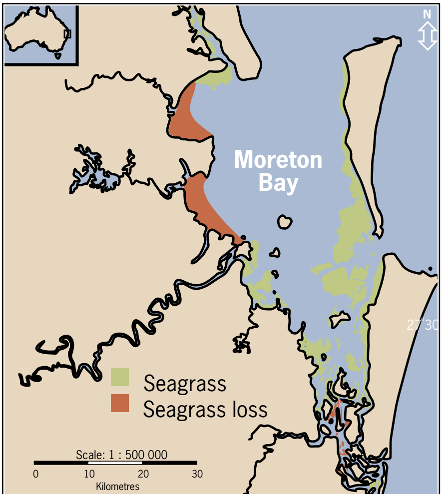
Bramble Bay had virtually no available light reaching the sea floor except for the small amounts measured in winter. The seasonal signal in light availability was most evident in the relatively clear water of the south Moreton Island site. However, this seasonal signal was dampened in the western Bay sites - Waterloo and Deception Bays. The seasonal improvement in water clarity that occurs in winter compensated for the lower light availability due to shorter day lengths and lower sun angle. It is quite evident from these long term measurements of light availability that insufficient light penetrates to the Bramble Bay sea floor to support seagrass. This is also supported by the consistently high total suspended solids and low secchi depth measurements made in Bramble Bay and southern Deception Bay during monthly sampling. Furthermore, the patterns of light attenuation observed at each of the sites is consistent with those spatial patterns observed in the intensive water quality surveys.



Photosynthetically active radiation reaching the sea floor at the light monitoring sites. No light reaches the Bramble Bay seafloor for most of the year and the winter depression in light availability observed at the surface was not seen at most sites.

Seagrass loss in turbid portions of Moreton Bay

No seagrass loss	Seagrass decline	No seagrass
Eastern Moreton Bay e.g. Amity Banks	Western and Southern Moreton Bay e.g. South Deception Bay	Western Moreton Bay e.g. Bramble Bay
High Secchi depth (5 m)	Low Secchi depth (2 m)	Very low Secchi depth (1 m)
Low K_d (0.5)	Medium K_d (1)	High K_d (2)
> 30% surface light	< 30% surface light	<<< 30% surface light

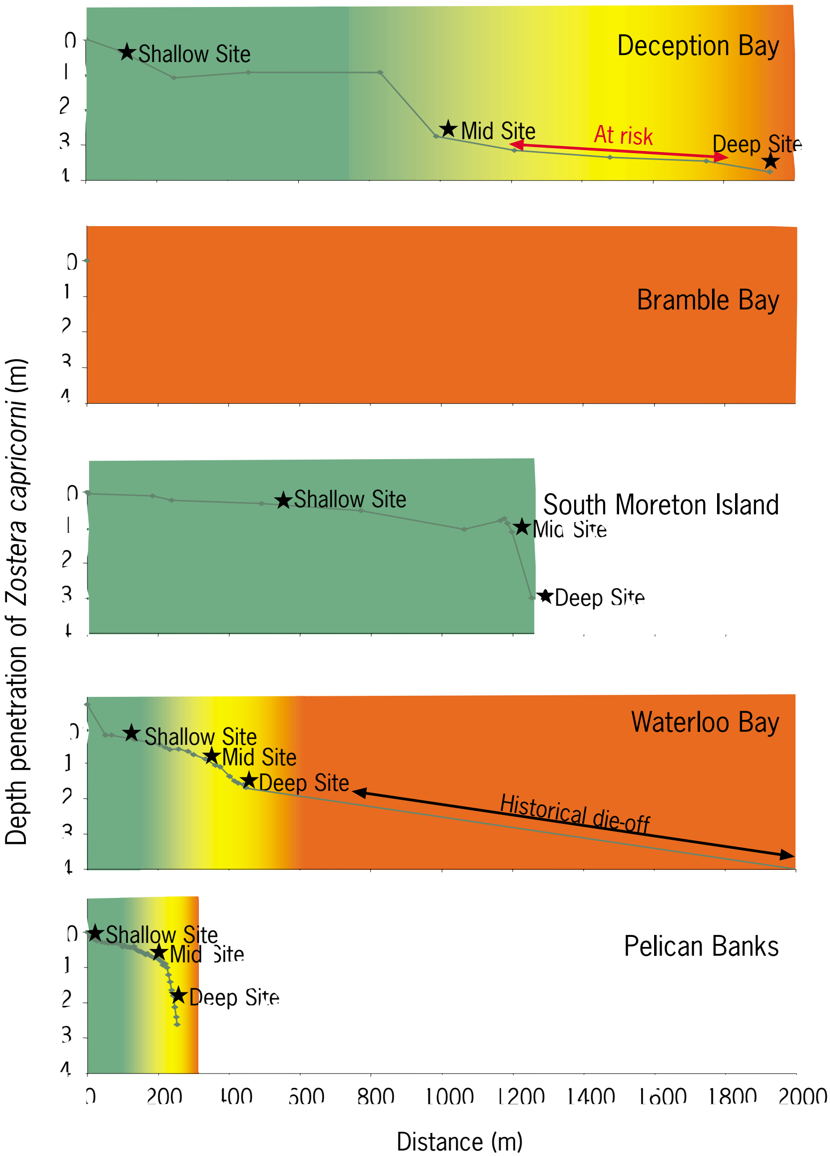


Anecdotal seagrass loss: Bramble Bay, and documented seagrass loss: southern Deception Bay and southern Moreton Bay.

Mud deposited in the central and western portions of Moreton Bay that is resuspended due to tidal currents, wind waves and ocean swell, results in turbid conditions and inadequate light penetration to support plants such as seagrasses. Seagrass losses in western Moreton Bay, in particular Bramble Bay and southern Deception Bay and in southern Moreton Bay near the Logan River mouth, have been observed. The southern Moreton Bay seagrass loss is documented to have occurred between 1987 and 1992 (Abal, E.G. and Dennison, W.C., 1996, Mar. Freshwater Res. 47). The southern Deception Bay seagrass loss occurred in 1996, Bramble Bay seagrass loss has not been documented, but probably occurred prior to the 1980's.

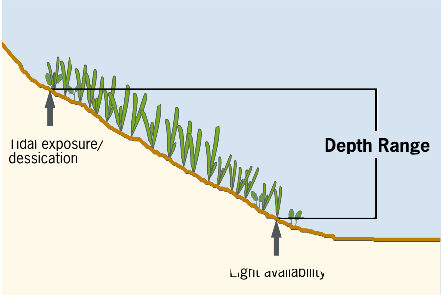
The distribution of seagrass along water depth profiles underscores the importance of light availability. Using a stoplight scheme of red, orange and green to indicate level of threat to seagrass, (green = no threat; orange = caution or danger; red = degraded) each site was characterised. Deception Bay seagrass penetrates to deep water, yet light sensor data indicates this may not be sustainable and the deeper portions of the Deception Bay seagrass beds are considered 'at risk'. Bramble Bay, currently with no seagrass, represents a totally degraded situation. South Moreton Island seagrass is in a stable light climate with no major threat to seagrasses based on light attenuation (K_d) processes. Waterloo Bay, with restricted seagrass depth distribution, is likely to have incurred historical seagrass loss. This seagrass loss, unlike Bramble Bay, southern Deception Bay and southern Moreton Bay, did not result in complete local extinction of seagrass but, instead, a reduction in seagrass depth range. The depth profile of Pelican Banks seagrass indicates a short steep water depth transect with deep penetration of seagrass. The depth profiles at the five sites were established at specific transects, but the water depth relationships are consistent regionally.

Seagrass distribution: light dependent

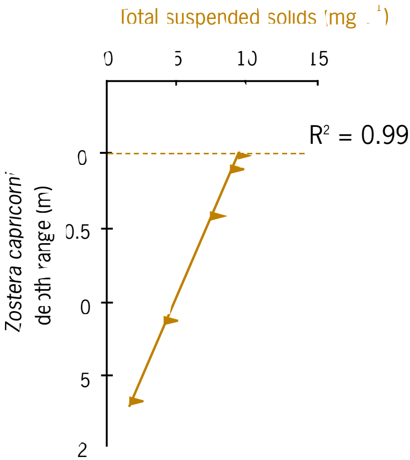


Seagrass depth *(Zostera capricorni)* profile at the five monitoring sites. Green represents healthy seagrass, yellow represents seagrass decline and red represents seagrass loss.

Light availability measured with seagrass



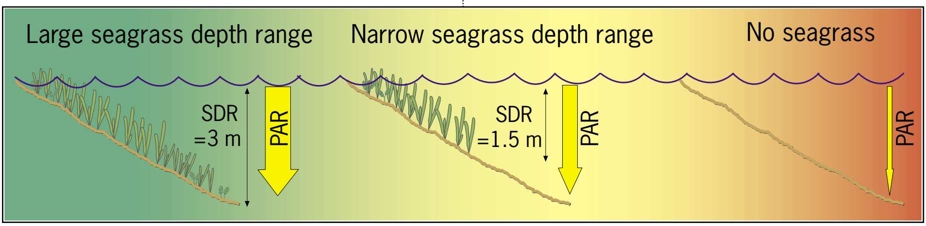
Schematic diagram of a depth profile with seagrass depth range indicated. Seagrass depth range measures the distance between the upper tidal limit of seagrass distribution and the lower, light-limited distribution.



***Zostera capricorni* depth range is strongly correlated with total suspended solid concentration in the water column.**

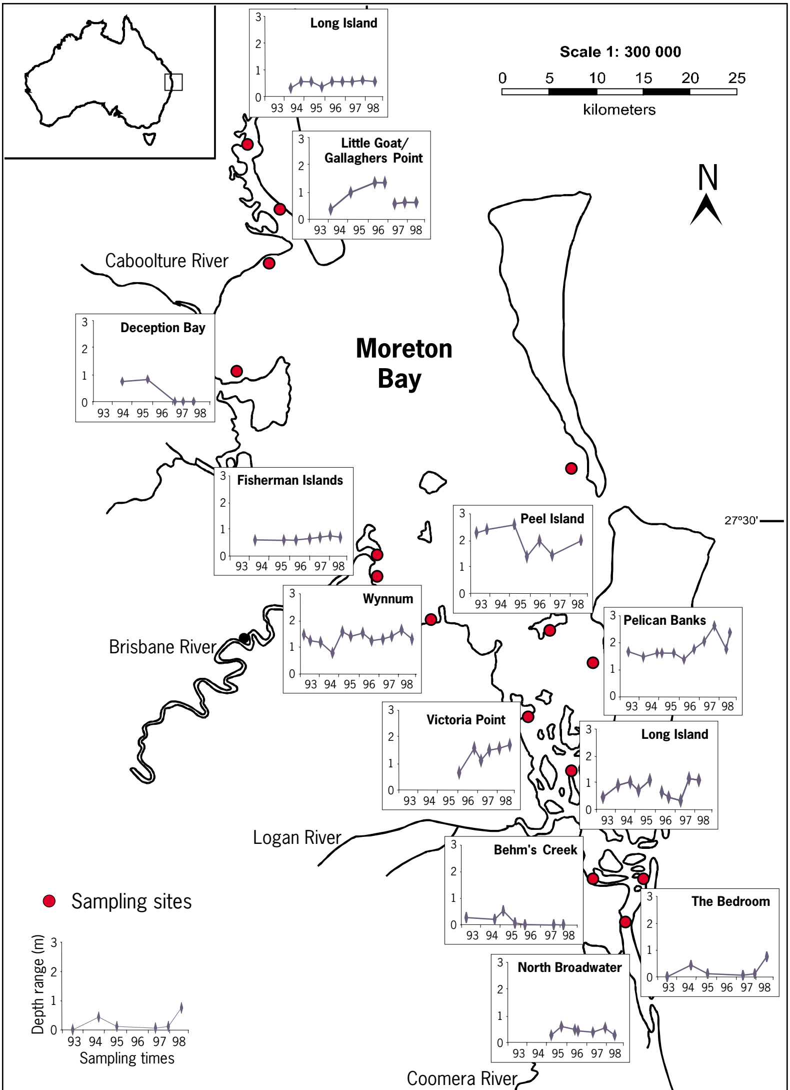
The relationship of seagrass depth range and light availability provides a robust management and monitoring tool. Accurate measurements of seagrass depth range can be used to infer long-term integrated changes in relevant light availability. Since 1993 the Moreton Bay Marine Park rangers have been monitoring seagrass depth range in conjunction with The University of Queenslands Marine Botany Group researchers. The upper range of seagrass is generally controlled by tidal exposure and desiccation, and the lower limit of seagrass controlled primarily by light availability. Channels, boating activity and bottom substrate characteristics can influence depth range, so sites were located specifically to avoid these complicating factors. The seagrass species monitored for depth range was *Zostera capricorni* (eelgrass). This seagrass species is rarely consumed by dugongs or turtles and its distribution is stable seasonally.

Annual and median water quality values collected fortnightly in the southern Moreton Bay region were compared with eelgrass depth range. A high correlation was obtained between total suspended solids and seagrass depth range (Abal, E.G. and Dennison, W.C., 1996, Mar. Freshwater Res., 47). Median annual total suspended solids concentrations in excess of 10 mg L^{-1} result in complete seagrass loss. This compares favourably with a similar study conducted in Chesapeake Bay in which 15 mg L^{-1} was established as a minimum habitat requirement (Dennison, W.C., 1993, et al., Bioscience, 43). Seagrass depth ranges, of



depth range

approximately 3 m, are associated with high light penetration, seagrass depth ranges of approximately 1-2 m correlated with reduced light levels, and no seagrass was associated with severely reduced light levels. Two seagrass losses were recorded over the 1993-98 period, Deception Bay in 1996 and Behms Creek, southern Moreton Bay in 1995-96. No recovery has been observed at either of these sites.



Temporal depiction of seagrass depth range from 1993-98. There is no consistent Bay-wide trend in decline or recovery, trends appear to be site-specific.

Impact of light deprivation pronounced in western Bay

In addition to chronic changes in light availability due to water quality degradation, there are changes in light that occur due to large runoff events. For example, in Hervey Bay in 1992, a series of large runoff events resulted in a widespread seagrass decline and associated dugong population migration and decline (Preen, A.R. et al., 1995, Aquatic Botany, 52). Large-scale flood events also occur in Moreton Bay. In May 1996 a large scale turbidity event reduced light penetration for a period of days to weeks. One of the features of seagrass persistence is the ability to withstand these light deprivation events associated with runoff. This is particularly relevant in this sub-tropical region in which runoff events are highly pulsed. In order to simulate a worst-case light deprivation event scenario, opaque shade screens were deployed at several sites in Moreton Bay. The results of these light deprivation experiments were variable, depending upon the site. Within 50 days of total light deprivation the seagrass biomass was reduced to essentially zero. However, the time course of this seagrass loss was variable between sites. Deception Bay seagrass which, based on light data, was most significantly at risk, had the lowest starting biomass and within forty days was essentially gone. Seagrass at Pelican Banks started with a much higher biomass, yet also declined rapidly and by forty days was essentially gone. In contrast Waterloo Bay, the site of chronic low light availability, was more persistent over the first forty days. The implications of these experiments are that seagrasses in Moreton Bay are susceptible to light deprivation events associated with high runoff. Future floods in the region, particularly successive flood events, could result in large-scale, widespread seagrass loss as has occurred elsewhere.

Opaque shade screen used to simulate worst-case light deprivation events

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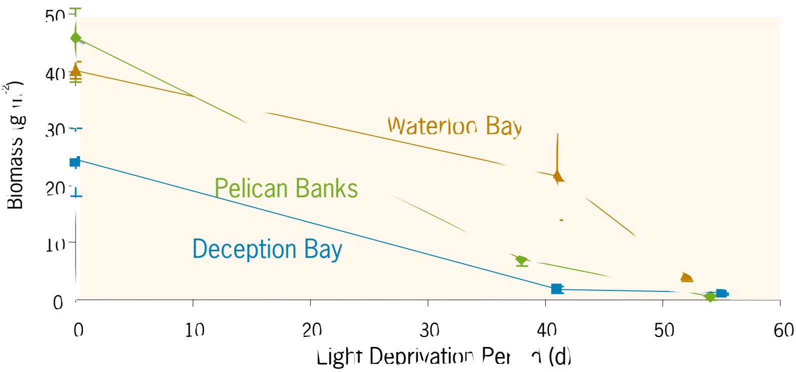

Effect of light deprivation on the biomass of the seagrass *Zostera capricorni*.

CHAPTER 7

Nutrient Distribution

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- Various forms of nutrients

Water Column Nutrients

- Rigorous testing of water column nutrients
- Nitrogen and phosphorus: river estuaries > western Bay > eastern Bay
- Spatial distribution patterns relatively consistent

Sediment Nutrients

- Intensive sediment sampling
- Diverse sampling techniques for different sediment nutrient forms
- Correlation of %mud with %total nutrients
- Porewater nutrients of surficial sediment: no pattern
- Exchangeable phosphate > exchangeable ammonium
- Depth profiling of sediment nutrients
- High ammonium in mud; high nitrate in sand

Water Column and Sediment Nutrients

- Strong gradients in both water column and sediment nutrients

Various forms of nutrients

Nutrients are elements that are essential for living organisms as they form the basis of all organic molecules and are required for structure, cellular functioning, growth and reproduction. Essential elements, including carbon (C), nitrogen (N) and phosphorus (P), are therefore those that, when deficient, lead to reduced growth. Other nutrients may be specifically important for groups of marine plants e.g. silica (Si) which is an essential component of the diatom skeleton.

Nutrients, particularly N and P, occur in various forms. Water column nutrients belong to two categories: dissolved or total, which includes both the dissolved and the organic particulate nutrient fraction. In aerobic environments, inorganic P occurs exclusively as orthophosphates, which refer to any salt of phosphoric acid. Phosphate (PO_4^{-3}) is the dominant form of P.

Nutrients are also found within sediments. Sediment nutrients occur in three interrelated forms: dissolved in the sediment porewater (porewater nutrients), adsorbed to the surface of the sediment particles (adsorbed or exchangeable nutrients) and fixed within the lattice structure or matrix of the sediment grains. The bioavailable fraction of sediment N and P includes the interstitial porewater nutrients and some fraction of the adsorbed nutrients. The interaction of nutrients within the mineral matrix and the surrounding environment is very weak and slow and essentially these nutrients become biologically unavailable. The time-scale of interaction between nutrients adsorbed to particles and dissolved in surrounding waters is relatively short, and these nutrients are generally considered biologically available. Sediment porewater nutrients are biologically available to organisms within the sediment and can become available to the water column by resuspension, bio-irrigation by animals or ventilation by rooted plants.

Major nitrogen species

Form	Species
Gas	Nitrogen gas (N_2)
Dissolved Inorganic Nitrogen (DIN)	Ammonium (NH_4^+) + Oxides of Nitrogen: Nitrate (NO_3^-) Nitrite (NO_2^-)
Dissolved Organic Nitrogen (DON)	e.g. urea
Particulate Organic Nitrogen (PON)	
Total Nitrogen	Dissolved + particulate

Major phosphorus species

Form	Species
Dissolved Inorganic Phosphorus (DIP), exculsively orthophosphates	Phosphoric acid (H_3PO_4) Dissociation products: Phosphate (PO_4^{-3}), $H_2PO_4^-$, HPO_4^{-2}
Dissolved Organic Phosphorus (DOP)	
Particulate Phosphorus	
Total P	Dissolved + particulate

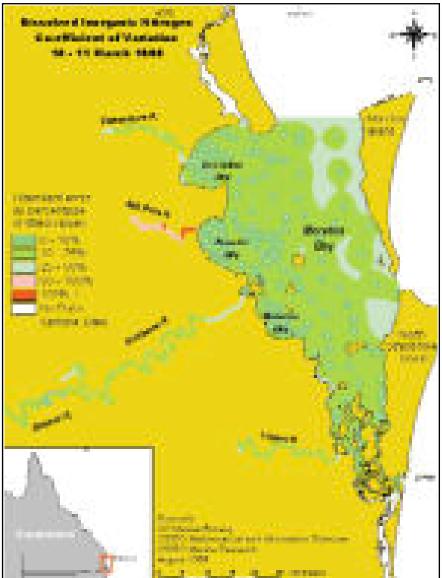
Redfield ratios

An oceanographer, A.C. Redfield, measured the relative abundance of C, N and P throughout the world's oceans and found a remarkable similarity in the atomic ratios of these elements. He consistently found C:N:P ratios of 1000:15:1 in seawater and in phytoplankton, he consistently found ratios of 106:16:1. This was interpreted as evidence that phytoplankton effectively regulate the availability of N and P in the upper, lighted portion of the ocean.

Oceanic Seawater:	1000C : 15N : 1P
Phytoplankton:	106C : 16N : 1P
Macrophytes (seagrasses & seaweeds):	550C : 30N : 1P
Seagrasses only:	480C : 18N : 1P

Note: Redfield ratios are molar or atomic ratios, not weight ratios

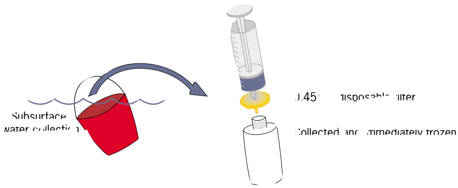
Rigorous testing of water column nutrients



Maps of Coefficient of Variation were created to estimate precision of interpolation of nutrient concentrations.

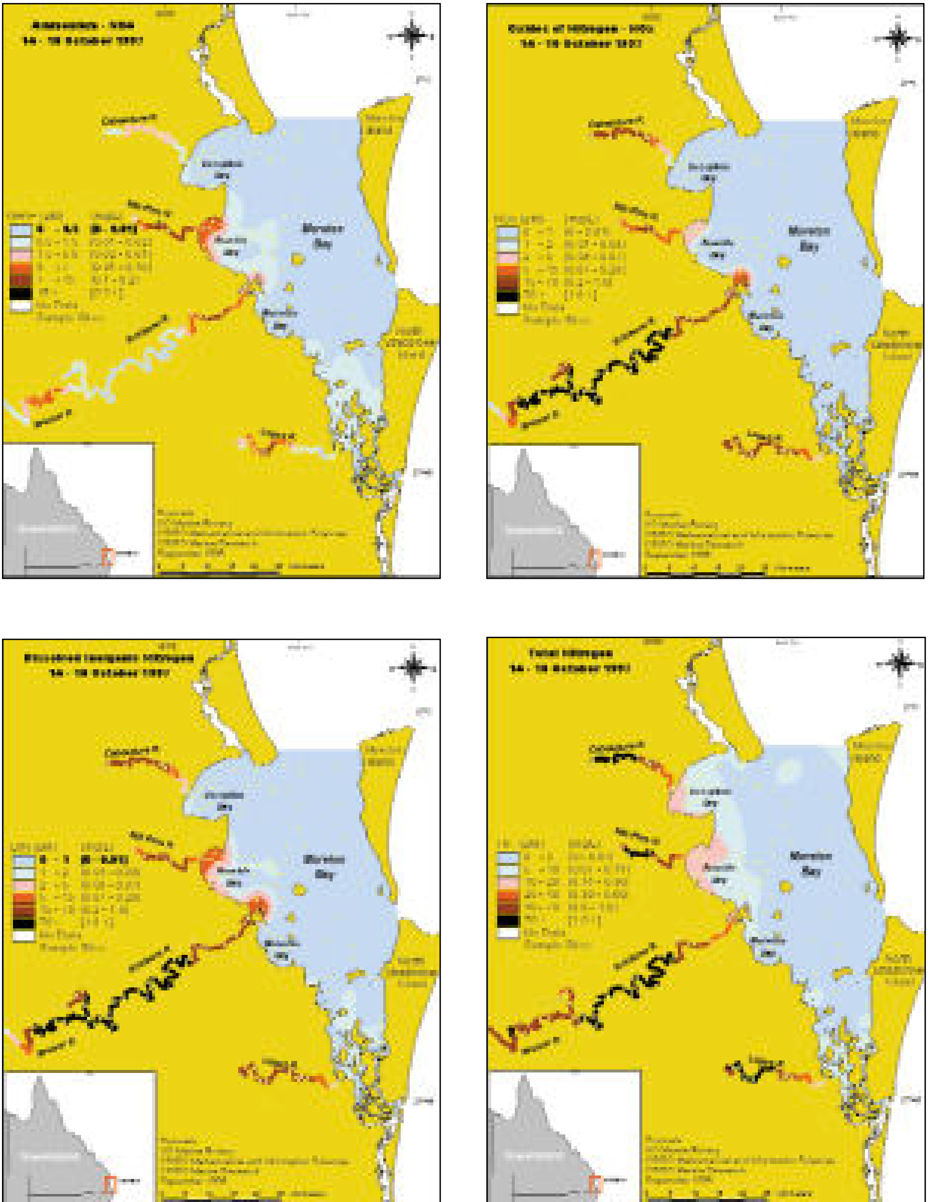
Intensive sampling for water column nutrients was conducted throughout Moreton Bay and the river estuaries. Sample sites were chosen to provide continuity with the existing data series i.e. maintaining sample sites used by Queensland Environmental Protection Agency and to obtain appropriate precision over the study area. Replicate nutrient samples were collected from the water surface and filtered in the field to remove particulate matter. Unfiltered (for analyses of total nutrients) and filtered water samples were frozen immediately using dry ice and transported to the Queensland Health laboratories where samples were analysed using auto-analyser chemical techniques. Standards were made up fresh for each sample run. Quality assurance/quality control was maintained using sample blanks prepared with the same filter techniques and nutrient analyses were conducted in the same laboratory by the same team.

Maps of nutrient concentrations and other water quality parameters represent the estimated water quality. These maps, however, were created from data taken from a finite number of sites. Since the maps seek to represent water quality at points other than those sampled, some process for generalising from the set of sites actually sampled, to all points in the study region, were made. However, sophisticated spatial analysis based on a statistical model was undertaken. The model combined two major components: the first is a large-scale fitted surface, which represents smooth changes in water quality over a study region. The second component represents small-scale deviations from the large-scale fitted surface, especially the correlations between deviations at neighbouring locations. Both of these components of the model were estimated from the sample data - and the fitted model was then used to interpolate values for any point of interest. Fitted values were accompanied by a coefficient of variation, which is defined as the ratio of standard error of prediction to the fitted value. Large coefficients of variation imply variable and uncertain interpolations. Small Coefficients of Variation imply precise interpolation. Coefficient of Variations were plotted on the maps similarly as with the fitted values (best estimates of all points, based on actual data). Coefficient of Variation maps took into account analytical error, sampling errors as well as errors introduced in interpolating between specific data points hence, providing a map of estimation accuracy.



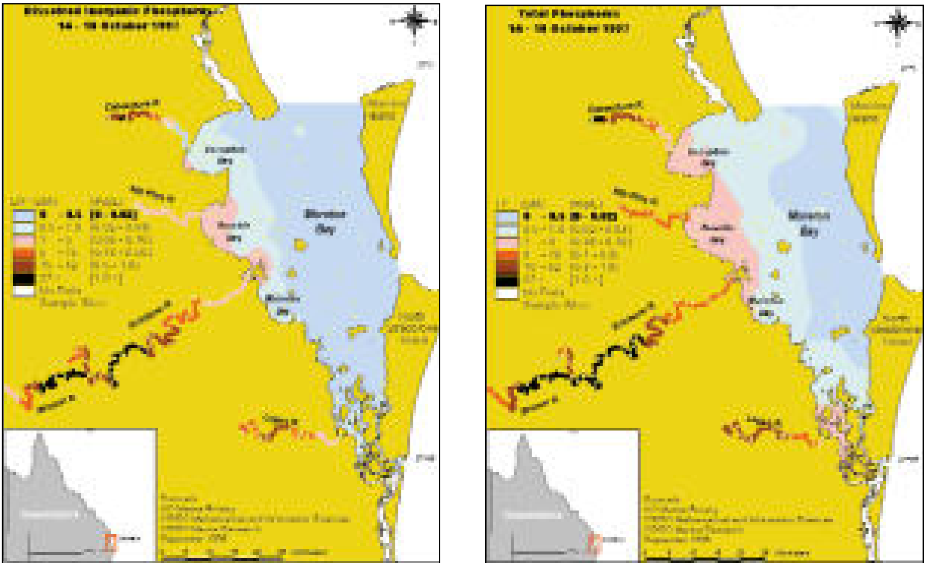
Methodology for analysis of dissolved water column nutrients

Nitrogen and phosphorus: river estuaries >



Spatial distribution of total nitrogen, dissolved inorganic nitrogen, ammonium and oxides of nitrogen in October 1997. Highest concentrations were consistently observed in the river estuaries and western areas of the Bay.

Western Bay > eastern Bay



Spatial distribution of total phosphorus and dissolved inorganic phosphorus in October 1997. The highest concentrations were found in the river estuaries and western areas of the Bay.

Nutrient concentrations were highest in the river estuaries and displayed both east-west and north-south trends within Moreton Bay.

All forms of nitrogen (N), including ammonium (NH_4^+), oxides of nitrogen (nitrate, NO_3^-; nitrite, NO_2^-), dissolved inorganic nitrogen (NH_4^+ plus NO_3^- plus NO_2^-), and total nitrogen (particulate and dissolved) showed distinct plumes of relatively high concentrations in the western embayments and southern Moreton Bay and low, sometimes near detection limit, values in the eastern and northern portion of Moreton Bay.

Phosphorus (P) also followed a similar pattern of highest concentrations in river estuaries, and distinct plumes in western and southern Moreton Bay. Nutrient concentrations in the river were very high, with concentrations 10-100 fold higher than Moreton Bay. Brisbane River had the highest nutrient concentrations, with particularly high nitrate concentrations in the reaches between the Bremer/Brisbane junction and Fig Tree Pocket.

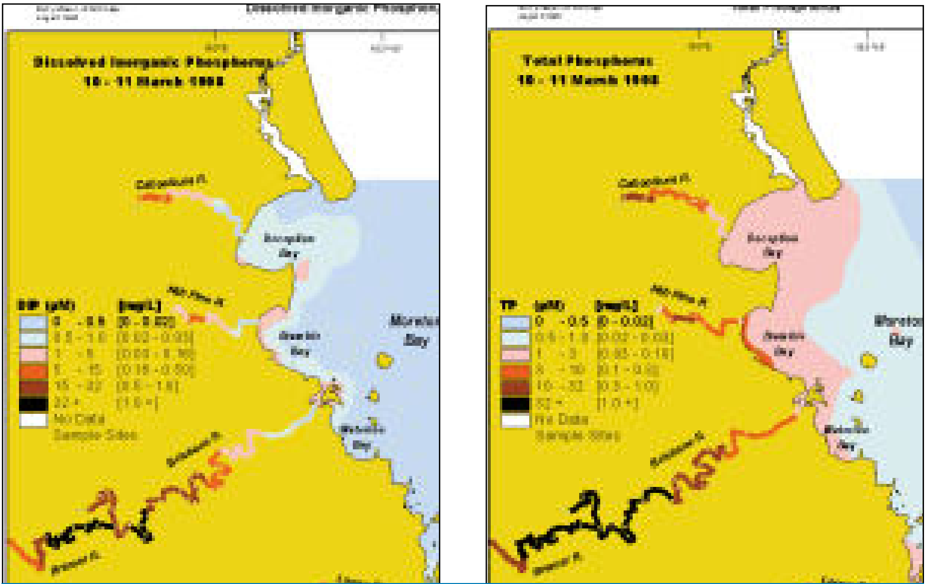
The three western embayments Deception, Bramble and Waterloo Bays had varying levels of water quality impacts. Bramble Bay was the most impacted with both Brisbane River and Pine Rivers/Hays Inlet contributing to high nutrient levels. Deception Bay had measurably less nutrient impacts, and Waterloo Bay exhibited strong localised water quality gradients. In particular, relatively clean oceanic water appearing to enter Waterloo Bay between Wellington Point and Green Island may contribute to these gradients.

The units used for nutrients are micromolar (µM), which express the concentration of nutrients in terms of number of atoms dissolved in a litre of water. Alternatively, the units of mg L^{-1} can be used, which express the concentration of nutrients in terms of the weight of a particular nutrient dissolved in a litre of water. Conversion between units can be done with the following equations:
mg N L^{-1} = µM N x 0.014
mg P L^{-1} = µM P x 0.031

Spatial distribution patterns relatively

Spatial distribution of total nitrogen, dissolved inorganic nitrogen, ammonium and oxides of nitrogen in March 1998. Nutrient distribution patterns were consistently highest in the rivers followed by the western embayments (in particular Bramble Bay), and lowest in the eastern Bay.

consistent



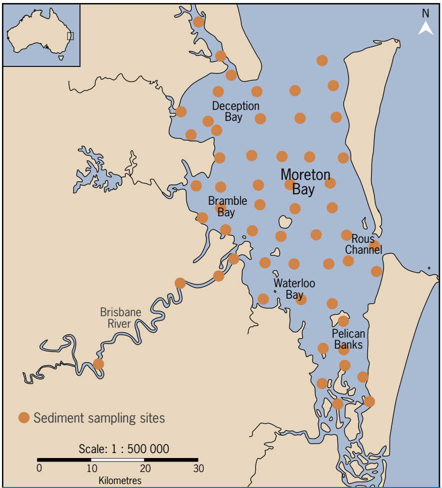
Spatial distribution of total phosphorus and dissolved inorganic phosphorus in March 1998. Nutrient distribution patterns were consistently highest in the rivers and western embayments (in particular Bramble Bay) and lowest in the eastern Bay.

The distributional patterns of nutrient concentrations were relatively consistent between the two intensive surveys. This consistency in distributional patterns indicates chronic sources such as sewage effluent and sediment nutrient release. In addition, the hydrographic regimes at the time of the two samplings were relatively equivalent, with little runoff occurring. The second sampling was designed for a wet season runoff event, however during Stage 2 of the study no significant runoff events occurred. Previous measurements of nutrient concentrations during and following a large runoff event in May 1996 indicated that a large temporal variability is possible in the region during these events (Moss, A., 1998, Moreton Bay and Catchment).

Overall, the water quality trends in the river estuaries and Moreton Bay were indicative of the hydrodynamic flushing patterns. The well-flushed north-eastern section of Moreton Bay had oceanic water quality values. In dry weather, the rivers are very poorly flushed, and water quality values reflected this poor flushing. In southern Moreton Bay, the Logan River plume diverges, with some of the flow extending to the north and some to the south. The extent of the Logan River plume during this dry weather sampling is largely confined to the channels between the islands of southern Moreton Bay. The most impacted areas in the Bay are the western embayments of Deception, Bramble and Waterloo Bays.

Sediment Nutrients

Intensive sediment sampling



Sediment nutrient sampling covered an intensive and broadly distributed range of sites.

Sediment nutrient sampling is much more involved and labour intensive than the standard water column nutrient sampling. Either scuba divers or remotely operated sediment coring devices are necessary to obtain intact and relatively undisturbed sediment samples. A wide sampling grid was used to provide a wide-scale distributional pattern of sediment nutrients in the region. A limited number of sediment nutrient samples were taken in the river estuaries due to complications resulting from dredging activities, difficulty in obtaining intact samples and difficult logistics of obtaining river estuary sediment samples.

The various forms of sediment nutrients were sampled and analysed using a variety of techniques. Total nutrient analysis involved collecting the intact sediments (2 cm depth), drying, then digesting them in an acid solution to release all of the nutrients in a dissolved form for analysis. Porewater nutrients were analysed by obtaining several millilitres of interstitial water and analysing for dissolved nutrient concentration. Exchangeable nutrients were measured using ion exchange techniques.

Sediment nutrient forms

Porewater interstitial nutrients - dissolved in the sediment porewater

Adsorbed/Exchangeable nutrients - adsorbed to the surface of sediment particles

Fixed nutrients - within the matrix/lattice structure of sediment grains

Sampling sediment porewater nutrients using 'sippers'

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Sampling sediment nutrients using sediment corer.

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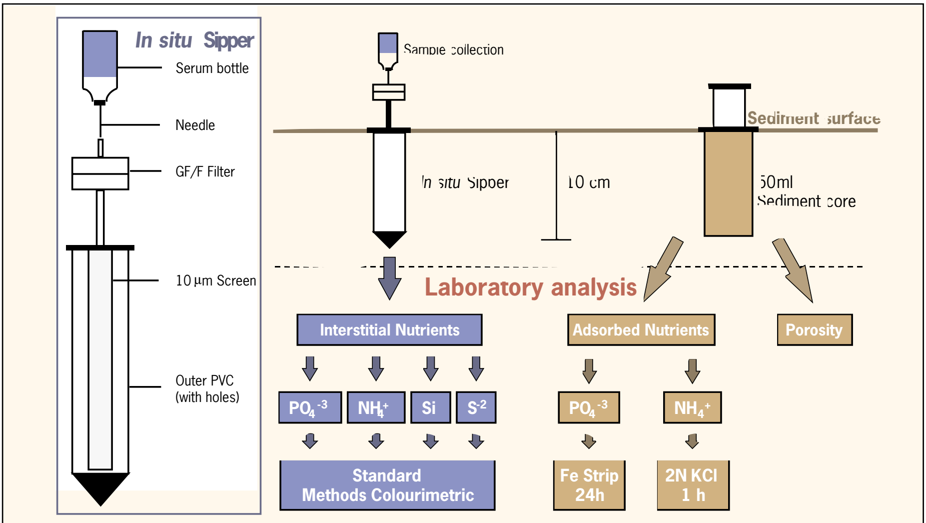
Diverse sampling techniques for different sediment nutrient forms



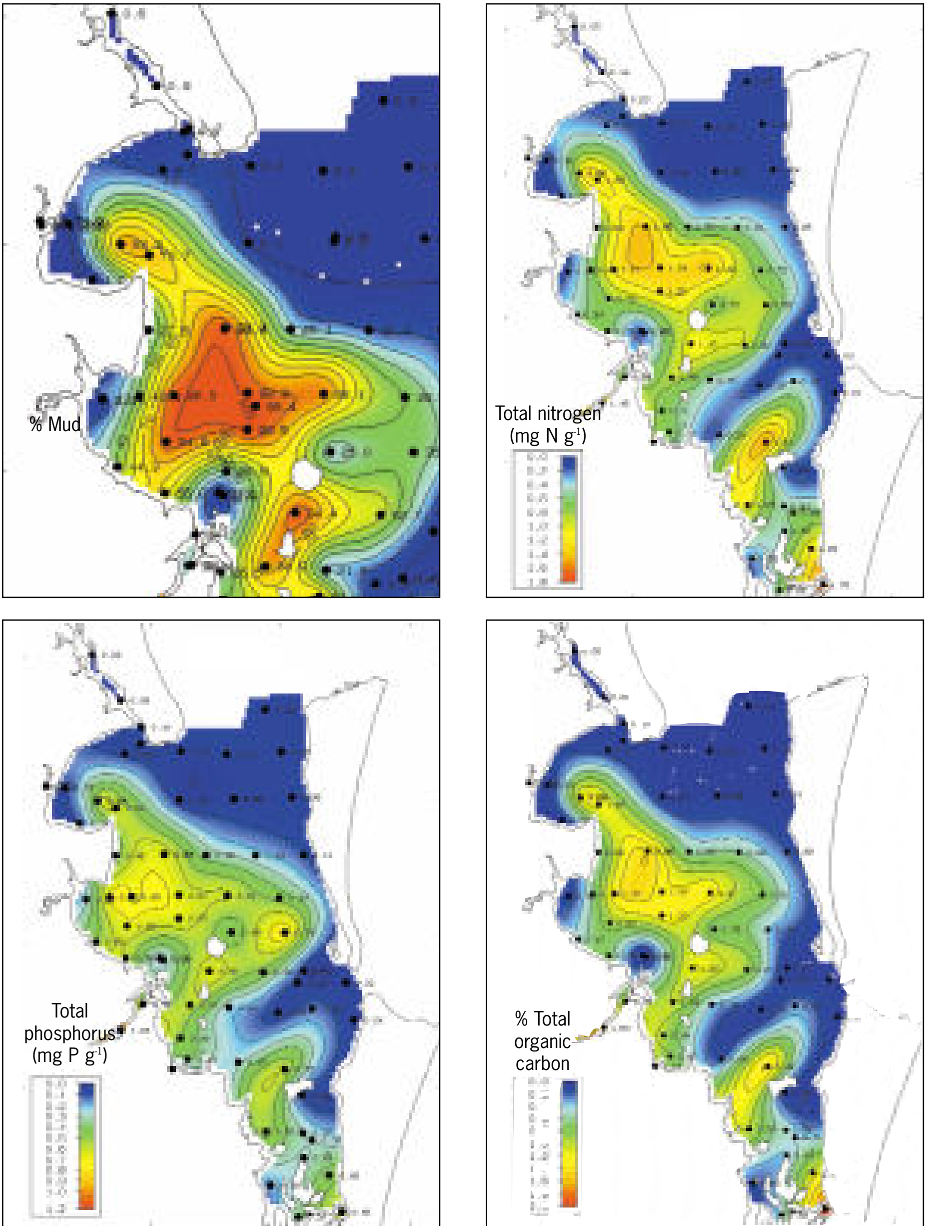
Sampling techniques for determination of porewater nutrients used a sipper and adsorbed nutrients used a sediment core.

For analysis of porewater nutrients, an *in situ* sediment sipper, developed in Moreton Bay sediments, was employed (Udy, J.W. and Dennison, W.C., 1997, Mar. Fresh. Res., 48). Sediment porewater sippers consisted of a small PVC pipe which was inserted into the sediments, and an inner 10 µm mesh screen, which together with the holes in the PVC pipe, prevent sediment particles from interfering and clogging the filter. The sipper was inserted into the sediment to a depth of 10 cm. A filter was fitted *in situ* to the top of the sipper. The first 10 ml of sample was discarded after rinsing the sipper and filter paper. A needle was fitted to the filter and an evacuated, acid - washed, glass serum vial was placed on top of the needle to draw the next 20 ml of sediment porewater sample into the sipper, up through the tube, through the filter and into the serum vial. Sediment porewater samples were immediately placed on dry ice, and analysed colourimetrically for ammonium, phosphate, silica and sulfide.

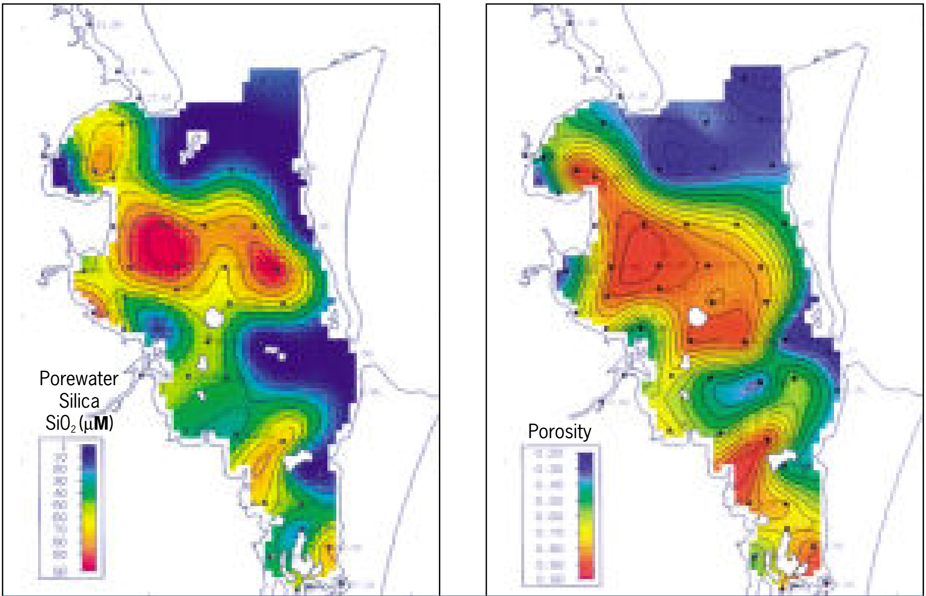
Adsorbed nutrient samples were obtained from the upper 10 cm of the sediments using 50 ml syringes with cut-off ends. The cores were chilled and brought to the laboratory for extraction. A strong salt solution of potassium chloride (KCl) was placed in contact with a known amount of sediment. The saturation of adsorption binding sites by the added potassium replacing the sorbed ammonium ions allows detection of ammonium released from the sediment. For exchangeable phosphate concentrations, a strip of filter paper, which has been impregnated with ferric chloride (FeCl), was used to selectively bind the phosphate ions when placed into contact with a sediment slurry. Acidification then releases the phosphate from the iron strip, and this is analysed by standard chemical techniques.

Sediment Nutrients

Correlation of %mud with %total nutrients



Distribution of the percent mud content correlated to the distribution of total nutrient content - nitrogen, phosphorus and carbon - of sediment.



Distribution of silica and sediment porosity also correlated to the distribution of percent mud content of sediment.

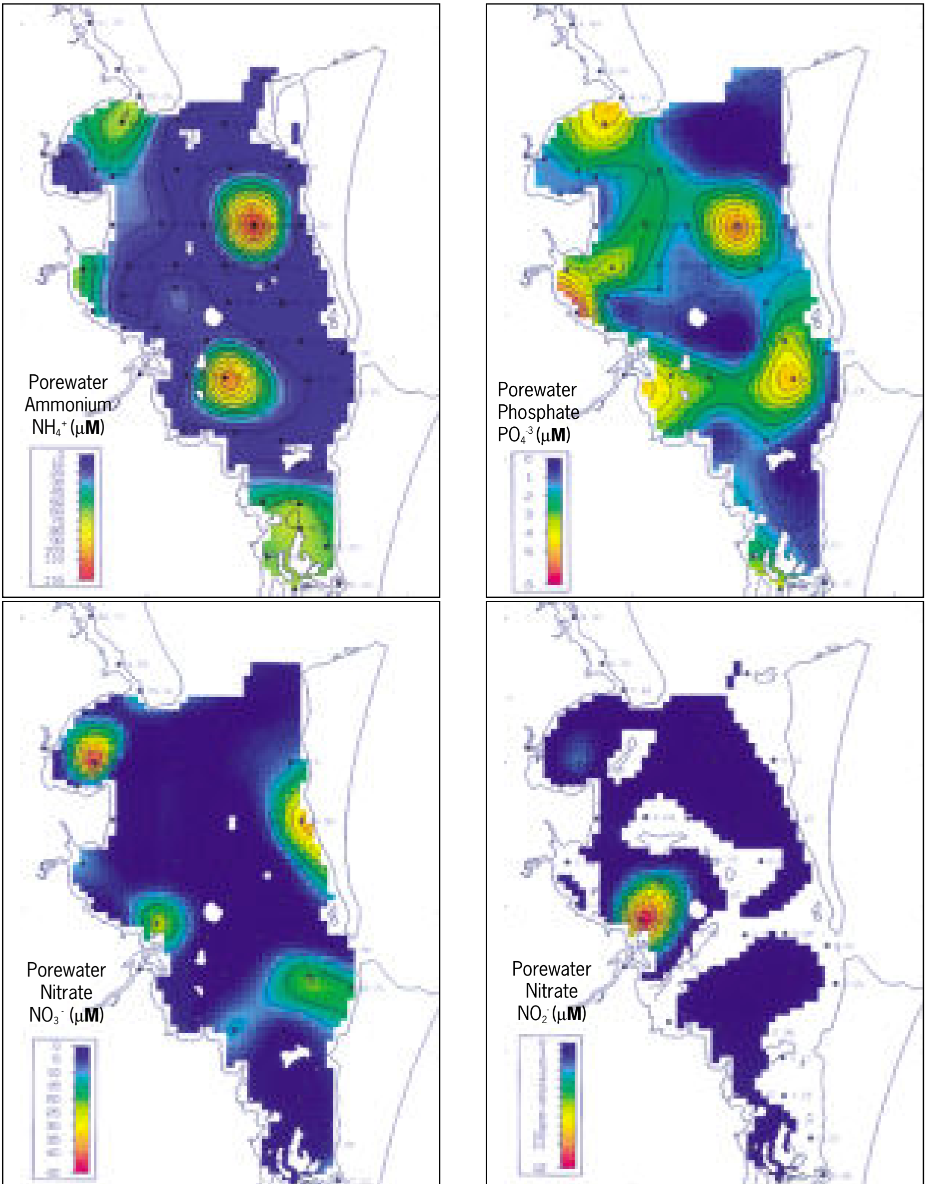
The distribution of muddy sediments in Moreton Bay occurs in a broad band which extends in an arc from Deception Bay, through the midbay and south to Waterloo Bay. Sandy sediment occurs at river mouths (Brisbane, Caboolture and Pine), in Pumicestone Passage, on Amity and Moreton Banks and on the tidal delta of North Passage. The high mud content of sediment in the western central portions of Moreton Bay was accompanied by high total nutrient concentrations (total nitrogen, total phosphorus and total organic carbon). Hence, the total nutrient content is determined by the type of sediments. In addition, high dissolved porewater silica (SiO_2) levels occurred in the muddy sediments. These sediments also had high water content as measured by porosity. The high correlation of total nutrients and porewater silicate with mud content indicates that similar sources and processes result in the accumulation of fine particle sediments and these nutrients.

These sediment maps are indicative of where the mud and nutrients from the catchment end up in Moreton Bay. These represent displaced resources needed to grow crops and maintain a green urban landscape. When runoff occurs and the nutrients and mud enter Moreton Bay, they have deleterious impacts. Stage 3 of this Study will look at sourcing this mud in the central part of the Bay and the nutrients adsorbed to them. It is aimed that key processes causing the deposition and misplacement of this mud, will be determined.

High % mud = High total nitrogen = High total phosphorus = High total organic carbon = High porewater silica

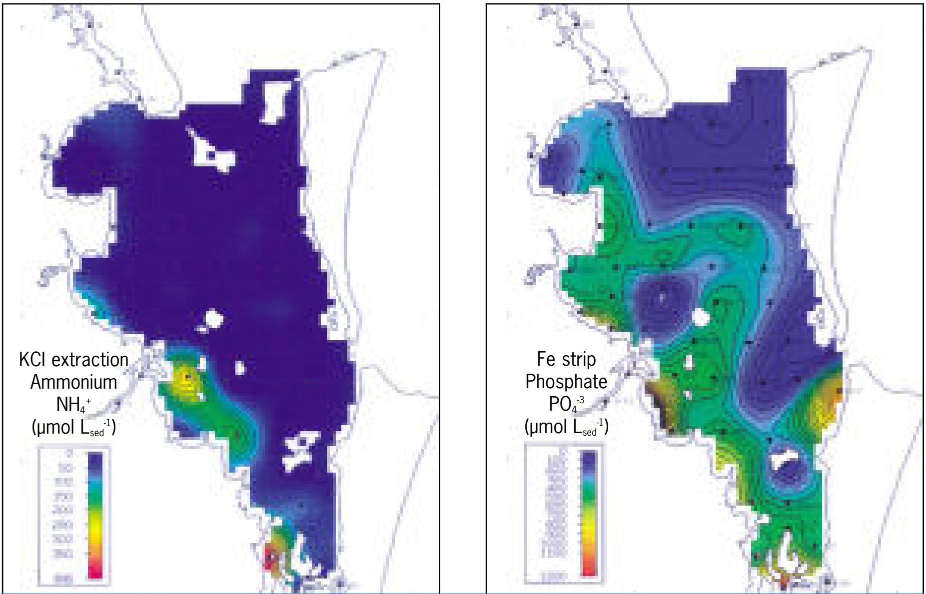
Sediment Nutrients

Porewater nutrients of surficial sediment: no pattern



Porewater nutrient concentration distribution patterns did not correlate with nutrients or with sediment type.

Exchangeable phosphate > exchangeable ammonium



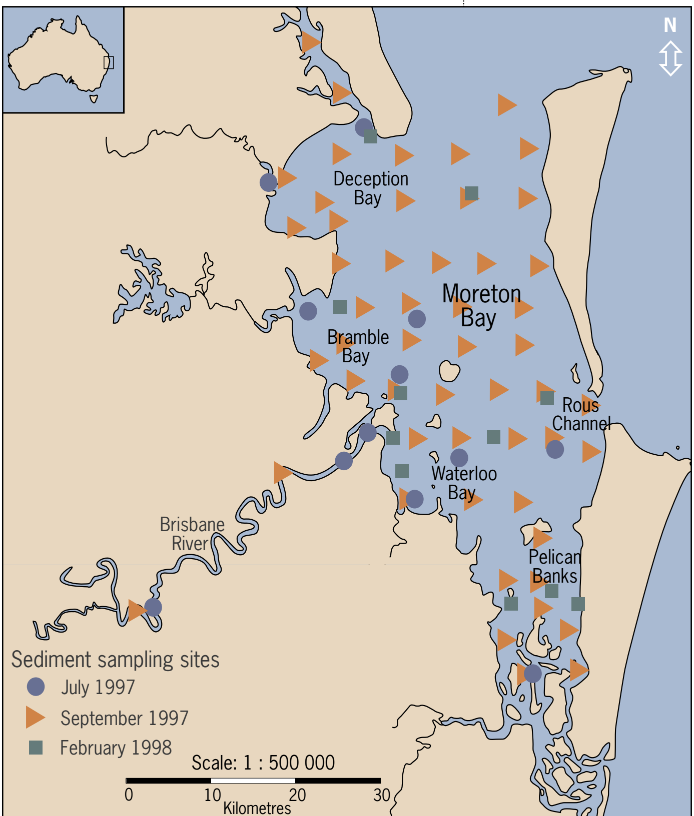
Baywide exchangeable sediment phosphate concentrations were higher than exchangeable ammonium concentrations.

There are no clear spatial trends in porewater values of ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) or phosphate (PO_4^{-3}). Occasional high values were observed, but not consistently in any particular location. Sediment sippers were used to collect porewaters, penetrating only 10 cm into the sediment. Subsequent analysis of downcore porewater revealed strong trends below the top 10 cm, so there may be spatial patterns in porewater nutrients measured to deeper sediment depths than measured in this survey.

Exchangeable ammonium and phosphate distributions are unlike those of the total nutrients and mud content where a trend toward higher values in the western and southern portions of Moreton Bay was observed. There were no clear spatial trends in exchangeable ammonium or phosphate concentrations. Like the sediment sippers, which collected the top 10 cm of sediment porewater, the sediment corers used for collecting sediments used in the exchangeable nutrient analyses also were from the top 10 cm of the sediments. Up to 5% of the total phosphorus (P) in surface sediments was exchangeable using the iron (Fe) strip method, whereas only 0.1-0.25% of the total nitrogen (N) in all sediments was potassium chloride (KCl) - extractable or exchangeable N. This comparison indicates that only very little of the total N adsorbed onto the sediments is 'weakly bound', extractable and potentially bioavailable. However, the dissolved inorganic N pool (porewater N) was about 60-70% of the total N pool in most zones. Dissolved P concentrations in the porewaters in most sediments were < 0.03% of total P pool.

Depth profiling of sediment nutrients

Sediment cores 20-40 cm long were obtained in clear plastic cores by scuba divers at several locations in the study region. Sampling locations were similar to those used for determination of total sediment nutrient concentrations. Sediment cores were stored as close as possible to *in situ* temperature in a bucket of ambient seawater with a wet, dark towel covering the top of the cores. The cores were carefully transported upright to the laboratory where they were extruded under an inert nitrogen gas atmosphere to avoid oxygenation. The cores were sliced at specific depth intervals, concentrating in the top few centimetres and extending to the bottom of the core. The sediment was centrifuged to separate porewater. Porewater was then siphoned from the centrifuge tubes, filtered through 0.45 µm filters and bubbled with nitrogen gas for 10 minutes. All porewater samples were analysed for dissolved inorganic nutrient concentrations on-site. Samples for dissolved organic nitrogen were analysed in the Marine and Freshwater Research Institute laboratories in Melbourne. Plots showing detailed depth profiles of sediment nutrient concentrations were constructed for the various sites.



Sampling sites for depth profiling of sediment nutrients

Sediment core sample for depth profiling

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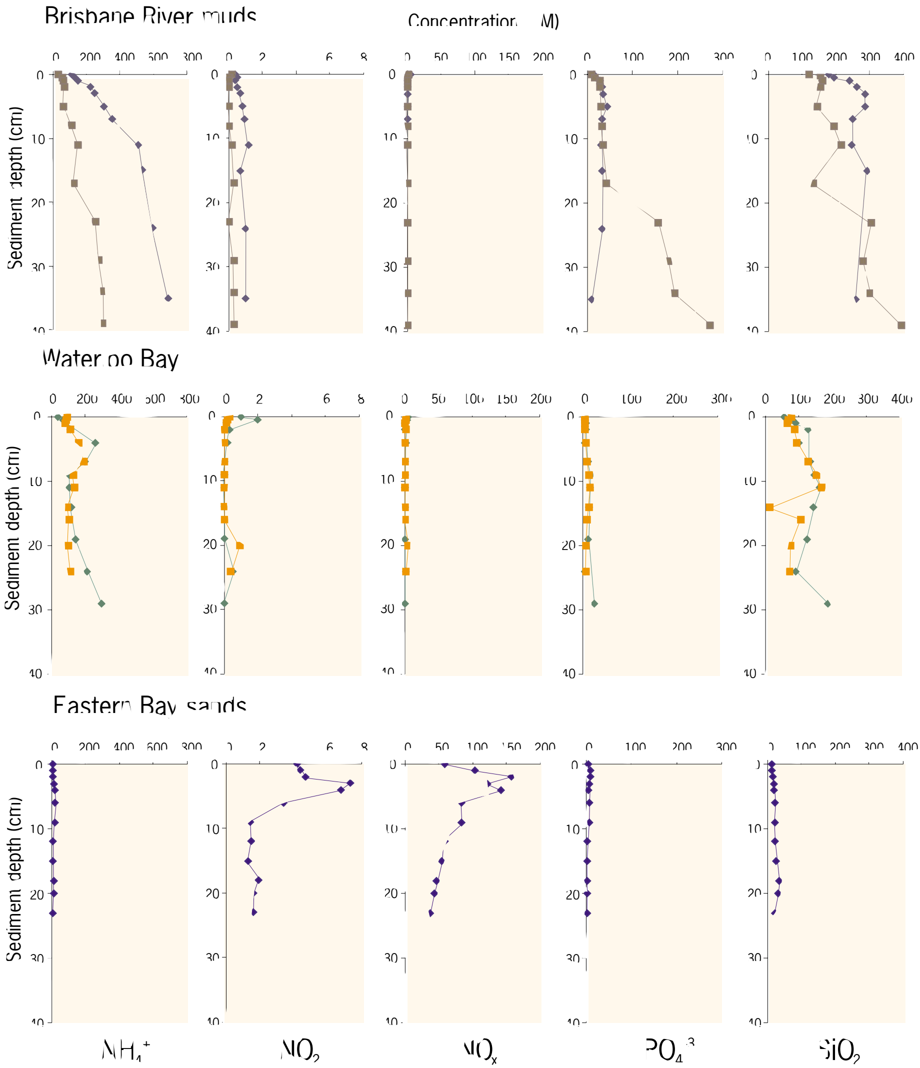
High ammonium in mud; high nitrate in sand

Sediment porewater profiles revealed high ammonium (NH_4^+) concentrations throughout muddy sediment and high nitrate (NO_3^-) concentrations throughout sandy sediments. In some cases high nitrate was only observed relatively deep in the sediment core i.e. 10-20 cm sediment depth.

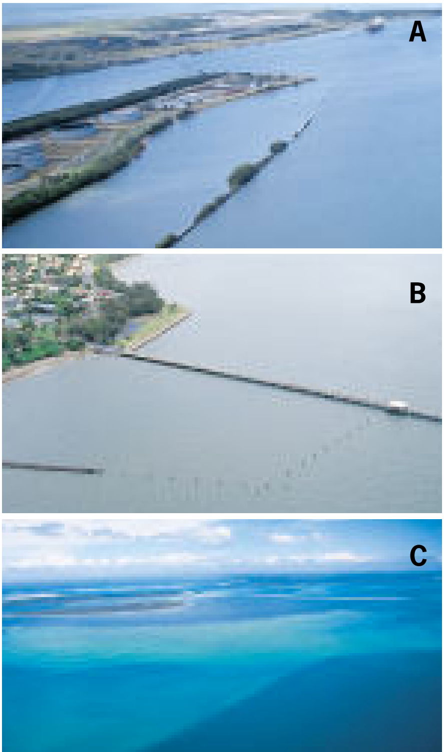


Sediment nutrient depth profiles at three sites within the Moreton Bay region. Ammonium concentrations were highest at western Bay sites (Brisbane River and Waterloo Bay), while nitrate concentrations were highest at eastern Bay sites (eastern Bay sands).

Strong gradients in both water column and sediment nutrients

Strong spatial gradients in both water column and sediment nutrients were observed in Moreton Bay and the river estuaries. In general, highest concentrations in both water column and sediment nutrients were observed in the river estuaries. The western central portions of Moreton Bay, particularly Bramble Bay, had consistently high concentrations of water column and sediment nutrients. The large influence of the Brisbane River discharge into Moreton Bay is evident in both water column and sediment nutrient distributional patterns. Near the oceanic inlets water column nutrients were extremely low. In these regions, all porewater nutrient except nitrate were low throughout the sediment profile.

The assessment of water column and sediment nutrients conducted in the study represents the most intensive sampling of nutrients conducted in this region. Both sets of sampling were relatively synoptic, with water column sampling occurring on two successive days for each of the intensive surveys and the sediment nutrient sampling occurring over a one week period in June, 1997. This sampling strategy ensured that minimal temporal variability would influence results.



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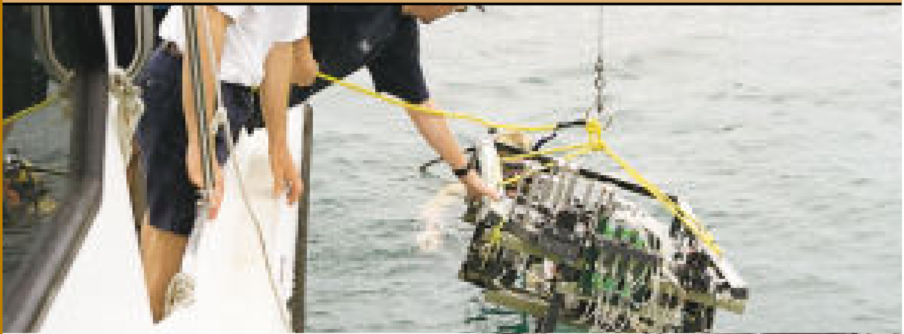
Gradient of water column and sediment nutrient concentrations, with highest values at A) Brisbane River, followed by B) western embayment (Bramble Bay) and lowest values at C) eastern Moreton Bay

Sediment and water column nutrient gradients in Moreton Bay

		Bremer River	Brisbane River	Bramble Bay	Pelican Banks	Rous Channel
Water column nutrients (µM)	NH_4^+	0.3	7	2	0.4	0.4
	NO_X	214	31	0.8	0.07	0.07
	PO_4^{-3}	39	4	1.4	0.2	0.3
	Total nitrogen	253	54	11	2.9	3.6
	Total phosphorus	45	7	2	0.4	0.5
Sediment nutrients ($\mu g\ g_{dry}^{-1}$)	Total nitrogen	47	104	49	82	1.9
	Total phosphorus	33	33	24	15	0.8
Sediment porewater (µM)	NH_4^+	39	32	69	35	4
	NO_X	73	1	185	2	59
	PO_4^{-3}	10	9	3	3	6

CHAPTER 8

Nutrient Processes



AUST. GEOLOGICAL SURVEY ORGANISATION

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Nutrient Cycles

- Relatively complex nitrogen (N) cycle
- Fewer transformations in phosphorus (P) cycle

Nitrogen Transformation Measurements

- Mixing plots: indication of nutrient processes
- Denitrification inferred in some river estuaries
- Nitrogen fixation measured using acetylene reduction
- Nitrogen fixation ubiquitous: highest rates associated with seagrass
- Denitrification measured using acetylene blockage
- Denitrification rates dependent on nitrate availability

Sediment Chambers

- Benthic chambers used to measure nutrient fluxes
- Redfield ratios used to interpret benthic flux measurements
- Ammonium and phosphate release dependent on oxygen availability
- 'Poised' denitrification efficiency in muddy sediment
- Sediment types control nutrient fluxes

Denitrification Efficiency

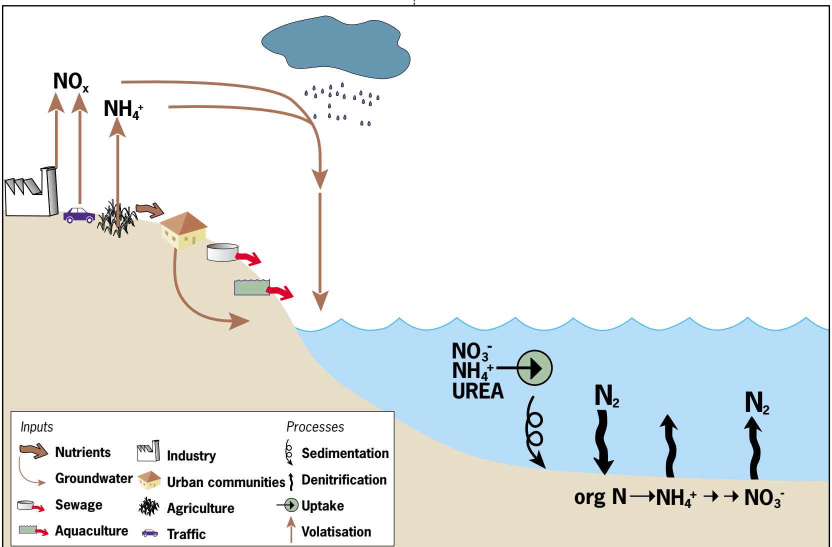
- Flushing time of Bay predicts denitrification efficiency ~ 25%

Nutrient Cycles

Relatively complex nitrogen (N) cycle

Nitrogen (N), a necessary structural component of living cells and the element limiting primary production over most of the coastal oceans, has a variety of inorganic and organic forms. It occurs in the gaseous, liquid and solid phases and is transformed and transported in a complex pattern. N_2 is abundant as a gas, making up nearly 80% of our atmosphere. N_2 gas can be converted into organic N by a select group of bacteria and cyanobacteria that expend a great deal of metabolic energy (ATP) to break the triple bonded N_2 molecule. This process is called nitrogen fixation.

Nitrogen contained in organisms is excreted into the environment as dissolved forms: uric acid, urea or ammonium ions. N from excretion and N from decomposition of decaying matter is converted into ammonium by bacteria via a process called ammonification. Ammonium ions (NH_4^+) are oxidised into nitrite (NO_2^-) by bacteria and then into nitrate (NO_3^-) by another group of bacteria collectively called nitrifying bacteria. Nitrifying bacteria derive metabolic energy from these N transformations but require oxygen to be able convert the reduced form of N (ammonium) to oxidised forms (nitrite and nitrate). This process is called nitrification. Nitrate (NO_3^-) is converted to N_2 gas through a sequence of reductions in which nitrite is the first intermediate and nitrous oxide is the final intermediate by a group of bacteria called the denitrifying bacteria. This process is known as denitrification. Denitrifying bacteria utilise NO_3^- as a terminal electron acceptor when oxygen is not available. All of these N transformations are biologically mediated and can occur both in the water column and in sediments (Carpenter, E. and Capone, D.,1983, Nitrogen in the Marine Environment). In coastal environments, these processes occur primarily in sediments.



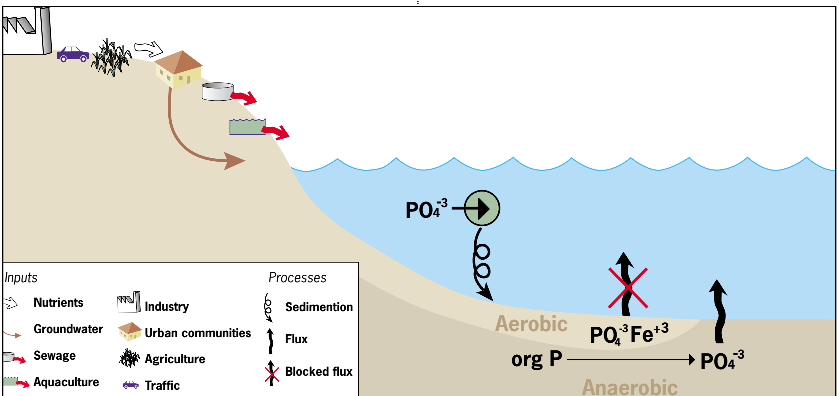
Conceptual model of nitrogen cycle in the environment. Nitrogen occurs in various forms and all processes are biologically mediated.

Fewer transformations in phosphorus (P) cycle

Phosphorus (P) has a smaller variety of forms and biologically mediated transformations than nitrogen. P is required in lesser amounts than nitrogen (N), and is used for metabolic energy as adenosine mono-, di-, and tri-phosphates and for use in the structure of DNA. P is also a component of phospholipids, which are essential components of living cells. Bacteria and other organisms convert organic phosphorus into inorganic phosphate, namely orthophosphates. P is taken up by organisms largely as phosphate (PO_4^{-3}), but organic P can also be absorbed and converted into inorganic P by the enzyme phosphatase.

There are at least two chemical aspects which play important roles in maintaining low dissolved P concentrations in the water column: the facility of P adsorption and its ability to form insoluble compounds with certain metals. Death, shedding or molting of organisms plus adsorption of phosphate onto particles produce particulate organic phosphorus (POP). Some of the POP is released as dissolved inorganic P as particles decay in the water column, but some settle onto the sediments. Further degradation of settled organic P to dissolved inorganic P (DIP) can occur in the sediments, but a fraction of this DIP is adsorbed back onto the sediments. In anaerobic conditions, bacteria and hydrogen sulfide (H_2S) can reduce ferric iron (Fe^{+3}) to ferrous iron (Fe^{+2}) which is much less effective at adsorbing phosphate. The reduction of iron thus results in greater availability of dissolved phosphate in anaerobic environments. Because of the chemistry of P and at least for human use, P must be treated as a nonrenewable resource in limited supply (Valiela, I., 1995, Marine Ecological Processes).

On a geologic time scale, both N and P buried in terrestrial soils or marine sediments are eventually recycled into the biosphere by volcanic igneous rock. Hence, older continental rocks that have been weathered contain less of these elements and geologically younger rock contain greater amounts. N is contained in the matrix of various clay minerals and is also strongly adsorbed onto their surfaces. P is incorporated into calcium carbonate minerals and is adsorbed onto their surfaces. These differences in biogeochemistry of N and P have implications in their relative availabilities in the environment.



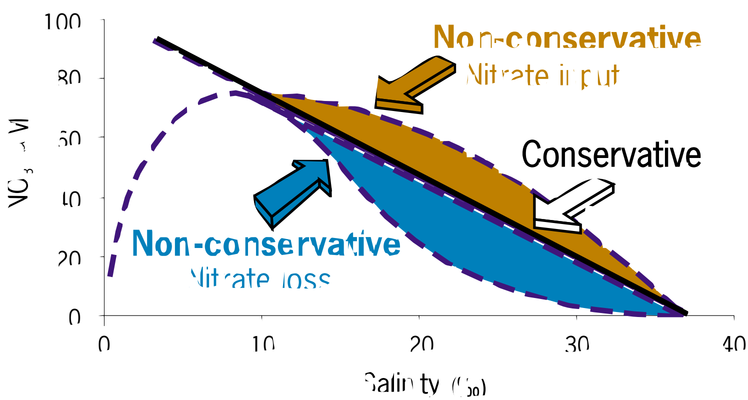
Conceptual model of phosphorus cycle in the environment. Phosphorus occurs in fewer forms than nitrogen and most processes in the cycle are chemically mediated.

Mixing plots: indication of nutrient processes

Mixing plots indicate a relationship between nutrients and the salinity gradient in an estuarine system. Salinity is a conservative component representative of seawater, which has generally lower nutrient concentrations than estuarine waters. Plots showing the relationships between salinity and other soluble substances in coastal and estuarine waters can be used to determine the conservative or dynamic characteristic of these substances.

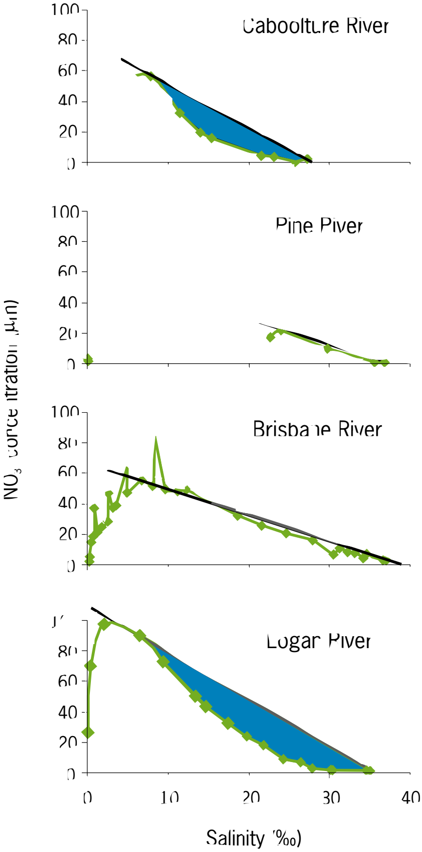
Salinity is measured from the river mouth upstream to freshwater, and concentrations of water quality parameters can be plotted against this gradient. Measurements are taken from the river mouth at high tide, moving upstream with the tidal movement to ensure an equal distribution of gradients. Nutrient inputs from non-point or point discharges into the system will lead to elevated nutrient concentrations. Due to tidal mixing of fresh and saltwater these input concentrations will be diluted with increasing distance from the discharge point. A line connecting the highest concentration of nutrients to the river mouth therefore represents the line of conservative mixing due to dilution effects. Concave or convex deviations from the linearity indicate a dynamic characteristic of consumption or production.

For example, mixing plots of nitrate (NO_3^-) versus salinity are useful tools to monitor estuarine nitrogen processes. Conservative dilution of nitrate added to estuaries is indicated by a linear relationship with salinity. A mixing plot following such a conservative line indicates that net decrease in nitrate along the river system is due to simple physical dilution. A decrease in concentration below the conservative mixing line indicates net nitrate loss due to biological processes. This can be the result of nutrient uptake by plants or bacterial denitrification. Denitrification is a process which removes nitrate from marine and estuarine systems. It is a valuable process in riverine systems as it causes a net loss of nitrogen from the aquatic environment and therefore reduces nutrient availability, which can lead to harmful algal blooms. Thus mixing plots can be used to indicate not only nutrient concentrations, but also the fate of nutrients and estuarine biological processes.



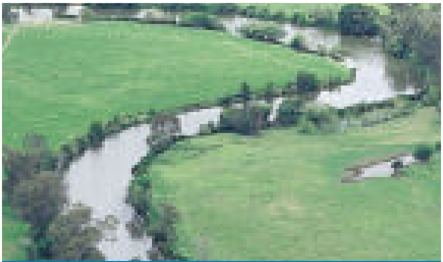
Diagrammatic representation of mixing plot of nitrate versus salinity. Mixing plots can be used to indicate fate of nutrients and river biological processes.

Denitrification inferred in some river estuaries



Mixing plots of nitrate versus salinity for the four major river systems. Non-conservative mixing plots in the Caboolture and Logan Rivers indicate net loss of nitrate from the system.

High nitrate (NO_3^-) concentrations resulting from nitrification and catchment run-off can impact the health of aquatic systems. Increased algal and phytoplankton growth can eventually result in decreased oxygen concentrations and light availability. Discharge of nutrients into our river systems lead to elevated nitrate concentrations, upstream of river mouths. With increasing mixing from saltwater, nitrate levels decrease in all rivers. However, mixing plots of the Caboolture and Logan Rivers show that concentrations drop below the conservative mixing line, indicating net loss of nitrate possibly due to denitrification. In both Pine and Brisbane Rivers, however, conservative mixing behaviours (as shown by the mixing plots following the conservative line) indicate that the net decrease in these rivers is due to simple physical dilution. These rivers discharge their nutrients directly into Moreton Bay.



Caboolture River - potential denitrification

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Brisbane River - little denitrification

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Logan River - potential denitrification

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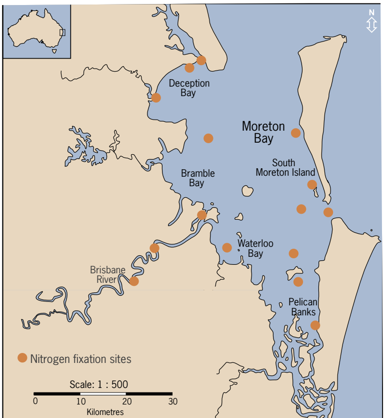
Nitrogen fixation measured using acetylene reduction

What is nitrogen fixation?

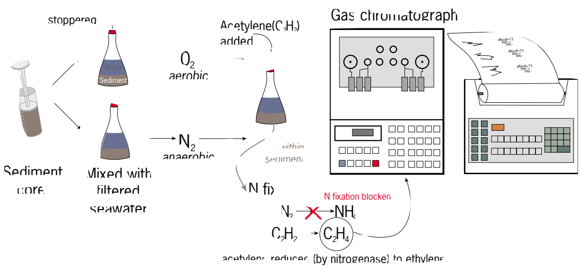
Certain organisms such as some free-living soil bacteria, free-living cyanobacteria, symbiotic cyanobacteria and other microbes can fix the gaseous form of nitrogen (N_2) into organic compounds. This process is called nitrogen fixation. This process requires energy, which in shallow sediments, may be supplied by the abundant organic matter (e.g. organic carbon compounds). Nitrogen fixation may be a key process in ecosystems where N is limiting productivity because of its potential to provide N in a usable form to plants.

Sediment samples were collected by a diver using cut-off plastic syringe cores (30 cm^3) for shallower sites and a sediment gravity core (10 cm diameter) for deeper sites. The top 4 cm of collected sediments was extruded directly into a 125 ml Erlenmeyer flask and mixed with 5 ml of filtered seawater. Half the number of cores from each location were incubated anaerobically by gassing with nitrogen gas (N_2) for anaerobic assays and sealed with a black rubber recessed stopper. The other half of the samples were slurried and shaken in air for aerobic assays.

Nitrogenase activity was measured to indicate nitrogen fixation rates. The reduction of acetylene (C_2H_2) to ethylene (C_2H_4) is used as basis for the nitrogen fixation assay. This methodology has been used widely and extensively to examine nitrogen fixation in a variety of marine ecosystems (Carpenter, E. and Capone, D., 1983, Nitrogen in the Marine Environment). A volume of acetylene (typically 10-20% of gas phase) was added through the stopper. Gaseous sub samples of the headspace were then taken over time courses of several hours and analysed by flame ionisation gas chromatography for formation of ethylene, which arises from the reduction of acetylene by nitrogenase. Rates of nitrogen fixation were generally linear over several hours. A ratio of 2 moles of acetylene per mole of nitrogen gas fixed was assumed. Nitrogen fixation rates were then expressed as μmol N per cross-sectional area subsampled.



Map of sites where sediment samples were taken for measurement of nitrogen fixation.



Nitrogen fixation methodology using the acetylene reduction technique.

Nitrogen fixation ubiquitous: highest rates associated with seagrass

Nitrogen-fixing bacteria are closely associated with seagrass roots. Seagrass roots exude dissolved organic carbon (DOC) compounds, which provide energy substrates for bacterial growth in the surrounding sediments. Most of this carbon is remineralised into inorganic nutrients which become available for seagrass uptake. Some of this DOC also provides energy substrates for the fixation of N_2 by bacteria. Seagrasses also pump oxygen from the leaves down to the roots via an efficient lacunal (gas space) system to maintain aerobic respiration in the roots. An excess of this oxygen results in the oxygenation of the sediments.

Nitrogen fixation rates associated with sediments of seagrasses along the Queensland coast are 5-100 times higher than those in seagrass beds anywhere else in the world. Nitrogen fixation in most seagrass beds accounts for 3-50% of seagrass N requirements, however in Moreton Bay, it can account for more than 100% of seagrass requirements. Very low interstitial N concentrations and the probability of N limitation in these seagrasses contributes to the importance of sediment nitrogen fixation (O'Donohue M.J. et al., 1991, Microbial Ecology 22 and Perry, C., 1998 Microbial processes in seagrass sediments, PhD Thesis, Univ. of Queensland).

CHRIS ROELFSEMA

Halophila spinulosa; high nitrogen fixation rates

Nitrogen fixation rates in rhizosphere sediments of different seagrass species in Australia compared to other parts of the world. (Perry, C., 1998 Microbial Processes in Seagrass Sediments, PhD thesis, Univ. of Queensland.)

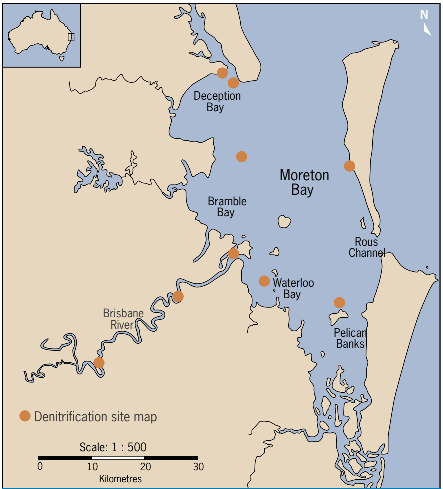
Seagrass species	Location	N_2 fixation rate (mg N m^{-2} d^{-1})	Reference
Halophila ovalis	Moreton Bay, Australia	28-108	Perry, 1998
Halodule uninervis	Moreton Bay, Australia	13-48	Perry, 1998
	Weipa, Australia	18-148	Perry, 1998
	Green Island, Australia	53-141	Perry, 1998
Zostera capricorni	Moreton Bay, Australia	16-49	Perry, 1998
	Moreton Bay, Australia	10-40	O'Donohue et al., 1991
Halophila spinulosa	Moreton Bay, Australia	17-130	Perry, 1998
Cymodocea serrulata	Moreton Bay, Australia	21-147	Perry, 1998
Syringodium isoetifolium	Moreton Bay, Australia	61-166	Perry, 1998
	Groote Eylandt, Australia	16-47	Moriarty and O'Donohue, 1993
Thalassia hemprichii	Groote Eylandt, Australia	13-19	Moriarty and O'Donohue, 1993
Enhalus acoroides	Weipa, Australia	25	Moriarty and O'Donohue, 1993
	Weipa, Australia	7-43	Perry, 1998
Thalassia testudinum	Florida, USA	8-11	Capone and Taylor, 1980
	Florida, USA	4-5	Capone et al., 1979
Thalassia and Halodule wrightii	Florida, USA	0.15-0.75	Perry, 1998
Syringodium filiforme	Bahamas	14	Short, 1990
Zostera marina	New York	5-8	Capone, 1982

Denitrification measured using acetylene blockage

What is denitrification?

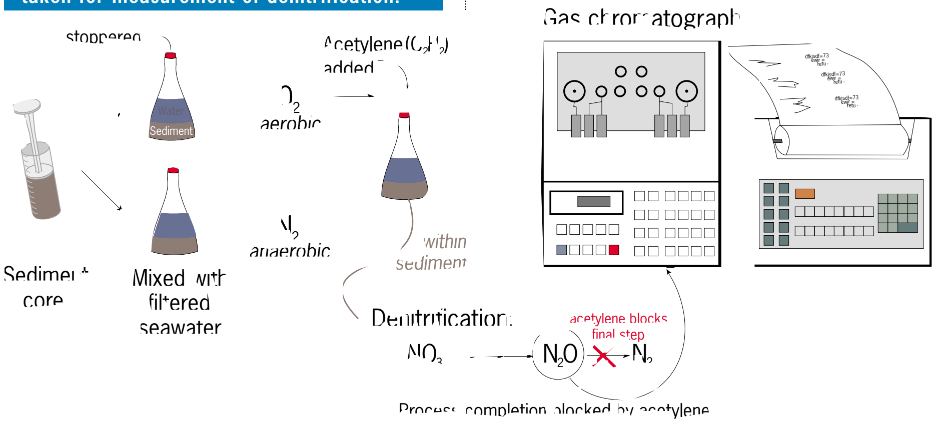
Denitrification is the process whereby nitrate is reduced by a group of specialised bacteria, in the presence of organic sugar (CH_2O) and hydrogen (H^+), to water (H_2O), carbon dioxide (CO_2) and nitrogen gas (N_2) which is often released into the atmosphere.

$$NO_3^- + 2CH_2O + 4H^+ \rightarrow\rightarrow\rightarrow N_2 + 3H_2O + 2CO_2$$



Map of sites where sediment samples were taken for measurement of denitrification.

The sampling and set-up for measurement of denitrification is similar to the acetylene reduction technique for measuring N fixation. Sediment samples were collected and treated in the same manner (refer to page 90). The acetylene blockage technique is based on the interference of acetylene with nitrous oxide (N_2O) metabolism and entails a relatively simple and sensitive asssay for denitrification. Acetylene blocks the last step of the denitrification chain, which is the reduction of N_2O to N_2. This results in the accumulation of nitrous oxide, which is measured by electron capture detection in a gas chromatograph. A limitation to this procedure is that the acetylene block often fails at low nitrate concentrations. As the acetylene inhibits nitrification (production of nitrate) as well, the acetylene blockage procedure cannot detect denitrification which is dependent upon nitrate generated internally from nitrification. For low nitrate environments, additions of nitrate at several levels to assess potential denitrification were made. Rates are expressed as μmol N per cross-sectional area of sediment subsampled.



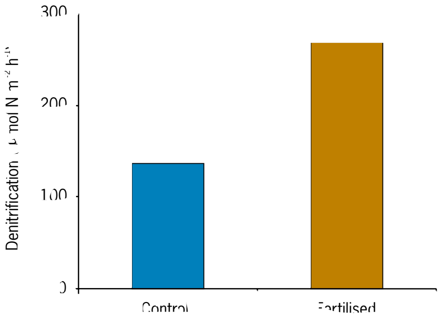
Denitrification methodology using acetylene blockage technique

Dentrification rates dependent on nitrate availability

Enrichment experiments were conducted on selected mangrove and seagrass sites. In unfertilised sites, there was little evidence of high rates of denitrification unless 50 µM of nitrate (NO_3^-) was added to the assay. However, in most fertilised sites, denitrification was readily measured without the need to supply exogenous nitrate. The addition of exogenous nitrate to all samples from the different sites resulted in increased denitrification rates.

Denitrification, as a heterotrophic process, would be favoured in environments with relatively high organic content, low oxygen (O_2), and either flux of nitrate into the sediments from nitrate-enriched overlying waters, from nitrate-enriched groundwater flux, or in situations favouring *in situ* nitrification. The process may be constrained in organically poor environments, and in zones of chronically low nitrate concentrations or supply. Results indicate that denitrification rates can and do respond to changes in the N regimes of sediments brought about by either anthropogenic or natural impacts.

high organic content
low oxygen
high nitrate
⇓
high denitrification



Denitrification rates in control and fertilised plots in mangrove forests at Pelican Banks. Denitrification was stimulated by increased nitrogen availability in enriched plots.

Denitrification rates in Moreton Bay sediments, with and without nitrate additions.

Site	Denitrification rate (µmol N m^{-2} h^{-1}) 0 µM nitrate added	Denitrification rate (µmol N m^{-2} h^{-1}) 50 µM nitrate added
Breakfast Creek	0.1	17
Brisbane River upstream	0.4	64
Brisbane River Mouth	0.4	73
Redcliffe Peninsula	0.7	94
Waterloo Bay	0.2	345
Pumicestone Passage - mud	0.5	28
Pumicestone Passage - sand	0.1	69
Peel Island	0.0	1
Tangalooma	10.0	112

Sediment Chambers

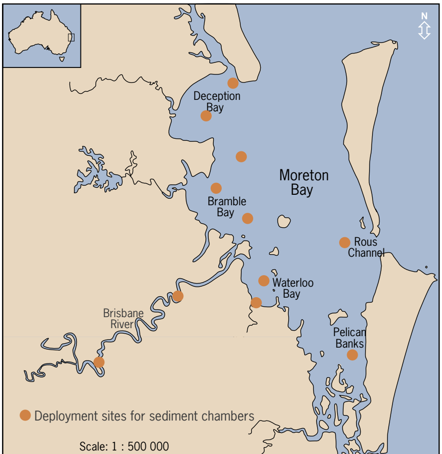
Benthic chambers used to measure nutrient fluxes

Lowering the benthic chamber to the sediment surface.

AUST. GEOLOGICAL SURVEY ORGANISATION

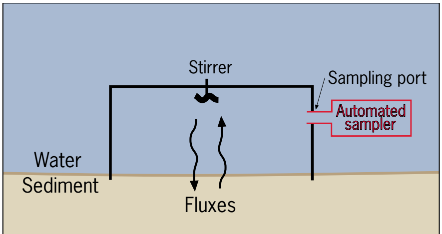
Nutrient fluxes were measured using benthic sediment chambers deployed at 10 sites representing sedimentary facies in Moreton Bay and 2 sites in the Brisbane River. At most sites, chambers were lowered slowly by hand line from a vessel to the sea floor. Two different sizes of chambers were used: one captured approximately 7 litres of water in contact with 0.073 m^2 of sea bed and the other captured approximately 15 litres of water over a surface area of 0.15 m^2. The latter chamber was designed so that the lid can be programmed to open and close repeatedly, allowing multiple flux experiments to be carried out.

The chambers were incubated for 4-16 hours at each site. A mixed cesium (Cs) and bromide (Br) spike was injected into the chamber to calculate chamber volume and verify that the chamber was not leaking and chambers were stirred by a rotating paddle. Oxygen concentrations within the chamber and from the ambient surrounding water were monitored by an electrode. Water samples were automatically removed from the chambers during each incubation and analysed for ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), silicate (SiO_4), phosphate (PO_4^{-3}), alkalinity, total carbon dioxide (TCO_2), radon and oxygen fluxes. Nutrient fluxes into and out of the chamber were calculated as the product of the slope of concentrations vs incubation time and chamber height.



Deployment sites for sediment chambers to measure sediment fluxes.

Benthic chambers integrate the reactions or processes occurring in the sediments, translated as benthic fluxes. Benthic chambers were also used to measure nutrient fluxes in the Port Phillip Bay Study.



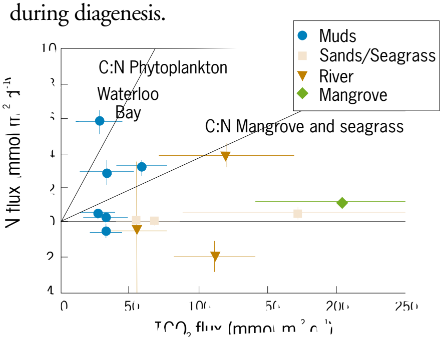
Diagramatic representation of sediment chambers to measure nutrient fluxes between sediments and overlying water column.

Redfield ratios used to interpret benthic flux measurements

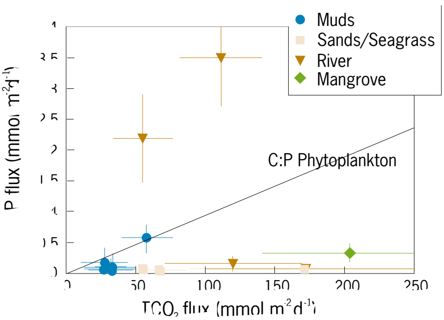
Interpretation of nutrient flux ratios includes assumptions about the organic matter driving benthic processes. If it is primarily marine phytoplankton, the Redfield ratio, C:N:P = 106:16:1 may be used for predicting N and P fluxes from organic carbon diagenesis. Seagrasses and mangroves have higher C:N ratios than phytoplankton. C:N ratios are indicative of the type of organic matter undergoing diagenesis, as well as the efficiency of nitrification/denitrification. Large deviations from the Redfield ratios for C:N:P may indicate the degradation of non-planktonic organic material. However, by careful interpretation of all the stoichiometries, including oxygen (O_2), alkalinity and silica (Si) fluxes, dominant biogeochemical processes may be determined. A ratio of 6.6 (106:16) for total carbon dioxide (TCO_2) to ammonium (NH_4^+) fluxes complemented by a ratio of 1 (106:106) for the TCO_2 to O_2 fluxes, would indicate the high probability that phytoplankton material was degraded and denitrification did not occur.

The ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) fluxes were summed to represent total dissolved inorganic N fluxes and this property was plotted against TCO_2. Most of the muddy sites show less return per unit of C oxidised than would be expected if the organic matter undergoing diagenesis is phytoplankton (i.e. below Redfield ratios). These data are indicative of denitrification. However, one site (Waterloo Bay) does show a complete return of all N (ratio = 106C:16N), indicating high probability of degradation of planktonic material and the possibility of no denitrification process. A succeeding section discusses the 'poised' nature of the Waterloo sediments.

Seagrass and mangrove sediments are extremely efficient at recycling sedimentary N and the net efflux of N is very small, although C:N ratios of these materials are slightly higher than expected C:N ratios for seagrasses and mangroves. In terms of P, all sediments of Moreton Bay are effective sinks for inorganic P. The Brisbane River sites are large sources of P to the system and they support a P flux that must be generated from sources other than organic carbon degradation, as indicated by their deviations from the Redfield ratio. Most of the muddy sites return less P for the amount of C oxidised and the seagrass and mangrove sites show very high efficiencies in retaining P generated during diagenesis.



Flux of dissolved inorganic nitrogen from various sediments plotted against total carbon dioxide (TCO_2) flux, indicating that N fluxes for muddy sediments are generally below Redfield ratio (line). Waterloo Bay was an exception.



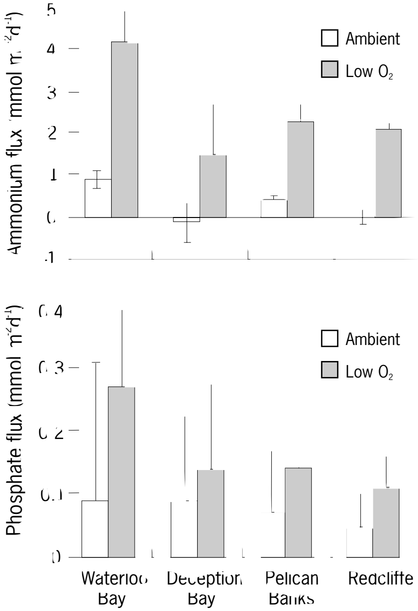
Flux of phosphate from various sediments plotted against total carbon dioxide (TCO_2) flux. Fluxes deviate from C:P ratio of phytoplankton, suggesting phytoplankton is not the primary source of P flux in river sediments.

Sediment Chambers

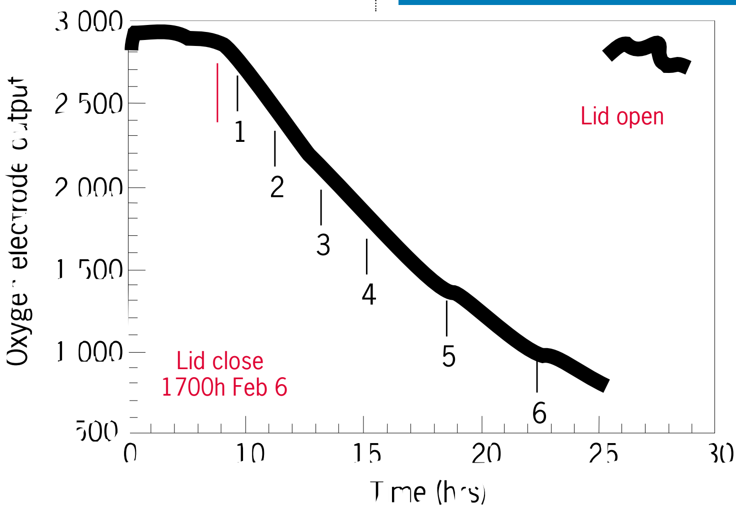
Ammonium and phosphate release dependent

Oxygen concentrations in the benthic chamber decreased over the incubation period due to the respiration of biotic communities. This typical linear decrease in oxygen uptake rates over time is shown in the graph for muds in the central portion of Moreton Bay. The numbered tick marks indicate sample draws and the oxygen uptake rate was ~21 mmol m^{-2} d^{-1}. After a few hours of incubation, the oxygen concentrations decreased to one half the value at the start of the incubation period.

This decline in oxygen availability corresponded to increasing ammonium and phosphate concentrations in all sites. Hence, in determining nutrient fluxes only the early portion of the oxygen versus time plot was used for the flux calculation.



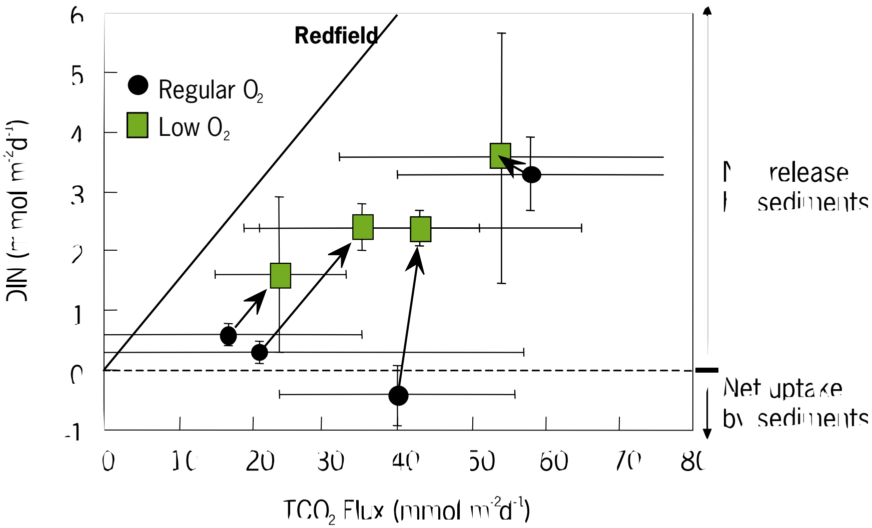
Sediment ammonium and phosphate fluxes in all sites. Low oxygen concentrations resulted in significant fluxes of both ammonium and phosphate from sediments at all sites.



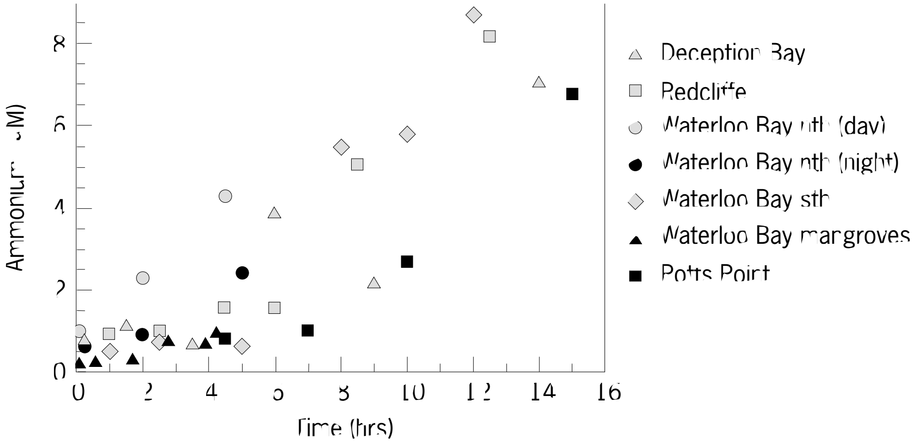
Oxygen concentration profiles from a muddy site in Waterloo Bay. Oxygen concentrations in benthic chamber decreased rapidly within a few hours of incubation.

on oxygen availability

A systematic increase in nitrogen fluxes (DIN) occurs as dissolved oxygen is lowered to approximately 50% of ambient levels. These results provide an indication of the role of oxygen supply and /or the utilisation of oxygen by organic matter in controlling sediment nutrient fluxes. In the muddy sediments of Waterloo Bay, ammonium fluxes occurred just after ~2 hours incubation, indicating the 'poised' nature of the sediments here. It takes a small decline of oxygen for the sediments in this site to release nutrients to the water column.



Dissolved inorganic nitrogen (DIN) fluxes at various total carbon dioxide (TCO_2) fluxes, indicating net release of DIN from muddy sediments at western embayments and the river estuaries.



Ammonium fluxes over time in sediment chambers at all sites. Ammonium fluxes occured after only a few hours of incubation, most likely a result of a decrease in oxygen availability.

Sediment Chambers

'Poised' dentrification efficiency in muddy sediment

Waterloo Bay has muddy sediments with 'poised' denitrification

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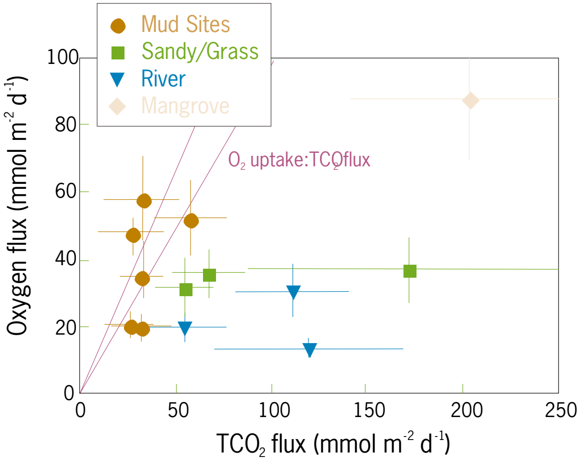
Sediments in muddy areas are sensitively 'poised' with respect to denitrification efficiency; small changes in the nitrification/denitrification coupling within the sediments determine the balance between the proportions of fixed biologically available N (as ammonium and oxides) and gaseous 'unavailable' N released to overlying waters. The denitrification efficiency of muddy sediments is dramatically reduced when oxygen (O_2) concentrations are reduced by 50%. This phenomenon has not been observed from any other coastal systems (Berelson, pers. com.).

The dramatic change in the ability of sediments to cope with a small change in bottom water oxygen content must reflect a sedimentary bacterial population which is poised at the very threshold of being capable of nitrifying ammonium (a key step in denitrification).

As oxygen consumption lowers oxygen concentrations in the benthic chamber to a level of about 50% ambient, the flux of ammonium from muddy sediments increases by a factor of 5.

In the absence of nitrification (process which drives denitrification), oxygen uptake and TCO_2 production have a 1:1 stoichiometry. As indicated on the graph, the muddy sediments show a relationship close to this ratio, indicating that oxygen is the predominant oxidant in the respiration of organic carbon and confirm that these sediments are 'poised'.

This may reflect a critical instability in the diagenetic/microbiological capacity of muddy sediments to tolerate increasing eutrophication. A little less oxygen in the water column, or a bit more organic matter added to the sediments could tip the scales towards a much greater release rate of biologically available N.



Oxygen uptake rate plotted against TCO_2 flux in four sediment types, with lines representing ratios of 1 and 1.3. Ratio of 1 indicates absence of nitrification and subsequent denitrification, especially in muddy sites.

Sediment types control nutrient fluxes

Mangrove mud at southern Bay

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Marine sand and seagrasses at eastern Bay

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Moreton Bay sediments in all regions (with the possible exception of Deception Bay) are net sources of N, P, and Si to the water column. The muds in the western areas of the Bay are the largest sources of N, mostly as ammonium but with a significant component as nitrate. Ammonium fluxes from the sediments show an interesting feature, showing a pattern of greater fluxes half-way through the incubation period, except for one site (Waterloo Bay) where high ammonium fluxes right from the start of the incubation. P fluxes have similar patterns as N fluxes, however, Si fluxes were generally constant throughout the entire incubation period. Silica efflux was largest at the mangrove and muddy sites, which is probably representative of the deposition and dissolution of diatom particles at these locations.

Ammonium fluxes from sandy/seagrass sediments were lower than those from the muddy sediments in sewage-impacted areas. Brisbane River sediments are a sink for nitrate, but a source of ammonium, as well as phosphorus and silica. The river sediments are a very large source for P with the average fluxes of this element 50 times greater than in the Bay sediments.

Average nutrient fluxes from sediments in Moreton Bay and river estuaries (all fluxes are in mg $m^{-2} d^{-1}$) Positive values indicate fluxes out of sediments; negative values indicate fluxes into sediments

	Oxygen	Carbon Dioxide	Ammonium	Nitrate/ Nitrite	Dissolved inorganic nitrogen	Phosphorus	Silica
Upper Brisbane River	-990	+1340	0	-24	-24	+120	+94
Lower Brisbane River	-520	+800	+50	-70	-24	+94	+120
Sewage impacted	-1190	+624	+35	+34	+69	+18	+211
Mangrove	-2800	+2500	+3	+5	+16	+11	+340
Mixed sand and mud	-811	+359	+1.4	+0.9	+2.4	+2.2	+175
Sand and seagrass	-1130	+1080	+3.2	-0.3	+2.9	+1.7	+38.4

Denitrification Efficiency

Flushing time of bay predicts denitrification efficiency ~ 25%

A linear relationship between the fractional net transport of nitrogen and phosphorus from the land to the coastal ocean and the log mean residence time has been established for a number of shallow coastal ecosystems from around the world (Nixon, S.W. et al. 1996, Biochemistry 35). This relationship suggests that similar physical and biogeochemical processes govern the transport, transformation and retention of nitrogen and phosphorus in estuarine systems.

Nixon et al. 1996 also established a linear relationship between the percentage of nitrogen load removed through denitrification and the log mean residence time for a number of estuaries around the world. Using a residence time of 46 days in Moreton Bay, the graph indicates that Moreton Bay has a predicted denitrification efficiency ~25%, indicating that fully a quarter of the nitrogen inputs to the bay will be ultimately denitrified. The remaining ~75% will be exported from the bay through flushing, sediment burial and removal of biota. Estimation of denitrification loss was highlighted as one of the major sources of uncertainty in the construction of the nutrient budgets for Moreton Bay (refer to Chapter 10).

Flushing and exchange with oceanic waters at South Passage

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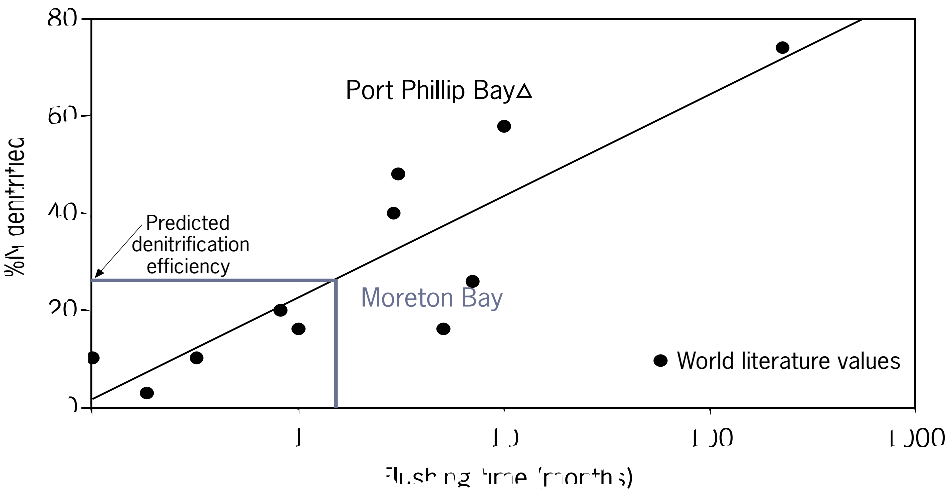

The fraction of total nitrogen input that is denitrified as a function of flushing time in Moreton Bay and other similar systems around the world.

Next section ▶

CHAPTER 9

Nutrient Responses

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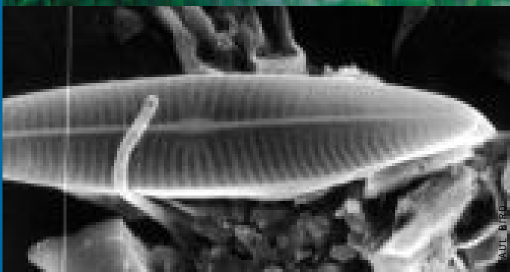

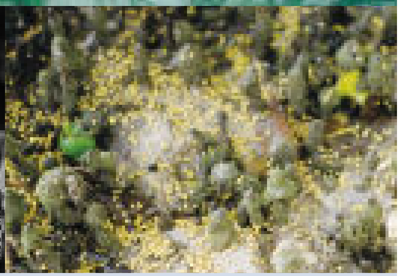

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Phytoplankton

- Phytoplankton blooms near nutrient sources
- Phytoplankton biomass: high and variable in Bramble Bay
- Phytoplankton productivity: high in Bramble Bay
- Nutrient uptake measured with isotope tracers
- Nutrient uptake rates variable
- Deviation of nutrient uptake from Redfield ratios
- Phytoplankton nitrogen preference: ammonium > urea > nitrate
- Inhibition of nitrate uptake by ammonium
- Phytoplankton assemblage predicted by the form of nitrogen

Seagrass

- Seagrass responses to nutrients tested
- Seagrass growth stimulated in eastern Bay

Mangroves

- Mangrove response to nutrients tested
- Mangrove growth stimulated in western Bay

Overall

- Marine plants responsive to different nutrient sources

Phytoplankton blooms near nutrient sources

Plants nutrient requirements and responses

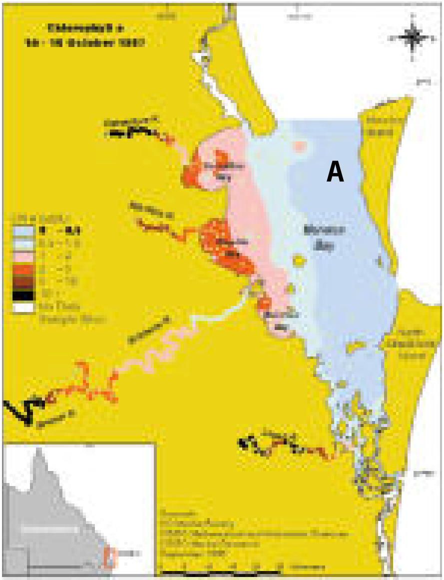
Plants typically absorb nutrients in inorganic forms and convert them into organic forms, although some marine plants are also able to take up organic forms of nutrients (e.g. urea) as well. Physiological responses of plants to nutrient additions can give an indication of the ambient nutrient environment and/or the nutrient status of the organism. Chemical analyses generally give a 'snap-shot' view of a particular parameter at a given time. Plants are particularly useful as indicators of changes in their environment as they can integrate various parameters over a length of time that may give a more accurate reflection of conditions. Marine plants may be used as indicators of a changing environment over varying time scales, from minutes or hours (phytoplankton) to months or years (seagrass and mangroves). Nitrogen and phosphorus, as the primary limiting nutrients for plant growth, have generally been a main research focus although other nutrients may also be important, depending on specific plant requirements and environmental conditions.

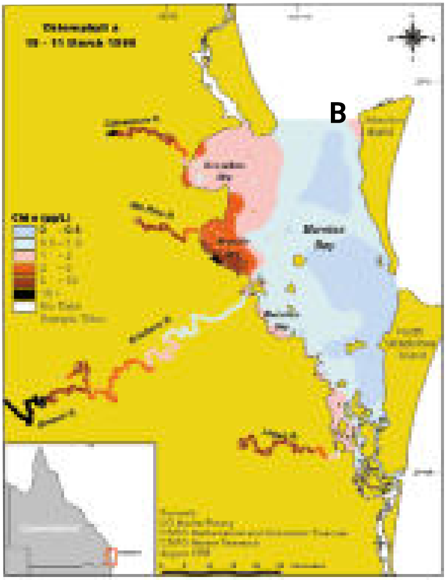
There was a strong east-west gradient in phytoplankton biomass with highest values of chlorophyll measured in the river estuaries and Bramble Bay, followed by intermediate levels at Deception and Waterloo Bays, with lowest values consistently found in the eastern Moreton Bay sites. These trends correspond to the observed gradients in nutrient availability (refer to Chapter 7).

Chlorophyll *a* is a measure of phytoplankton biomass

Phytoplankton are microscopic marine plants containing chlorophyll *a* along with other pigments (e.g. carotenoids). These pigments enable plants to gain energy from light through the process of photosynthesis. The amount of chlorophyll *a* in the water column gives an estimate of the abundance or biomass of phytoplankton and is a relatively simple assay procedure. Chlorophyll *a* concentrations were determined by filtration onto glass-fibre filters, extraction with acetone and fluorometric analysis.

Uptake of readily available nutrients allows the biomass of phytoplankton populations to rapidly increase on time scales that their zooplankton grazers cannot keep up with. Grazers are often unable to control bloom populations and instead light or nutrient limitation control bloom biomass.





Water column chlorophyll *a* concentrations in A) October and B) March. Phytoplankton biomass was the greatest in the riverine and western Bay sites.

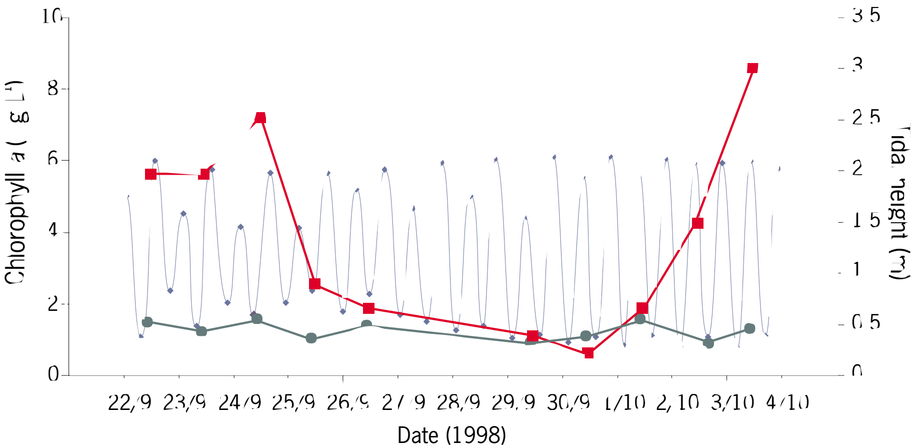
Phytoplankton biomass: high and variable in Bramble Bay

Of all Bay sites, Bramble Bay exhibited the highest phytoplankton biomass. A significant decreasing gradient in chlorophyll *a* concentrations from the western Bay to the eastern Bay sites was evident. Phytoplankton biomass was significantly highest in the Bremer River estuary, however, this was not correlated to the productivity values measured for this site (refer to next section) and may be related to the heterotrophic plankton population occurring in this site (refer to Chapter 13).

Bramble Bay phytoplankton biomass is high but variable between day and night samplings. Higher abundances in the day compared to night may be due to several factors including

- physical settling of diatoms as wind drops at night
- increased grazing pressure at night from diel migration of zooplankton populations into the water column
- or from interactions with short-term re-suspension events

On longer time scales, observations indicate that the Bramble Bay phytoplankton population experiences bloom crash cycles of biomass reflecting the fluctuating conditions of the area. Bramble Bay is characterised by very high nutrient concentrations which are attributed to the high loads from both the Brisbane and Pine Rivers, as well as the general circulation patterns in the Bay (refer to chapter 3). As nutrients correlate strongly with phytoplankton biomass, variable nutrient delivery may result in bloom crash cycles. In addition, Bramble Bay is a shallow embayment which is susceptible to resuspension events from the build-up of wind waves from the south-easterly winds which may lead to cycles of physical settling and resuspension.



Phytoplankton biomass (chlorophyll *a* concentration) at Bramble Bay (■) and the Brisbane River (●) mouth and tidal changes, over 13 days. Bramble Bay experienced bloom/crash cycles of phytoplankton biomass unrelated to tidal cycles.

Phytoplankton

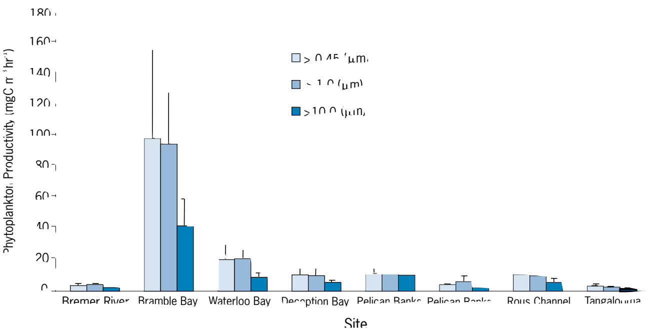
Phytoplankton productivity: high in Bramble Bay

Biomass vs Productivity

Biomass refers to the quantity of phytoplankton which is present or the 'standing stock'. Productivity refers to the rate at which the biomass is produced. These concepts can be explained in terms of grocery stores. A large biomass is comparable to a supermarket and a small biomass to a corner store. The rate at which the groceries are removed from the shelves is comparable to productivity. A quiet store (whether small or large) has its groceries on the shelves for a long time. Likewise, a phytoplankton population with a large biomass or stock (e.g. Bremer River) may have a slow rate of productivity or replacement. On the other hand, a busy store has groceries rapidly removed from the shelves and these must be continuously replaced. Bramble Bay which has a lower biomass or stock (than Bremer River) is continuously replaced by the rapid productivity.

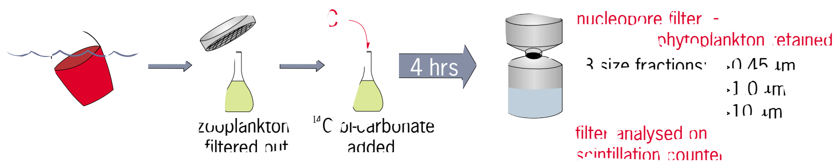
Phytoplankton primary productivity is the rate at which carbon (C) is incorporated by phytoplankton through photosynthesis, into new biomass. It is estimated by incubation of phytoplankton samples with the radioisotope of carbon (^{14}C) which is incorporated as the phytoplankton photosynthesise. The amount of ^{14}C present in a phytoplankton sample after a given time period is determined by using a scintillation counter.

Water column nutrient concentrations correlated with phytoplankton biomass was also observed with productivity in Moreton Bay. Bramble Bay had a phytoplankton productivity which far exceeded that of all other measured sites, correlating with the areas of high nutrient concentration. In contrast, the phytoplankton in the oceanic waters of Rous Channel exhibited low productivity.



Phytoplankton productivity in the >0.45µm , >1.0µm and >10µm size fractions. Productivity was the highest at Bramble Bay and the lowest at Tangalooma

In the Bremer River, however, productivity did not correlate with phytoplankton biomass and nutrient concentrations. The Bremer River had a lower productivity despite having the highest phytoplankton biomass and nutrient concentrations. At this site, productivity is instead limited by light (refer to Chapter 10).



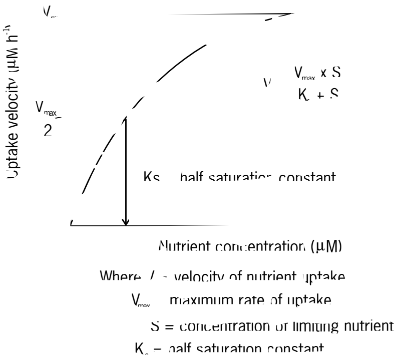
Phytoplankton productivity method. Water was collected and incubated with ^{14}C and uptake measured after 4 hours.

Nutrient uptake measured with isotope tracers

Nutrient uptake rates were measured in order to determine the response of phytoplankton populations to nutrient availability.

Nitrogen (N) uptake was measured using stable isotope techniques in which ^{15}N labelled substrates, ($^{15}NH_4^+$, $^{15}NO_3^-$ (inorganic) and ^{15}N-urea (organic) were added to the phytoplankton samples. These substrates were added at a range of concentrations: 10%, 50% and 100% ambient nutrient concentrations. The samples were incubated under ambient light and water temperature conditions for 30 minutes to an hour. They were then filtered and analysed for ^{15}N content of the phytoplankton using mass spectrometry.

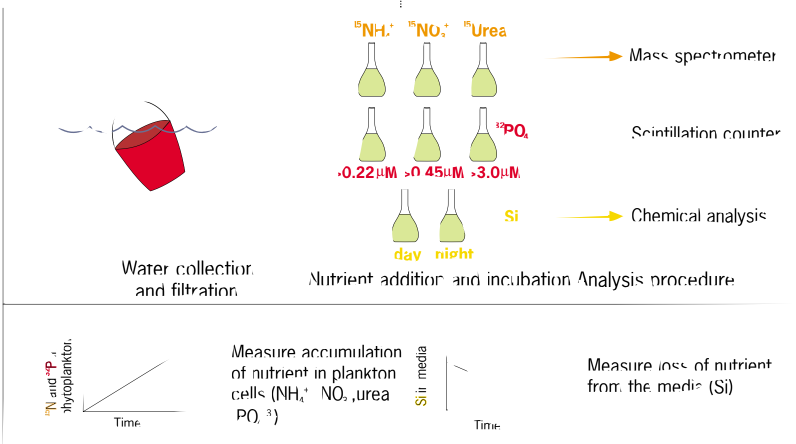
Phosphate (P) uptake was measured by incubation with a radioactive $^{32}PO_4^{-3}$ substrate. Incorporation of ^{32}P into phytoplankton was measured using a scintillation counter. As stable isotope studies of silica (Si) are costly and require a specially adapted mass spectrometer, Si uptake in this study was measured by the decline of reactive SiO_2 from the incubation media.



Michaelis-Menten uptake kinetics describing rate of uptake and enzyme saturation.

Uptake Kinetics

Nutrient uptake by phytoplankton can be described by Michaelis-Menten uptake kinetics, a mathematical expression developed to describe enzyme kinetics which may be adapted to phytoplankton nutrient uptake. The velocity of nutrient uptake is explained based on the maximum rate of uptake (V_{max}) and the nutrient concentration at half of V_{max} (K_s). At low nutrient substrate concentrations uptake is directly proportional to availability. At higher concentrations, uptake rate becomes saturated.



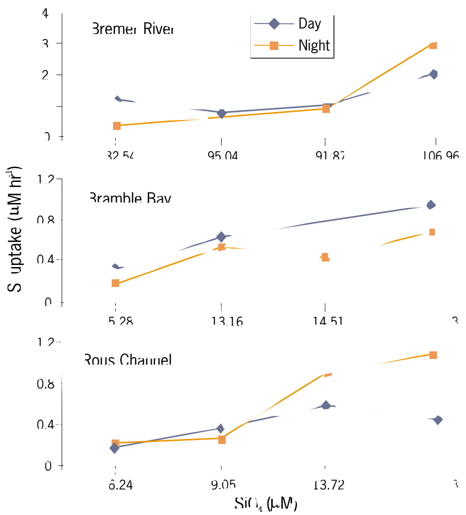
Phytoplankton nutrient uptake method. Water was collected and incubated with ^{15}N, ^{32}P or Si. N and P uptake were analysed as accumulation in phytoplankton over time and Si is based on loss from the incubation media.

Phytoplankton

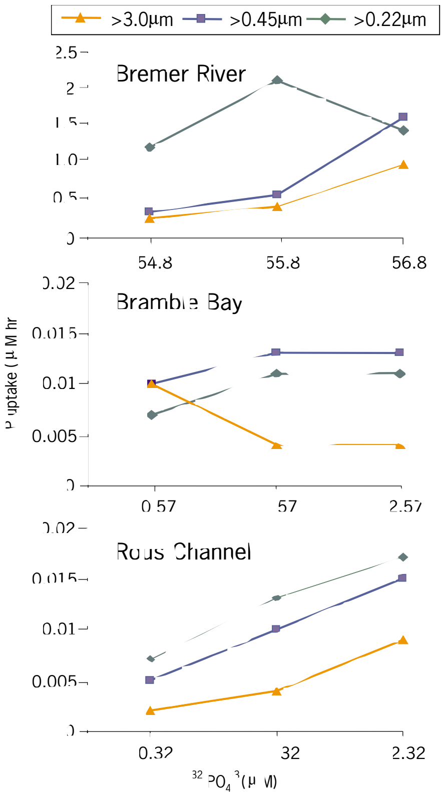
Nutrient uptake rates variable

Nitrogen (N) uptake rates in western Moreton Bay and in the rivers were very high. Ammonium (NH_4^+) , nitrate (NO_3^-) and urea were assimilated at all sites. No consistent diel (day/night) patterns of uptake were observed in any of the sites.

Size fractionation of photoplankton for phosphate (PO_4^{-3}) uptake was necessary as studies have shown that a significant fraction of phosphate uptake within coastal marine systems can be attributed to bacterial uptake. Phosphate uptake measurements indicated highest rates in the bacterial (> 0.22 µm) and microzooplankton (> 0.45 µm) fractions at each site. Highest phosphate uptake was recorded in the Bremer River. Phosphate dynamics at this site were dominated by chemical and abiotic processes (e.g. adsorption and desorption) rather than biological uptake. Formalin-treated samples analysed for ^{32}P incorporation allowed for the differentiation of this abiotic process from biological P uptake.



Phytoplankton silica uptake rate at a range of substrate concentrations. Uptake rates were generally highest during the day.



Phytoplankton phosphate uptake rates at a range of substrate concentrations. Phosphate uptake was the greatest at Bremer River and in the smaller size fraction which included bacteria.

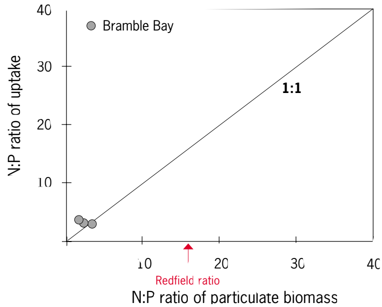
Silica is an important nutrient for diatoms as it is a component of their skeletons.

Silica uptake rates were generally highest during the day. Uptake rates were also highest in the Bremer River, however, this process requires further investigation.

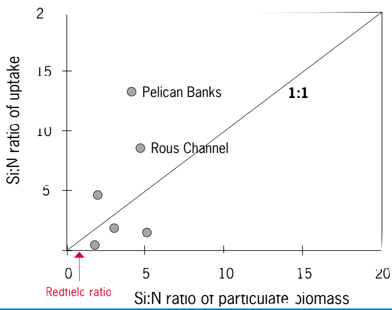
Deviation of nutrient uptake from Redfield ratios

The Redfield ratio gives an average nitrogen (N) and phosphorus (P) ratio of 16N:1P for phytoplankton in the world's oceans and is useful in describing the nutrient status of a system (refer to Chapter 7). Phytoplankton N:P uptake ratios were compared with particulate N:P ratios to infer nutrient availability and nutrient limitation in Moreton Bay and Brisbane River (refer to Chapter 10 for discussion of nutrient limitation). N:P ratios less than 16 indicate that there is sufficient phosphorus and not enough nitrogen available for phytoplankton growth and biomass. At all Bay sites, N:P ratios of particulate matter (which includes phytoplankton, sediments, and other particles in the water column) were less than 16 (~< 5), indicating P is present in excess of the requirements of ambient phytoplankton populations. Similarly, N:P ratios of uptake rates were also below 16 at most sites, indicating excess P uptake by phytoplankton. A 1:1 correlation between particulate and uptake N:P ratios at most sites indicates that particulate N and P concentrations reflect uptake rates. However, in Bramble Bay, uptake N:P ratio was greater than 35. The absence of 1:1 correlation between the particulate (< 5) and uptake N:P ratios may be attributed to: a) 'luxury uptake' of N by phytoplankton in response to high nutrient concentrations in Bramble Bay (refer to Chapter 7 for nutrient distribution in the Bay), explaining the high uptake N:P ratio; and b) large amounts of resuspended sediments which 'scavenge' P (high phosphate (PO_4^{-3}) adsorption to particulate matter), explaining the low particulate N:P ratios (high P concentrations result in low N:P ratios).

Silica (Si) is an essential nutritional element for phytoplankton which have a siliceous skeleton, mainly diatoms and Chrysophytes. Diatoms require N and Si at a ratio of 1:1. In Australian coastal waters, Si is often assumed to be unimportant due to high concentrations of this nutrient in river waters and runoff . However, in systems with considerable enrichment of N and P (western parts of Moreton Bay), Si may play a potential role controlling phytoplankton productivity. Ratios of Si:N uptake in Moreton Bay were generally above that of the Redfield Ratio (1:1), while the ratios of particulate Si: N were near the Redfield ratio, suggesting that Si is present in excess of the requirements of phytoplankton within Moreton Bay. Phytoplankton populations in Moreton Bay appear to be P and Si replete.



Ratio of N:P taken up by the phytoplankton cells vs the ratio of N:P in particulate biomass. N:P ratios of uptake and particulate biomass were lower than Redfield ratio with the exception of Bramble Bay.

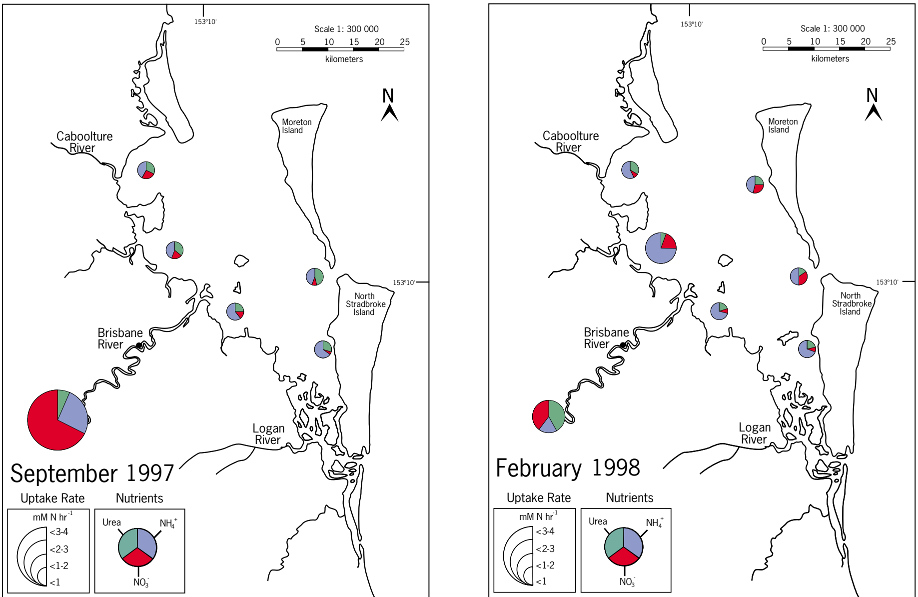


Ratio of Si:N taken up by the phytoplankton cells vs the ratio of Si:N in particulate biomass. Pelican Banks and Rous channel had ratios of nutrient uptake which far exceeded the Redfield ratio of 1:1

Phytoplankton nitrogen preference: ammonium > urea > nitrate

Phytoplankton are able to utilise both organic and inorganic sources of nitrogen (N). Inorganic forms, ammonium (NH_4^+) and nitrate (NO_3^-), are generally the most abundant sources and previous studies have predominantly focussed on the potential of these inorganic forms to be limiting to phytoplankton growth. Studies of the phytoplankton populations in Moreton Bay, however, indicate that the organic form, urea may at times be taken up at rates comparable to that of ammonium. The general preference was ammonium > urea. Both ammonium and urea are more reduced forms of nitrogen than nitrate and, therefore, require less energy for incorporation into cellular material. Nitrate, however, must undergo reduction to ammonium prior to incorporation into organic molecules. This is an energy requiring process and it is therefore energetically more favourable for phytoplankton to utilise the forms of N which are already reduced. Nitrate, however, was the preferred form for phytoplankton in the Bremer River where extremely high ambient concentrations of the oxidised form were available.

Overall uptake rates were greatest at sites receiving highest ambient nutrient concentrations. In particular, Bremer River had rates up to 3 orders of magnitude greater than other sites. This was driven predominantly by nitrate uptake, at this site. Bramble Bay also had rapid rates of uptake in February, comparable to those observed in Bremer River. In this Bay site, ammonium was taken up at rates faster than other forms of N.

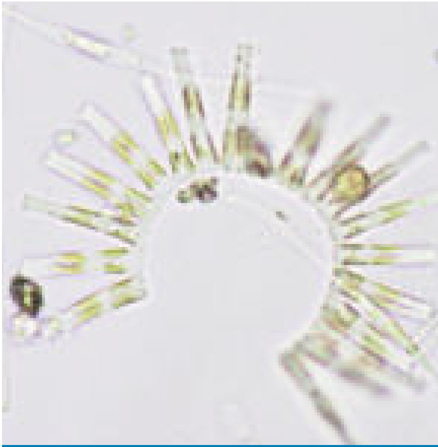


Phytoplankton urea, ammonium (NH_4^+) and nitrate (NO_3^-) uptake in September and February. Uptake rates were highest in the Bremer River, followed by Bramble Bay. Except for Bremer River, ammonium was preferred, followed by urea.

Inhibition of nitrate uptake by ammonium

Lower rates of nitrate (NO_3^-) uptake by phytoplankton (compared to ammonium (NH_4^+) may be to inhibition by ammonium as availability increases. Where ambient ammonium concentrations were high enough to represent a greater percentage of the total available nitrogen, the rate of nitrate uptake was lower. Incorporation of nitrate is energetically expensive at the cellular level as it must be reduced to ammonium prior to its incorporation into organic molecules. The first and controlling stage of the conversion of nitrate to ammonium within plant cells requires the enzyme nitrate reductase. Nitrate reductase is a temperature sensitive enzyme. In addition, it has a low temperature optimum (~15-16 °C) which is unusual for enzymes, and its function therefore declines with increasing temperature. The dogma that diatoms prefer nitrate may therefore not apply in the tropical and sub-tropical environment due to the higher temperatures.

The utilisation of ammonium is energetically favourable over nitrate. This may explain the observed phytoplankton preference of ammonium at all Bay sites (refer to previous page) and the phytoplankton preference of nitrate at Bremer River, where ambient ammonium concentrations were low (0.29 μM) and nitrogen oxide concentrations (214 μM) were two orders of magnitude higher than at western Bay sites.



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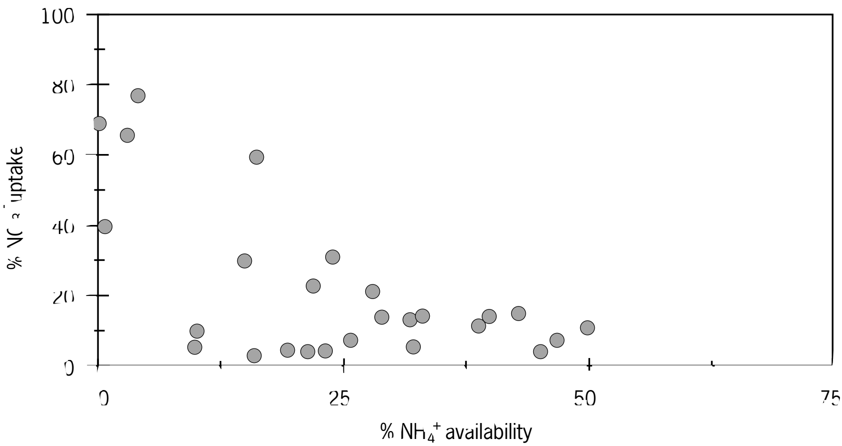
Phytoplankton: *Asterionella*



The influence of ammonium availability on nitrate uptake. As ammonium concentration increases nitrate uptake is reduced.

Phytoplankton assemblage predicted by the form of nitrogen

Typical diatom

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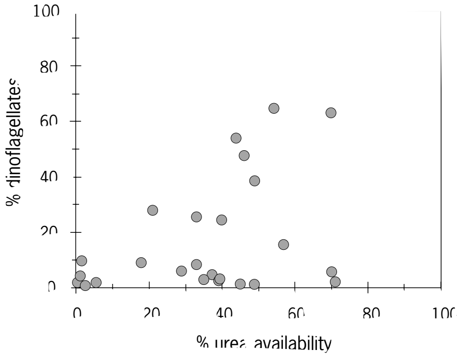
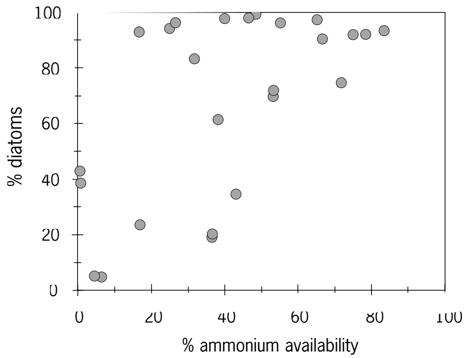
Phytoplankton community composition was influenced by the form of nitrogen (N) available. The percentage of the phytoplankton assemblage represented by **dinoflagellates**, correlated to the concentration of **urea** (organic nitrogen). The percentage of the phytoplankton assemblage represented by **diatoms** correlated to the concentration of **ammonium**.

Dinoflagellates have a longer evolutionary history than that of the other phytoplankton populations. Most dinoflagellates are not purely autotrophic. Autotrophic organisms photosynthesise and incorporate inorganic sources of carbon (C) and N and fix them into organic molecules. Heterotrophs on the other hand are only able to utilise sources of carbon which are already incorporated into organic molecules. The responsiveness of dinoflagellates to organic N may reflect their partial dependence on organic sources of C for nutrition. Diatoms require inorganic N forms of which ammonium is the most easily assimilated (refer to previous section).

In Moreton Bay, analysis of the form of N dissolved in the water column, may enable some prediction of phytoplankton assemblage. As these results are the first obtained describing such a relationship, further research is required to refine these findings and allow development of an additional biological indicator tool.

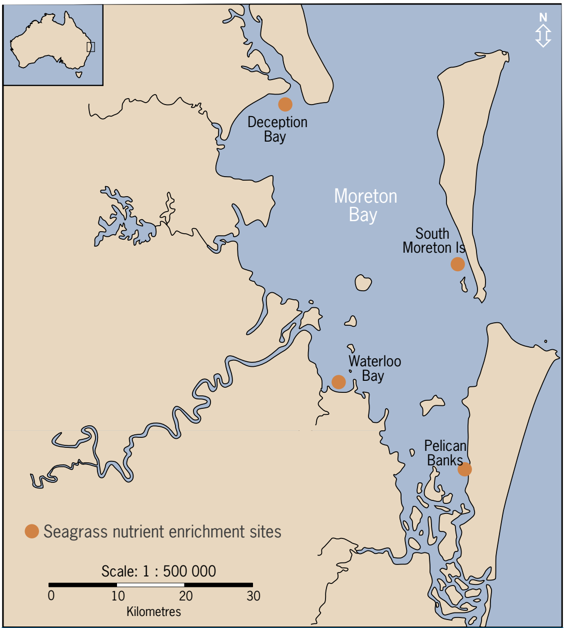


Percentage of the phytoplankton community composition composed of dinoflagellates versus urea availability. As urea availability increased, the percentage of dinoflagellates increased.



Percentage of the phytoplankton community composition composed of diatoms versus ammonium availability. As ammonium availability increased, the percentage of diatoms increased.

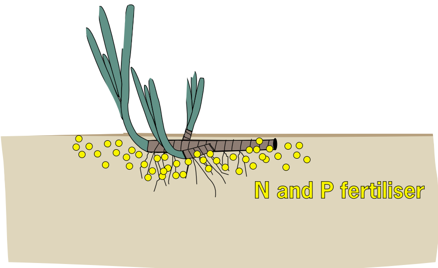
Seagrass responses to nutrients tested



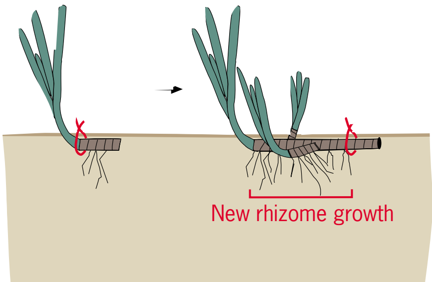
Seagrass nutrient enrichment sites

Fertilisation of seagrass beds was carried out in order to determine the response of *Zostera capricorni,* the species most commonly found in the Bay, to experimental sediment nutrient enrichment. Four sites were established encompassing a range of ambient water column nutrient conditions (refer to Chapter 7 for Bay-wide water column nutrient concentrations). Sites with high ambient nutrient concentrations were established at Deception and Waterloo Bay. Sites with low ambient nutrient concentrations were established at Pelican Banks and south Moreton Island. Slow release fertiliser pellets containing nitrogen, phosphorus and potassium (Osmocote) were applied to the sediment around the roots of the seagrasses. These pellets remained in the sediment and slowly released nutrients over several months.

Growth rate of *Z. capricorni* was measured over 2 months by the rhizome tagging method. This method wrapping a small piece of wire around the base of a shoot at the commencement of the fertilisation period. As the seagrass grows, new shoots are produced and old leaves fall off leaving scars on the rhizome. The piece of wire remains where it was initially wrapped around the rhizome and the distance between the original rhizome tag and new shoot is an estimate of seagrass growth.

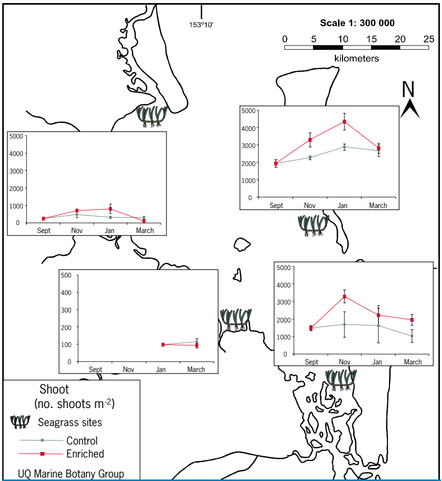


Seagrass sediment nutrient enrichment. The sediment is gently brushed away and the osmocote placed around the roots and rhizome.

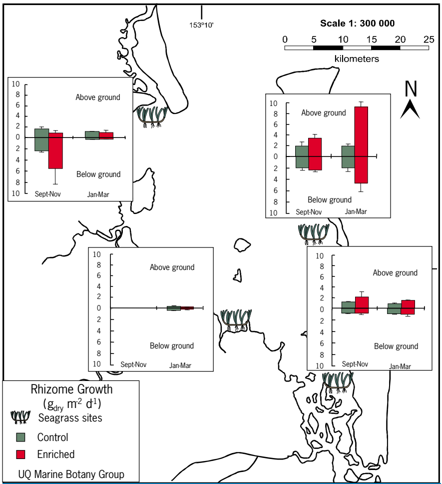


Seagrass rhizome tagging. A wire was wrapped around the rhizome at the base of the shoot and remained in place as the seagrass shoot grew.

Seagrass growth stimulated in

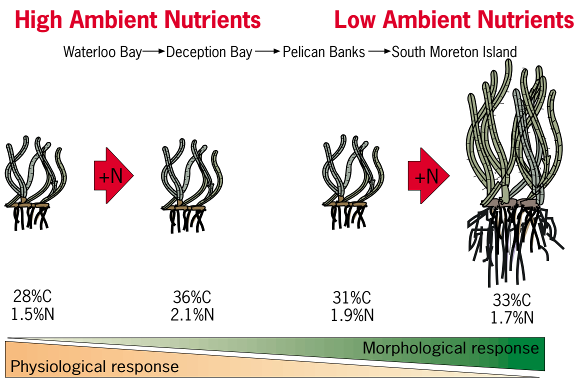


Seagrass shoot density. Enriched seagrasses at the eastern Bay sites had the greatest shoot density followed by the control seagrasses at eastern Bay sites.



Seagrass productivity (g m^{-2} d^{-1}) during September to November and January to March. Productivity at the northern sites (South Moreton Is and Deception Bay) was higher than at the southern sites (Pelican Banks and Waterloo Bay).

Seagrasses located at eastern Bay sites where ambient nutrients were low, responded differently to sediment nutrient enrichment than plants at western Bay sites, where ambient nutrients were much higher. At the eastern Bay sites (south Moreton Island and Pelican Banks), increased growth and shoot density resulting from enrichment indicates that seagrass growth at these sites was limited by nutrient availability. At the western Bay sites (Waterloo Bay and Deception Bay), lack of growth response indicates that there may be excess sediment nutrients than required for growth. However, physiological responses such as increased tissue nutrient content (nitrogen and carbon) were observed in seagrasses at these sites. 'Luxury uptake' may occur in high nutrient concentration environments. At these western Bay sites, growth may instead be limited by light availability so excess nutrient uptake is not invested into new growth as was observed at eastern Bay sites where higher light penetration occurs.



Seagrass response to experimental nutrient enrichment. Western Bay seagrasses responded physiologically through increased tissue nitrogen content, and eastern bay seagrasses responded through growth and morphology.

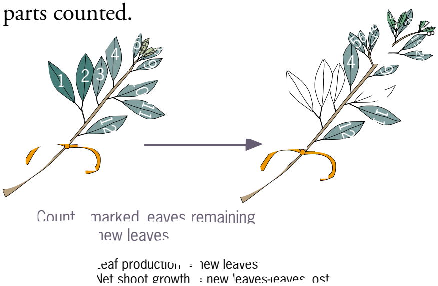
eastern Bay

Pressed seagrass from the control and nutrient enriched sites. The seagrasses at south Moreton Island responded the greatest while at Deception Bay, Algae became more dominant.

Mangrove response to nutrients tested

The response of mangrove forests to experimental sediment nutrient enrichment was tested at four sites in Moreton Bay. Experimental plots were established at two sites in the western embayments (Deception Bay, at the mouth of the Caboolture River and Waterloo Bay at the mouth of Tingalpa Creek). These sites may already receive high nutrient loads from overlying waters. 'Clean water' eastern Bay sites were situated at Myora Springs and Pelican Banks. At each site, six plots were established - three control and three nutrient enriched. Slow-release Osmocote pellet fertiliser was applied to plots in September, December and June. The fertiliser contained nitrogen as ammonium (NH_4^+) and nitrate (NO_3^-), phosphate as (PO_4^{-3}) and potassium as (K^+) and was applied in approximately equal amounts to each plot.

Mangrove responses to nutrients were measured over a ten month period as leaf fall, leaf production and tissue nutrient concentrations. Leaf fall was measured using 1 m^2 litter traps which were suspended under the trees above the high water mark. One litter trap was installed in each treatment plot. Leaf production was estimated by 'tagging' six shoots on each treatment tree. Flagging tape was tied at the base of each 'shoot', each leaf was marked and the leaves, growing tips and reproductive parts were counted in September. In December, March and June, the new leaves were counted and marked and the growing tips and reproductive parts counted.



Mangrove leaf production method. Leaves are numbered and tagged and the rate at which leaves are produced is recorded

Mangrove leaf litter trap. The mesh is strung in 1m x 1m traps and suspended in the trees to capture leaf litter as it falls.

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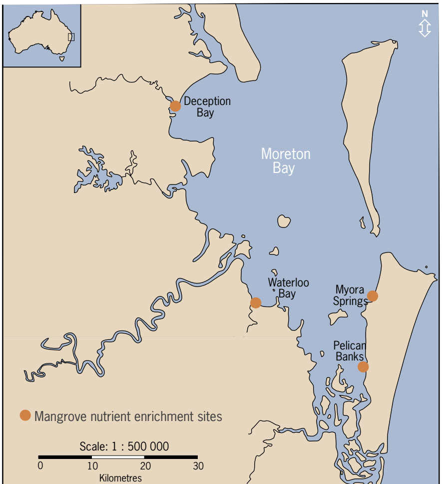

Mangrove nutrient enrichment monitoring sites.

Mangrove growth stimulated in western Bay

Despite significant increases in bioavailable sediment nutrient concentrations in fertilised plots, there was no increase in mangrove leaf litter fall rates over ten months when compared to control plots. The seasonal variability which occurred in leaf litter fall was consistent between control and fertilised plots.

However, at some sites, rates of mangrove leaf production were responsive to sediment nutrient enrichments. Leaf production was significantly greater in enriched plots compared to control plots, at the western Bay sites (Deception Bay and Waterloo Bay). The higher rates of production (up to twice that of control plots) occurred within three months of enrichment, and were sustained throughout the remainder of the experiment (six months). No corresponding increase in leaf production in response to fertilisation was observed at eastern Bay sites (Pelican Banks and Myora Springs).

In the western Bay sites, although an increase in leaf production was observed, the rate of biomass turnover (leaf production and leaf fall) did not increase. The potential for mangrove forests to assimilate increased loads of nutrients may instead be limited to an initial biomass increase.

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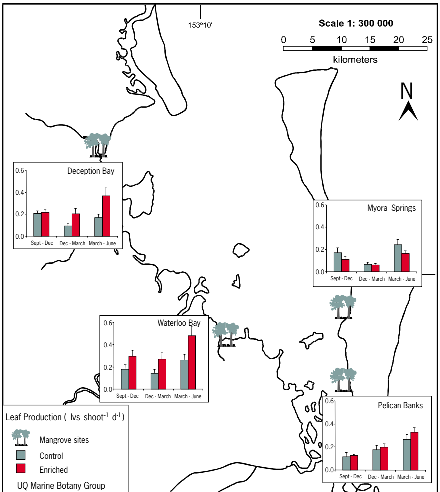
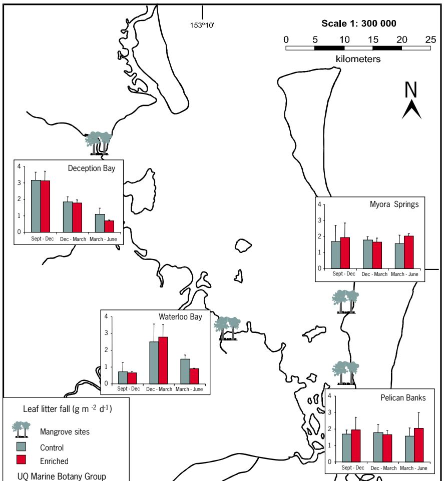
Tagged mangrove 'shoot' for leaf production measurement



Mangrove leaf production at control and fertilised sites Western Bay sites only responded to nutrient enrichment and no significant seasonal trends were observed.



Mangrove leaf litter fall for control and fertilised sites. There were no significant differences between site and treatment rates of leaf litter fall.

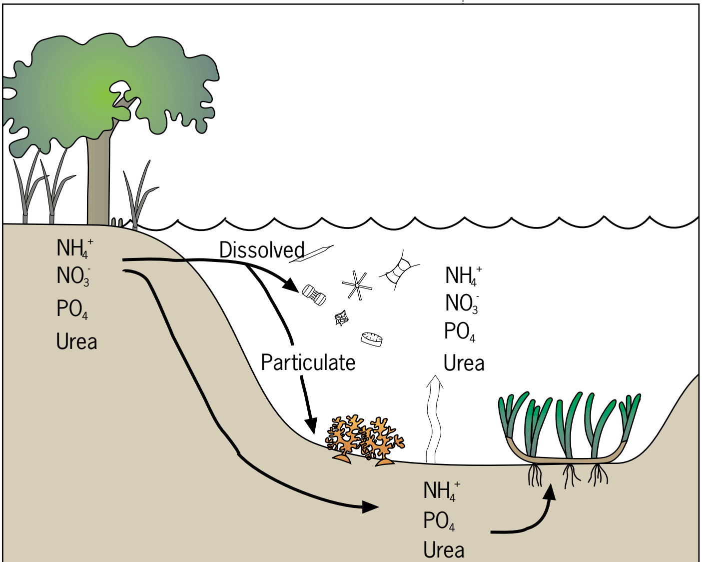
Overall

Marine plants responsive to different nutrient sources

Nutrients are available to marine plants in dissolved form in the water column or particulate matter (sorbed to inorganic sediment particles or in particulate organic material) forms. Utilisation of dissolved and particulate nutrient varies between different marine plants. Phytoplankton and macroalgae rely predominantly on dissolved forms of inorganic or organic nutrients in the water column. The preferred dissolved form of nitrogen also varies between taxa. Seagrasses have access to dissolved nutrients in the water column through leaf uptake but also use their roots to access particulate forms present in the sediments. Nutrients are replenished by the settling of particulate matter, decomposition of organic material and by exchange of dissolved nutrients with the water column. Mangroves rely principally on sediment nutrients.

The assimilatory potential of plants to additional nutrients depends upon the ambient nutrient conditions the plants are exposed to. The form and the mechanism by which nutrients are available, is therefore, an important consideration in determining which groups may respond to nutrient availability. While plants frequently respond to elevated nutrients with increased uptake and tissue nutrient content, productivity responses to nutrient additions in Moreton Bay were limited to phytoplankton and seagrasses that were not limited by the availability of light. Mangroves demonstrated no productivity response when fertilised and therefore have limited potential to assimilate and incorporate excess nutrients.

The responses of plant groups to nutrient availability can indicate the ambient nutrient environment and/or the nutrient status of the organism. However, responses may be specific to species or higher taxonomical levels and to locations. As many coastal ecosystems are becoming increasingly nutrient enriched due to anthropogenic eutrophication, a greater understanding of the impacts which these nutrients have on primary producers is essential for maintaining healthy ecosystems.

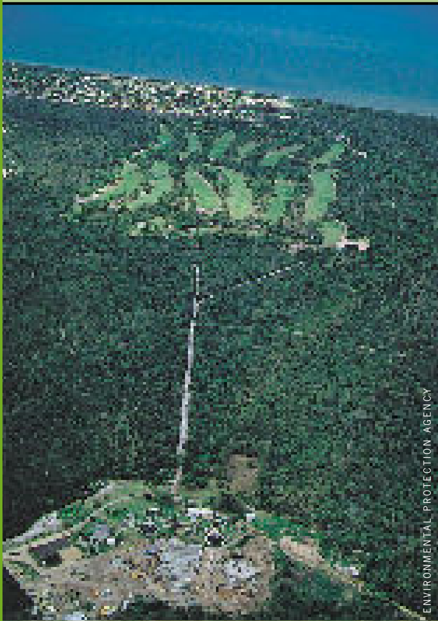


Conceptual model depicting the sources of nutrients available to the various marine plants. Phytoplankton and macroalage access the water column nutrients, mangroves access the sediment and seagrsass access both.

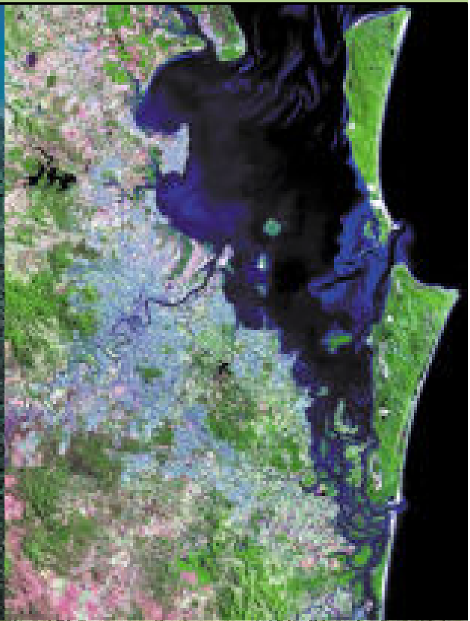
Next section ▶

CHAPTER 10

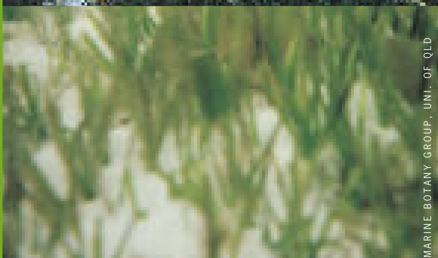
Limiting Nutrients and Nutrient Budgets



ENVIRONMENTAL PROTECTION AGENCY



AUSTRALIAN CENTRE FOR REMOTE SENSING



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ENVIRONMENTAL PROTECTION AGENCY

- Nutrient in least supply = limiting
- Nitrogen: primary limiting nutrient in river estuaries and Bay
- Nitrogen limitation: water column nutrient ratios and turnover times
- Nitrogen limitation: phytoplankton nutrient uptake rates and bioassay responses
- Nitrogen limitation: macroalgal and seagrass responses
- System-wide nutrient budgets constructed
- Carbon budget dominated by metabolism of marine biota
- Large uncertainties in nitrogen budget
- Phosphorus budget corresponds to flushing time

Nutrient in least supply = limiting

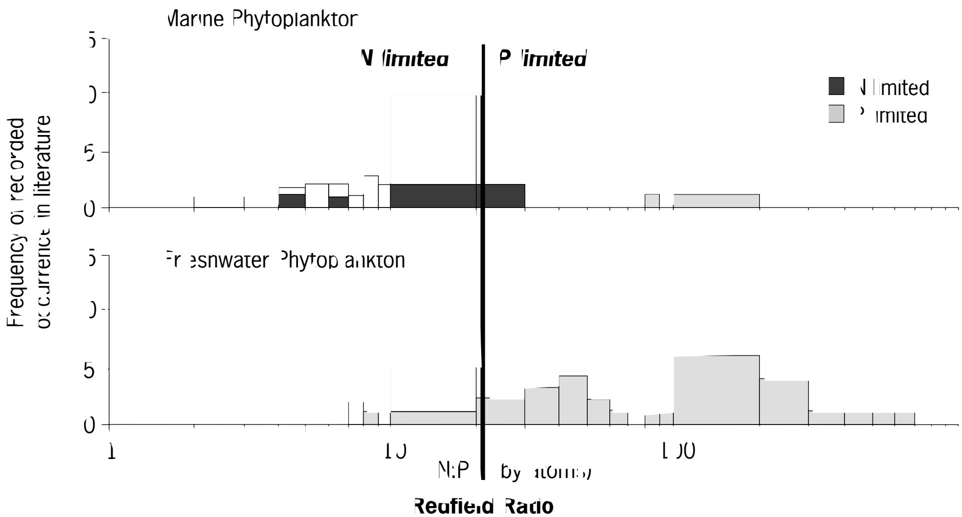
A nutrient is limiting when it is in short supply relative to the availability of other nutrients. For example, if concentrations of all nutrients except nitrogen are high, nitrogen may become limiting. The concept of limiting nutrients stems from Liebeg's 'Law of Minimum' which states that the element in least supply is that which limits the growth of an organism. Originally developed with regard to agricultural crop management, this concept has been applied extensively in freshwater and marine environments. Nutrients can be viewed as limiting either productivity, growth or ecosystem production. The different time scales of these processes can lead to different limiting factors operating at a particular location.

Phytoplankton Redfield ratio N:P = 16:1

Phytoplankton with: N:P > 16 are P limited

N:P < 16 are N limited

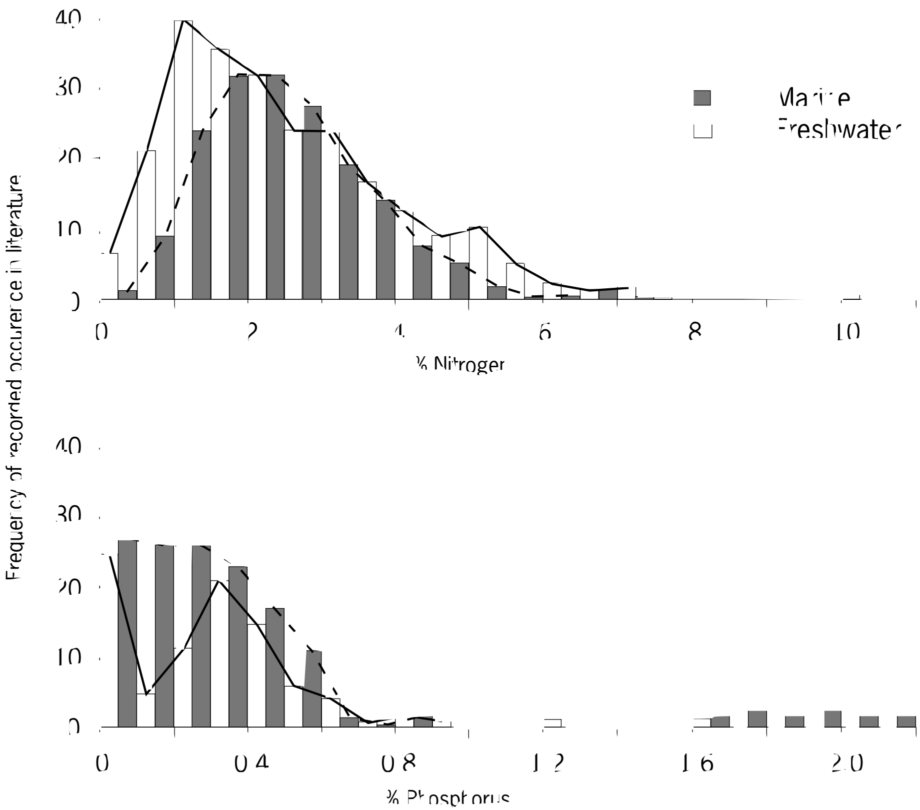
The Redfield ratio of 106:16:1 has provided the baseline for assessing limitation of phytoplankton productivity. The similar N:P ratios of phytoplankton (16N:1P) and water column (16N:1P) have been interpreted as evidence that phytoplankton effectively regulate the availability of N and P in the upper, lighted portions of the coastal systems. Laboratory experiments have indicated that there is a threshold below which algal cells are N limited and above which the cells are P limited. Phytoplankton with N:P ratios greater than 16:1 are considered to be P limited (have more N relative to P) and less than 16:1 to be N limited (have less N than P). In addition, Redfield ratios have been extended to other marine organisms (refer to Chapter 7 for more detailed discussion of Redfield Ratios).



N:P ratios in marine and freshwater phytoplankton, unshaded bars indicate phytoplankton collected from a low P environment or grown in a N or P limited culture. (Valiela, I., 1995, Marine Ecological Processes). Redfield ratios for marine phytoplankton are generally lower than 16:1 indicating N limitation of these communities.

Nitrogen: primary limiting nutrient in river estuaries and Bay

The general paradigm of nutrient limitation is phosphorus (P) limitation in freshwater and nitrogen (N) limitation in coastal marine waters. An abundance of N fixing cyanobacteria may alleviate N limitation in lakes, reservoirs and river systems. In Moreton Bay and estuaries, phytoplankton bioassays, macroalgal, mangrove and seagrass fertilisation experiments indicate nitrogen stimulation and little or no response to phosphorus. The relative paucity of N fixing cyanobacteria and abundance of denitrifying bacteria in marine sediments contributes to the relative lack of N and therefore N limitation. Management strategies for estuarine and marine areas thus focus on N loadings.



Nitrogen and phosphorus contents of marine and freshwater macroalgae and vascular plants (Valiela, I., 1995, Marine Ecological Processes). Marine vascular plants have lower %N than freshwater species suggesting N limitation of marine plants.

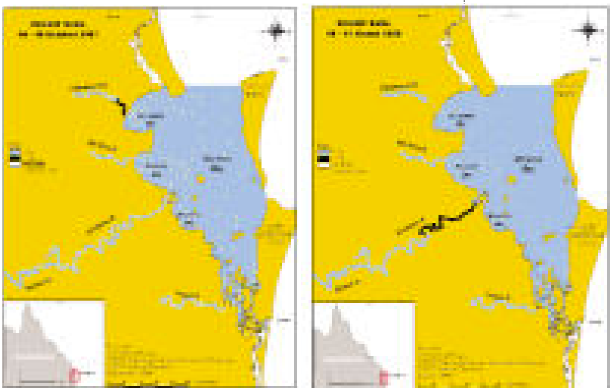
Nitrogen limitation: water column nutrient ratios and turnover times

The ratio of dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorus (DIP) is an aspect of nutrient concentrations that can provide insights into the relative limiting nutrient and processes that affect nutrient concentrations. The average DIN:DIP found throughout the world's oceans has been originally estimated as 15:1 by Redfield (1958 American Scientist, 46) is now conventionally taken as 16:1 for dissolved nutrient concentrations as well as for phytoplankton. This N:P ratio of 16:1 (known as the Redfield ratio, see beginning of this chapter) can be used to infer the relative importance of the N vs P as a limiting nutrient for growth of plants (particularly phytoplankton). Values of DIN:DIP below 16: 1 are indicative of N limitation. Values of above 16:1 indicate P limitation. DIN:DIP values of less than 16:1 occur all throughout Moreton Bay, indicating that the Bay is nitrogen limited. One-off values of greater than 16:1 were observed both at the Caboolture and Brisbane River lower estuaries and the vicinity of their mouths. However, these areas are very turbid and support little phytoplankton growth such that DIN:DIP ratios may not imply nutrient limitation at all. Bio assays indicated that phytoplankton within the river was consistantly stimulated by increased light availability (refer to next section), and hence are light-limited.

Nitrogen limitation was also indicated from estimates of biological nutrient cycling in Moreton Bay. Phytoplankton nitrogen uptake rates were estimated to be 144,300t and phosphorus uptake rates were 15,015t, resulting in an N:P uptake ratio of 9.6:1. This ratio of nutrient uptake, which is once again less than the Redfield ratio of 16:1, indicates nitrogen limitation of the phytoplankton community in Moreton Bay.

Biological nutrient uptake (tonnes yr^{-1}) in Moreton Bay

	Nitrogen Mean	Phosphorus Mean
Mangroves	2,300	200
Seagrass	1,500	200
Macroalgae	1,200	160
Benthic microalgae	15,000	2,100
Phytoplankton (Redfield)	53,000	7,300
Total	73,000	9,960



DIN:DIP ratios in Moreton Bay and the river estuaries in October 1997 and March 1998. Ratios were below 16:1 across the bay and in most estuaries and were similar at both sampling times indicating consistent nitrogen limitation of phytoplankton.

Nitrogen limitation: phytoplankton nutrient uptake rates and bioassay responses

Increases in phytoplankton biomass, measured as chlorophyll *a* fluorescence during bioassays, reflect the combined effects of parameters such as light intensity and nutrient availability on phytoplankton communities. Trends displayed in the monthly phytoplankton bioassays, from October 1997 to July 1998, highlighted quicker responses to nutrient additions for samples from the Brisbane River and Bramble Bay relative to other sites. Elevated responses in phyoplankton biomass, especially to nitrogen were observed for the majority of the year at both sites.

The responses of phytoplankton bioassays in Moreton Bay and its estuaries can be separated into three major categories:

Primary nitrogen limitation (e.g. Bramble Bay)

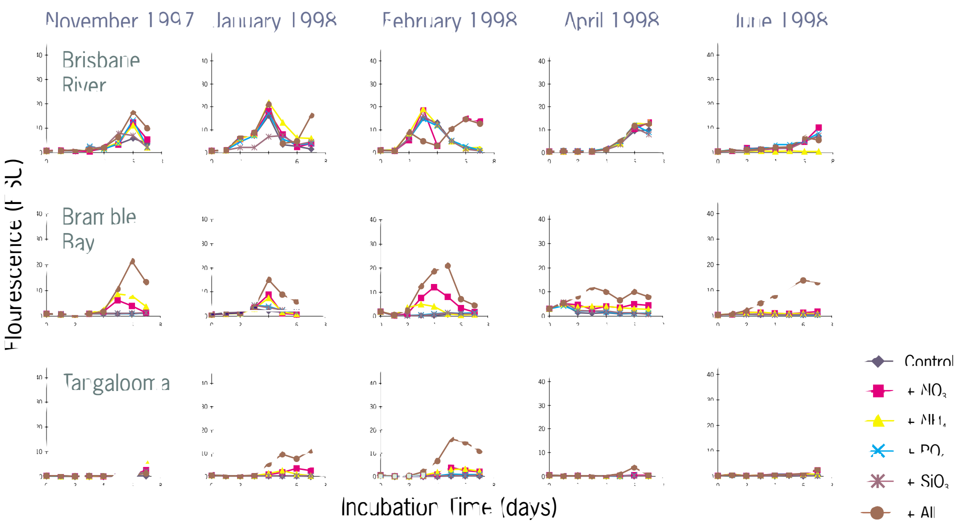
Nitrogen in the form of either nitrate (NO_3^-) or ammonium (NH_4^+) generally stimulated phytoplankton growth but growth response was not observed with either phosphorus (as PO_4^{-3}) and silica (SiO_2) additions.

Light limitation (e.g. Bremer River)

In turbid environments, phytoplankton growth was limited by light availability. Increased biomass in the control treatments was observed when the suspended sediments were allowed to settle and light became sufficient in the shallow bioassay containers.

Co-limitation (e.g. Tangalooma)

In some environments, the availability of more than one nutrient may limit the growth of phytoplankton. An increase in biomass occurred only where a combination of nutrients have been added (+ All).



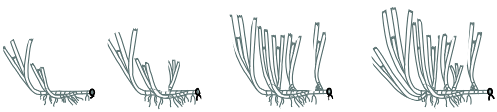
Examples of light limitation (Bremer River), primary nitrogen limitation (Bramble Bay) and nutrient co-limitation (Tangalooma) of phytoplankton biomass from phytoplankton bioassay experiments. (FSU = Flourescence Standard Units)

Nitrogen limitation: macroalgal and seagrass responses

Macroalgae tissue nitrogen (N) and seagrass growth responses to nutrients (either ambient or added), have allowed us to infer that the estuarine and marine portions of the Moreton Bay waterways are primarily nitrogen (N) limited.

The relative importance of N and phosphorus (P) in controlling marine plant growth was tested in eastern Moreton Bay seagrasses (refer to page 111). None of the P fertilisation stimulated growth, but N or N+P additions often stimulated growth. The conclusions from these experiments were that N and not P was the major limiting nutrient for seagrasses in Moreton Bay.

Time-course analyses of water column nutrients and macroalgal tissue nitrogen showed more significant correlations with nitrogen than with phosphorus. Close tracking of dissolved inorganic nitrogen (DIN) with %N in the macroalgal tissue deployed in the Logan River and other southern Moreton Bay sites was in sharp contrast to the overall lack of correspondence of dissolved inorganic phosphorus (DIP) and macroalgal %P. This correspondence of DIN with %N and the lack of correspondence of DIP with %P indicates that N is the primary limiting nutrient for macroalgae in Moreton Bay and estuaries. Water column N:P ratios were less than 16:1

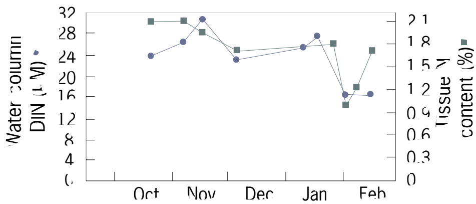


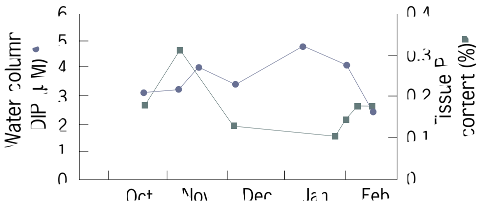
Growth responses of the seagrass *Halodule uninervis* with additions of N and/or P in Moreton Bay. Greatest responses in growth were following N and N+P additions (Udy,J. and Dennison, W., 1997. Journal of Exp. Mar. Biol. and Ecol.:217)

N:P ratios of water column and macroalgae, indicating nitrogen limitation in the Logan River and Moreton Bay (Horrocks, J., 1995 Mar. Freshwater Res.:46)

Distance from Logan River mouth (km)	N:P ratios	
	Water Column	Macroalgae
+15 (upstream)	5.7	20.0
0	6.2	22.7
-8	2.9	18.8
-11	2.1	20.0
-24	2.3	21.0

(indicating N limiting conditions for phytoplankton) and the N:P ratios of macroalgae deployed in the Logan River and Moreton Bay were all below 30:1 (Redfield ratio of macroalgae and seagrass).





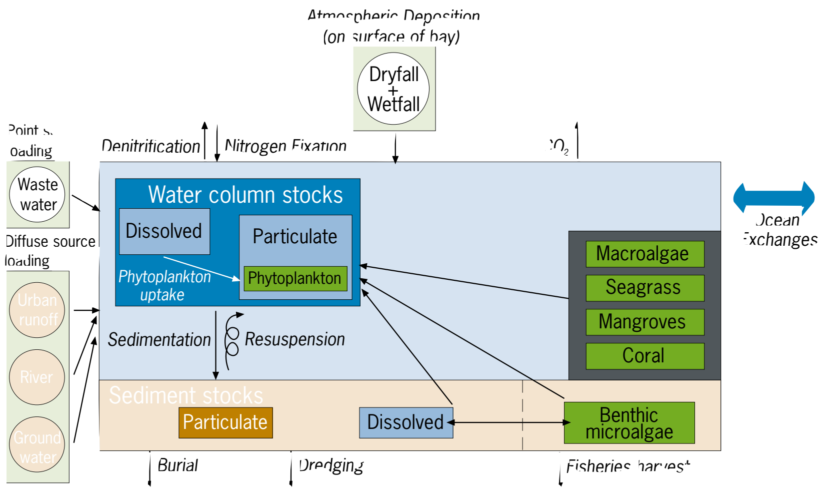
Correlations of DIN and DIP with tissue nutrient content (%N or %P) in the red algae *Gracilaria spp.* incubated at the Logan River. The correspondence of DIN with %N and lack of correspondence of DIP and %P indicates N is the primary limiting nutrient of growth for macroalgae (Horrocks, J. et al., 1995, Mar. Freshwater Res:46).

System-wide nutrient budgets constructed

A mass-balance nutrient budget defines all the input, output and storage of nutrients in a specified region. A nutrient budget was constructed for Moreton Bay to provide a quantitative inventory of the nutrient inputs, exports, standing stocks, and the cycling between major compartments in the study area and also to provide a check on the outcomes of the numerical Receiving Water Quality Model. Nutrient budgets for shallow coastal ecosystems provide insights into the controls on biogeochemical and ecological processes and are helpful in predicting the effects of future changes in these systems. Nutrient budgets have also been used to compare Moreton Bay with other systems that have been evaluated in a similar way and place the findings in a regional and global context (discussed in Chapter 16).

The conceptual model of the Moreton Bay nutrient budget assumes a steady state, hence the sum of inputs, outputs and storage of each of the nutrients (C,N,P) within the system should equal zero. The model indicates four major inputs of these nutrients: point sources, diffuse/catchment run-off, groundwater sources and atmospheric deposition. Primary production is considered as input for carbon and nitrogen fixation is considered as an additional source of nitrogen. Outputs for the nutrients include burial in sediments, fisheries harvest, exchange through Pumicestone Passage, dredging and ocean exchange. A nitrogen loss through denitrification and a carbon loss through CO_2 exchange are also considered as outputs. Standing stocks include dissolved and particulate nutrients in the water column, solid phase sediment nutrients, porewater nutrients, floral biomass (mangroves, seagrass, macroalgae, benthic microalgae and phytoplankton). Four nutrient cycling pathways are considered: biological uptake by the different flora, sediment/water fluxes, phytoplankton sedimentation, and sediment resuspension.

Quantification of all inputs, outputs and storages of material was done by Stage 2 tasks (e.g. point source load task, Catchment run-off load tasks, etc.).



Conceptual model of the Moreton Bay nutrient budget showing nutrient sources, storages, recycling pathways and losses (modified from Boynton, W.R., 1995 et al., Estuaries, 18).

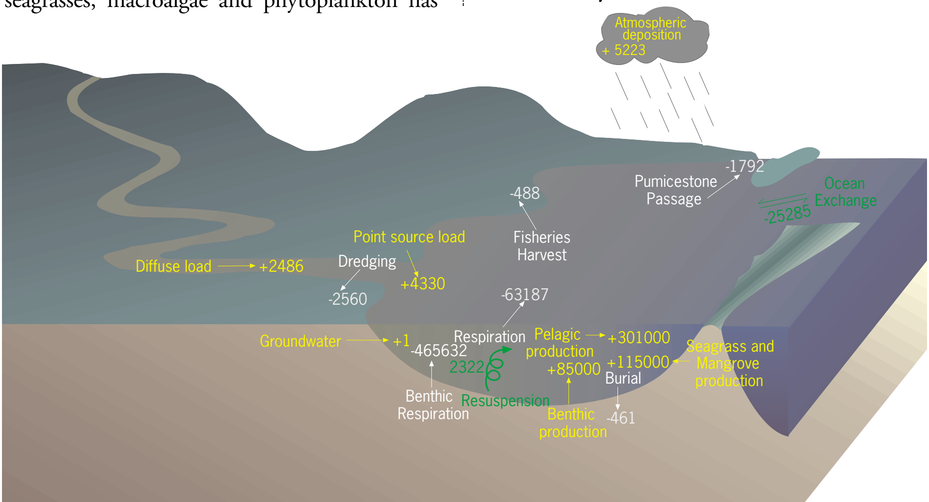
Carbon budget dominated by metabolism of marine biota

Primary production (carbon fixation) in Moreton Bay

Flora	Primary Production (tonnes C year^{-1})
Mangrove	59,000
Seagrasses	36,000
Macroalgae	20,000
Benthic microalgae	85,000
Phytoplankton	301,000
TOTAL	501,000

Moreton Bay receives an average of about 513,000 tonnes of carbon (C) per year, predominantly from primary production or C fixation (501,000 t), and a substantially lesser contribution from point sources, non-point loads, groundwater sources and atmospheric deposition. There are five major floral groups in Moreton Bay considered in the calculation of C fixation. Primary production by mangroves, seagrasses, macroalgae and phytoplankton has been measured both spatially and temporally. Benthic productivity from microalgae was quantified using the total biomass of benthic microalgae in Moreton Bay (300 t) and benthic productivity rates from Port Phillip Bay, resulting in a microalgae productivity estimate of 85,000 t. The relative contribution of the five major floral groups in Moreton Bay to primary production are summarised in the table.

C outputs were estimated as 534,000 t, giving a net deficit of about 21,000 t (534,000 t - 513,000 t). An additional export term of 25,000 t of C to the ocean is estimated, assuming that C is flushed to the ocean in proportion to phosphorus based on average TC:TP ratio in the Bay (21C:1P). The total 46,000 t C in deficit (21,000 t plus 25,000 t; 9% of C) may be attributed to the uncertainty in the primary production estimates, particularly benthic productivity. Further work is clearly required to better estimate primary production, particularly benthic production in Moreton Bay.



Annual carbon budget for Moreton Bay (tonnes year^{-1}). Phytoplankton and benthic microalgae constitute significant contributions to the carbon budget of the bay.

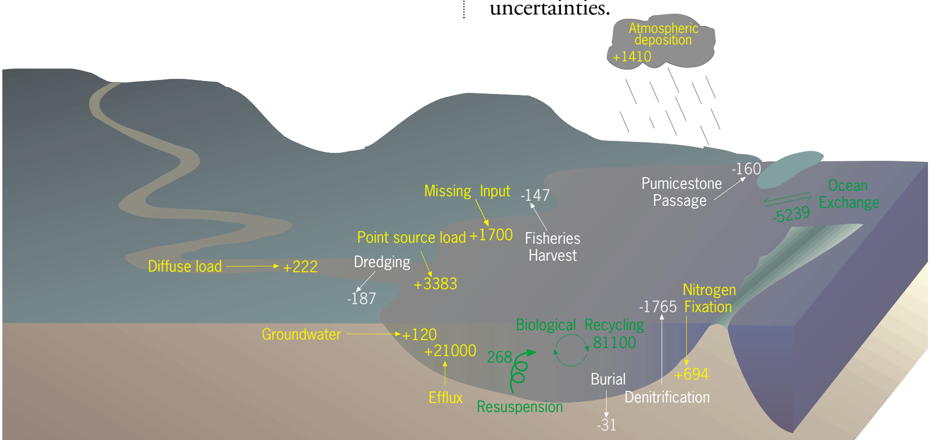
Large uncertainties in nitrogen budget

A lot of uncertainties often accompany the construction of nutrient budgets. As such, error estimates are critical to nutrient budget calculations, particularly when dealing with surpluses and deficits, as these terms also contain the sum of all the errors of the measured fluxes. Two types of errors are considered: measurement error and uncertainty. A measurement error is assigned to each of the input and output terms and the total error is included in the ocean exchange (difference) term.

The biggest uncertainties in the nitrogen (N) budget lie in estimates of atmospheric deposition loads (input term) and denitrification loss (output term) of N. The modeled nitrogen estimates from atmospheric deposition (69 t) are quite low compared to loads estimated using world literature concentrations for rainfall, measured average rainfall for the Brisbane airport and surface area of Moreton Bay (1,118 t). The latter estimate was used as this was closer to atmospheric deposition loadings calculated using rainfall concentration data for coastal northern NSW (1,410 t).

Another uncertainty is the estimation for denitrification loss. Two different approaches for estimating denitrification rates for the study area have been used (refer to Chapter 8): potential, based on sediment/water fluxes and sediment stoichiometry (14,819 t yr^{-1}) and predicted, based on acetylene block (12,447 t yr^{-1}). These values were seasonally adjusted based on denitrification rate versus temperature developed for Galveston Bay (similar temperature ranges and similar latitude as Moreton Bay) and the denitrification loss was estimated to be 6,712 t yr^{-1} for Moreton Bay.

Moreton Bay receives an average of about 5,829 t of N per year. Output of N by ocean exchange is estimated to be 5,239 t. This data implies that there is little loss of N (difference between input and output is small). The denitrification loss estimate above (6,712 t yr^{-1}) is much greater than this difference. Reasons for this discrepancy may include additional unaccounted sources/inputs such as N fixation input and N trapping from cyanobacteria and benthic microalgae, respectively (hence an overestimation of denitrification loss). Clearly, further work is needed to resolve some of these uncertainties.



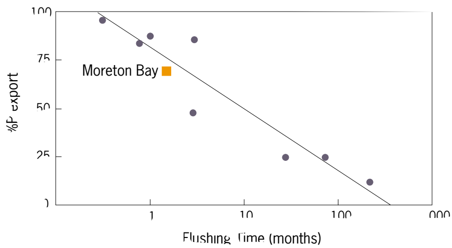
Annual N budget for Moreton Bay (in tonnes per year). Uncertainties accompany the construction of this budget.

Phosphorus budget corresponds to flushing time

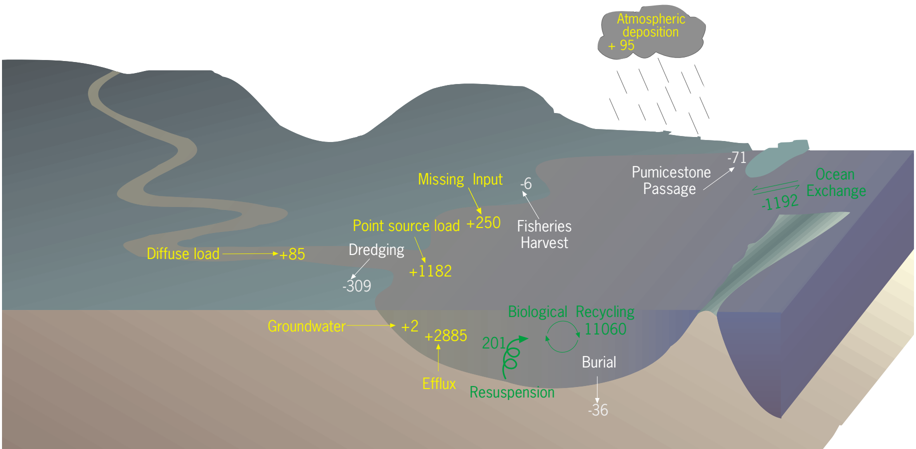
Budgeting of phosphorus (P) is more straight forward than that of nitrogen (N) and carbon (C) because it has no gaseous pathways. As such, P provides a useful check on the overall conceptual framework of the Moreton Bay budget. P input is dominated by point sources. Some uncertainties in the estimates of atmospheric deposition of P are recognised. P outputs are dominated by ocean exchange. Most of the remaining P is removed through dredging, with a small amount also buried and exported through Pumicestone Passage. Fisheries harvest only accounts for a small amount of phosphorus loss. Moreton Bay receives an average of about 1364 t of P per year. Using this annual loading and a flushing time of 46 days suggests that 1,192 t of P are flushed to the ocean each year.

A linear relationship between the fractional net transport of N and P from the land to the coastal ocean and the log mean residence time has been established for a number of shallow coastal ecosystems from around the world. (Nixon, S.W. et al., 1996, Biogeochemistry 35).

Based on mass balance calculations of both inputs and outputs, it estimated that 70% of the total P load is exported out into the ocean. Using Nixon's graph, this equates to about 46 days residence time for Moreton Bay. Hence, P budget corresponds to flushing time of the bay. This imparts a degree of confidence in the loading and ocean export terms of P in Moreton Bay nutrient budget.



Percentage of the total input of P from the land that is exported as a function of flushing time for Moreton Bay and a number of shallow ecosystems around the world. The P budget corresponds to the flushing time of the bay as mass balance calculations predict that 70% of total P is exported (Nixon, S.W. et al., 1996, Biogeochemistry 35).



Annual P budget for Moreton Bay (in tonnes per year). P input is dominated by point sources and outputs by ocean exchange.

CHAPTER 11

Tracing Sewage

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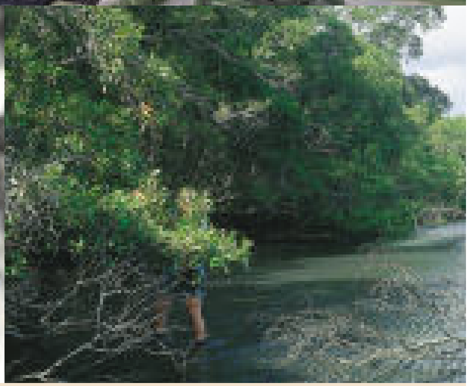

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- Sewage nitrogen traced using stable isotopes
- Elevated plant and sediment $\delta^{15}N$ values near sewage discharges
- Localised influence of sewage nitrogen in Bramble and Waterloo Bays
- Biomarkers used to determine sources of organic matter
- Most organic matter derived from microalgae and higher plants
- Hydrodynamic model and dye predict sewage plume in Bramble Bay
- Salinity measurements trace sewage plume in Bramble Bay

Sewage nitrogen traced using stable isotopes

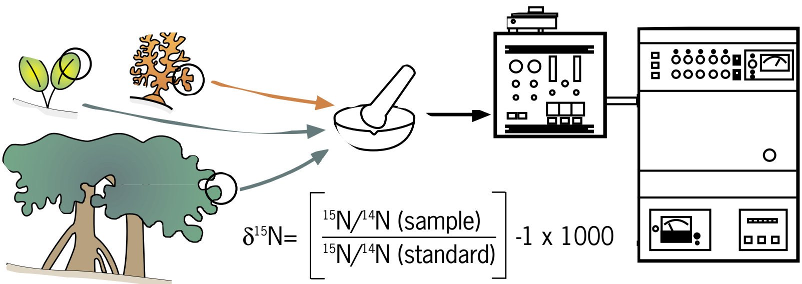
Sewage effluent discharged into coastal and estuarine waters has been implicated in eutrophication occurrences worldwide. Detection of the source and extent of sewage in receiving waters is imperative for designing and implementing monitoring strategies. There are various innovative techniques that have been used to detect the distribution of sewage and these will be discussed throughout this chapter. Of these, the use of nitrogen (N) stable isotopes enables detection and delineation of sewage-derived N from other N sources entering coastal ecosystems and its potential influence on the community.

Atmospheric N exists in two stable isotopic forms, ^{14}N and ^{15}N. The most abundant form is ^{14}N (~99.6%), with ^{15}N comprising a much smaller fraction (~0.4%). The relative proportion of ^{15}N to ^{14}N compared to a world-wide standard is referred to as $\delta^{15}N$ and is measured in parts per thousand (‰).

Sewage is generally enriched in ^{15}N compared to ^{14}N and, therefore, the $\delta^{15}N$ signatures of effluent are elevated (approximately 10‰). This results in an elevated $\delta^{15}N$ signature in receiving waters of sewage treatment plants. Marine plants incorporate and reflect the signature of this source.

A gradient of $\delta^{15}N$ signatures was found in marine plants in response to sewage nutrient inputs, thus enables $\delta^{15}N$ to be applied as a technique for mapping the intensity and distribution of sewage-derived N. $\delta^{15}N$ signatures of marine plants provide information on the biological influence that sewage has in receiving waters and indicates the long term availability of sewage N. Plant biological indicators act as sentinels enabling early detection of sewage N in the environment. These biological indicators can therefore detect whether a community is under threat prior to an observed decline in ecological health and enables the early initiation of management practices. This provides an alternative to a procedure which identifies impacts once they have occurred. For environments already degraded, identification of the influence of sewage N may direct management practices.

The sampling technique is not restricted to vegetated regions but can also be applied to unvegetated regions. For vegetated areas, the method involves collection of macrophytes (seagrass, macroalage, and mangrove leaves), while for unvegetated areas, macroalgae is deployed. Sample material was dried and ground, then analysed by a mass-spectrometer for the $\delta^{15}N$ value. The results of such a sampling protocol is the production of spatially integrated maps providing information on the source, extent and fate of sewage-derived N.



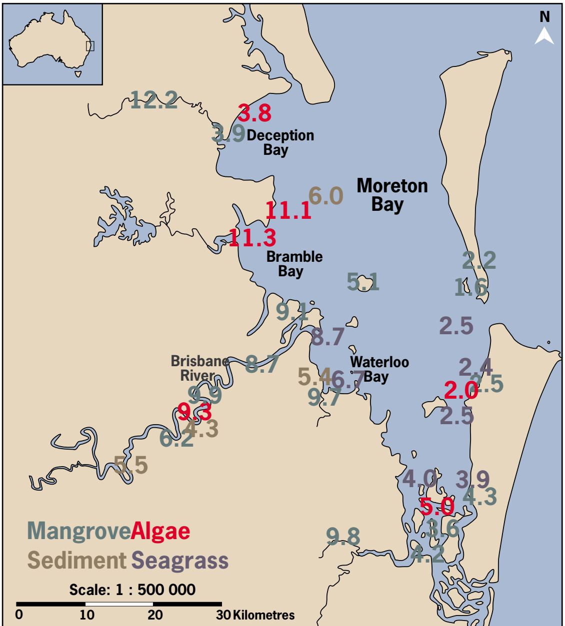
$$\delta^{15}N = \left[\frac{^{15}N/^{14}N\ (sample)}{^{15}N/^{14}N\ (standard)} \right] -1 \times 1000$$

Methodology for determining vegetation isotopic signatures. The sample was collected, dried, ground and then analysed on a mass spectrometer.

Elevated plant and sediment δ15N values near sewage discharges

Passive vs Active Bioindicators

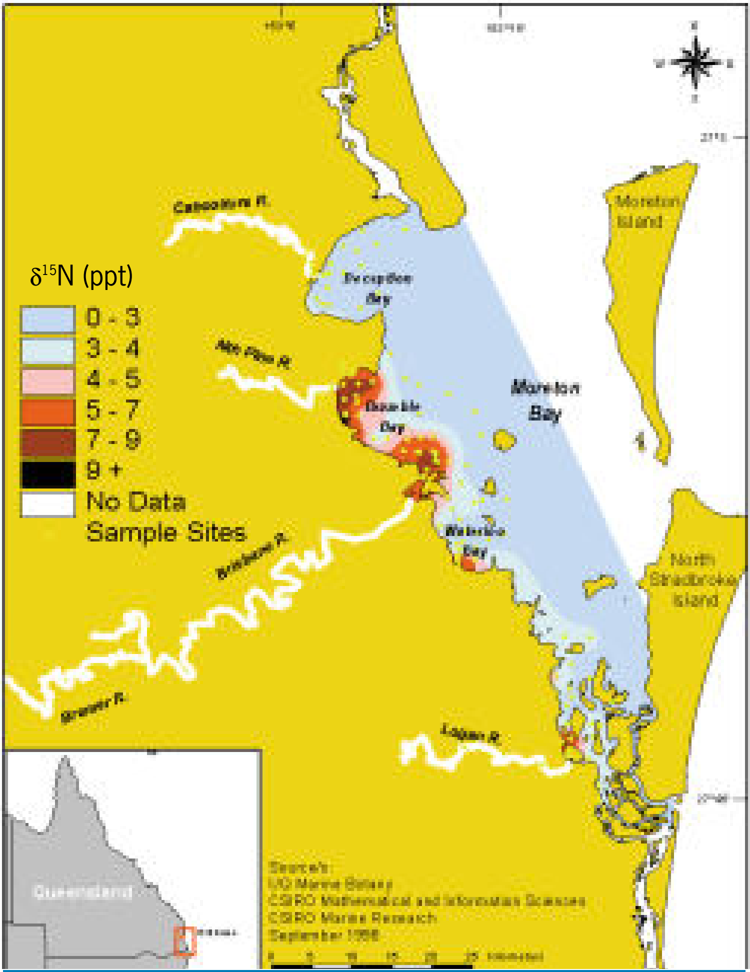
The collection of macrobiota (including algae, mangroves and seagrasses) allows detection of the δ15N signature from plants which over time have integrated the signature of their environment. These are passive indicators as they incorporate the signature in their natural environment throughout their growth cycle. However, there are many sites in which these biological indicators are not available for collection such as in the open water and in degraded areas. Here, biological plant indicators may be actively deployed to incorporate the signature over smaller time periods (days). These are therefore active indicators which provide a view of the δ15N of the environment at the time in which the indicator was deployed. The results of active sampling varies at different sampling times and therefore provides insight into temporal variation (such as seasonal) of the extent of sewage nitrogen.



Ambient δ15N signatures of sediments and marine plants in Moreton Bay. High δ15N signatures were found near sewage discharges, while at sites distant to sources, signatures were low.

Nitrogen (N) discharge from sewage treatment plants was identified from analysis of ambient algae, seagrass, mangrove and sediment samples. The elevated signature detected in the sediment identified that sewage N was available in the environment. The presence of the elevated signatures in the plant bioindicators distinguished that the N was incorporated into the vegetation. This identified the extent to which plant communities are influenced by the discharge of sewage. δ15N signatures of marine plants were highest when grown in the vicinity of sewage outfalls within the rivers and the estuarine portions of the Moreton Bay. At sites adjacent to sewage treatment plants (STPs) in the rivers, the δ15N signatures of mangrove leaves were greater than 9 (and reached 12.2 in the Caboolture River and 9.8 in the Logan River where STPs discharge upstream). In the Bay, at sites adjacent to STPs, mangrove leaf values were 9.1 at the Brisbane River mouth and 11.3 (for macroalgae) at the Pine River mouth, while in the eastern Bay, the mangrove leaf δ15N signature was as low as 1.6. These values demonstrate the strong influence of sewage in the rivers and western Bay near to sewage discharges. High tidal flushing, particularly through North and South Passages results in low values in the eastern Bay. As this strong gradient is consistent in all plant groups this technique is reliable as a biological indicator of sewage N.

Localised influence of sewage nitrogen

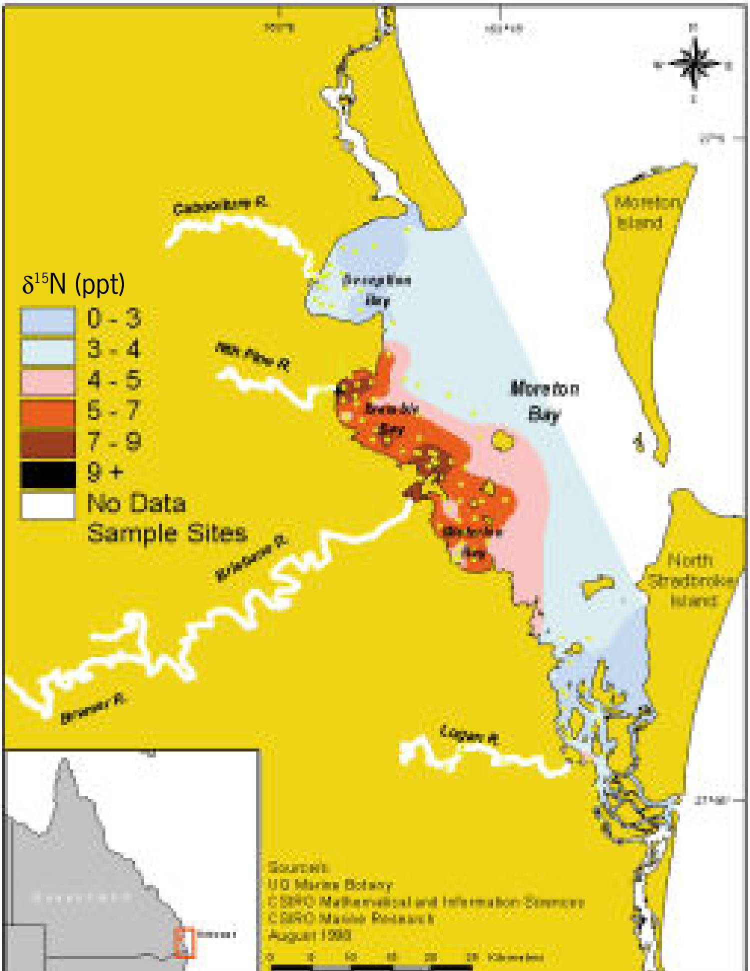


Sewage plume map as indicated by $\delta^{15}N$ signatures of macroalgae deployed for 4 days in September, 1997. Distinct sewage plumes (high $\delta^{15}N$ values) were detected radiating from the Brisbane River mouth and Pine Rivers into Bramble Bay.

Macroalgae (*Catenella nipae*) was collected from a low nutrient environment in the eastern Bay. This was then deployed in perforated chambers at half secchi depth at more than 100 sites around the Bay. This active bioindicator identified distinct sewage plumes originating from the Brisbane and Pine Rivers in September. These result in plumes of sewage nitrogen extending into Bramble and Waterloo Bays.

Seasonal variations in the geographical extent of the sewage plumes were identified using active markers at different times of the year. During

in Bramble and Waterloo Bays



Sewage plume map as indicated by $\delta^{15}N$ signatures of macroalgae deployed for 4 days in March 1998. Distinctive sewage plumes (high $\delta^{15}N$ values) originating from the Brisbane and Pine Rivers were less evident and the plume also extended into Waterloo Bay.

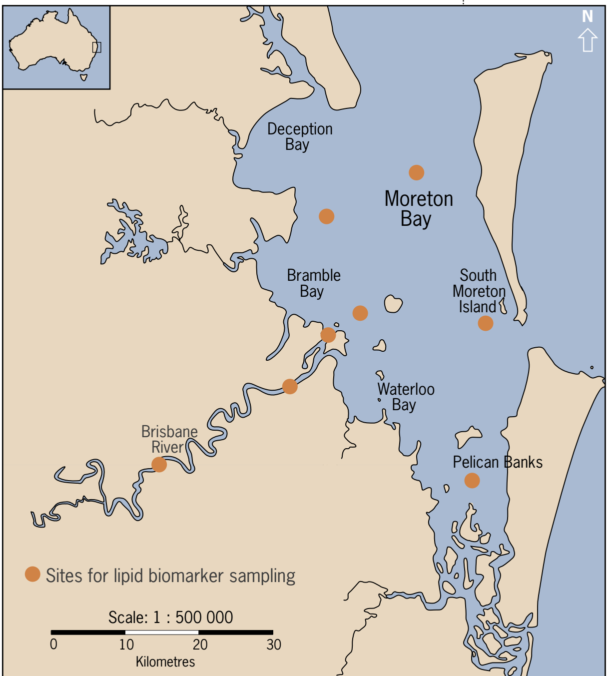
September, the plumes were predominantly confined to the southern and northern ends of Bramble Bay. In February, the plume extended further into the central portions of Bramble Bay and was also evident in Waterloo Bay. This variation could be attributed to various causes Increased water temperature with increased light intensity and duration in February, could increase algal productivity and affect $\delta^{15}N$. Also, the Moreton Bay hydrodynamic model predicts a south-westerly water current in February that may be driving water containing sewage, south from Bramble Bay into Waterloo Bay.

Biomarkers used to determine sources of organic matter

Lipids are present in all living organisms and occur in many biochemical forms which break down to free fatty acids in the sediments. Groups of organisms have characteristic fatty acids which occur in a greater predominance than in other groups. This allows identification of the sources of organic material based on the fatty acid composition within the sediment.

Sterols are a group of compounds (including cholesterol) which are present in all organisms with the exception of prokaryotes (the bacteria). Like lipids, the specific composition of sterols is characteristic for groups of organisms. This provides an additional tool for the identification of organic matter derivation which can be used in combination with fatty acid determination.

From these it is possible to trace whether organics are obtained from sewage or from other non-anthropogenic sources. The data also provides information on the direct inputs of organic matter to systems and indicates inputs from internally stimulated productivity. This data indicated that the organic matter in the sediments 1) had mixed and variable sources; 2) was dominated by micro- and macroalgae; 3) had minor amounts of seagrass and terrestrial material; 4) was reworked by bacteria and 5) was low in sewage biomarkers.



Site map indicating locations of sediment extraction for analysis of lipid biomarkers

CHRIS ROELFSEMA

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Organic matter sources were dominated by micro- and macroalgae

Most organic matter derived from microalgae and higher plants

Sewage discharge has little direct contribution to the organic matter content in the sediments throughout Moreton Bay and estuaries. Within the estuaries and in the sewage impacted western Bay sites, the fatty acids were predominantly of bacterial and higher plant origin while sterols at these sites indicated that the organics were derived from algae and higher plants. The combination of these findings suggest that algal (micro- and macroalgae) and bacterial productivity is stimulated by high nutrient concentrations. In the sediment of Pelican Banks, the seagrass sand of Moreton Banks and the marine sand of central north Moreton Bay, organic material is predominantly of diatomaceous (microalgae) origin.

Limited input from the estuarine-derived bacterial, higher plant and algal organic material, reaches the sediment of the eastern reaches of Moreton Bay. Also, the nutrients which stimulate the communities responsible for production of the organic matter in the rivers, appears to have little influence on stimulating the production of organic matter of these communities in the eastern Bay waters. Instead, this site is dominated by oceanic processes of productivity. In the mixed sediment of the central north Bay, analysis of the fatty acids and sterols indicated that the organics in the sediment were derived from a combination of the processes acting in the rivers and in the eastern Bay, with bacterial, diatom and higher plant depositions.

Fatty acid and sterol content and source for sediments in Moreton Bay and Brisbane River

Sediment type	Site	Fatty Acid content (µg g^{-1})	Source of fatty acids	Sterols (µg g^{-1})	Source of sterols
River muds	Brisbane River upstream	45	Bacterial & higher plant	13	Algal & higher plant
	Brisbane River mouth	65	Bacterial & higher plant	13	Diatom & higher plant
Sewage impacted	South Bramble Bay	21	Bacterial	0.5	Algal & higher plant
	Waterloo Bay mangroves	170	Bacterial	37	Algal & higher plant
Mixed sediment	Central north Bay	150	Bacterial	17	Diatom, dinoflagellate & higher plant
	Pelican Banks	130	Diatom	10	Diatom & dinoflagellate
Marine/seagrass sand	Moreton Banks	245	Diatom	4	Diatom dominated
Marine sand	Central north Bay	65	Diatom	1	Diatom

Hydrodynamic model and dye predict

In February, 1973 a dye marker was used to monitor the potential path of sewage released from the Luggage Point sewage treatment plant at the mouth of the Brisbane River. The dye was a neutral buoyancy vegetable dye called Rhodamine WT, detectable by its fluorescence properties. The dye persists in the environment for periods long enough to be measured but decays at a rate of about 5% per day.

In total, 316 kg of dye were discharged just upstream from Luggage Point. This release occurred over a period of four days. The concentrations of dye were monitored in and around the point of release every day of the dye release period, and three days after it had ceased. Standard fluorometry equipment was used to detect its presence and concentration. This was sampled at a range of locations.

The information obtained from the dye tracer experiment was presented as hand drawn contours, which have recently been digitised. The contour maps indicate that the plume from Luggage Point extended out from the river mouth and in response to the south-easterly winds and resulting water currents, the plume dispersed throughout Bramble Bay. Another of the contours extended around Fisherman Islands and into the northern end of Waterloo Bay within 72 hours of discharge from the mouth of the river.

Data obtained from the dye tracking experiment was recently used for input into the hydrodynamic model. The advantage of integrating the information into a modelling package is that it can be applied over a greater spatial and temporal range than the dye will allow, as dilution and degradation limits the monitoring time and the distance of tracking. In addition, once the calibration parameters are set within the model, based on actual versus predicted patterns, the model can provide dispersion characteristics over a range of environmental conditions.

The dye distribution model results corroborate the other sewage tracking results. The relatively localised impact of sewage discharges into Moreton Bay identified with the dye tracer

Luggage Point sewage treatment plant. Dye was released from the sewage plant in 1973 as an indicator of the path of sewage

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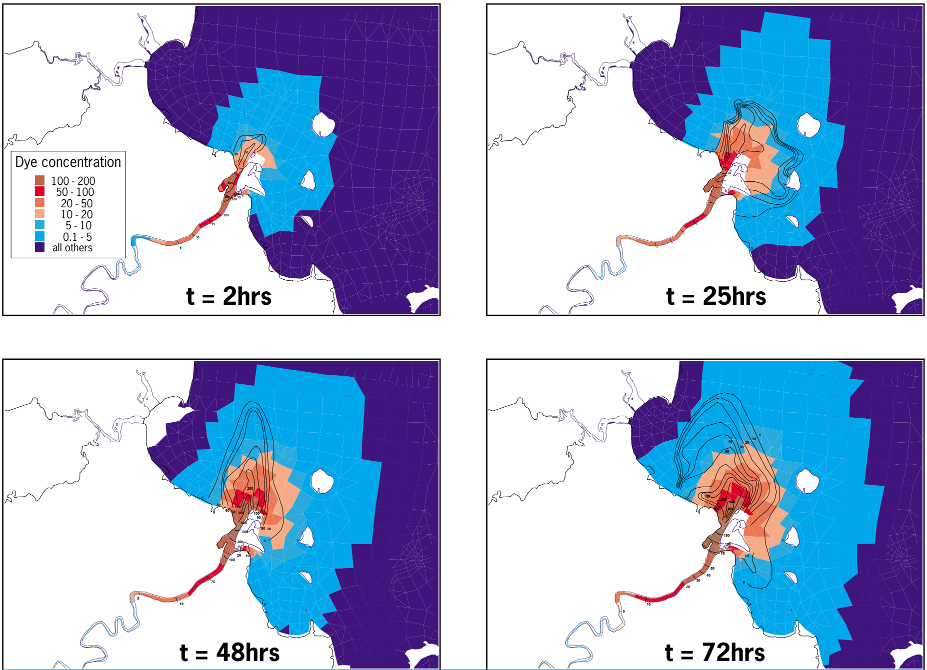
sewage plume in Bramble Bay



Model predictions and dye flow contours over a 72-hr time course for Luggage Point sewage flows. Model predictions allow the application of data to a greater spatial and temporal range.

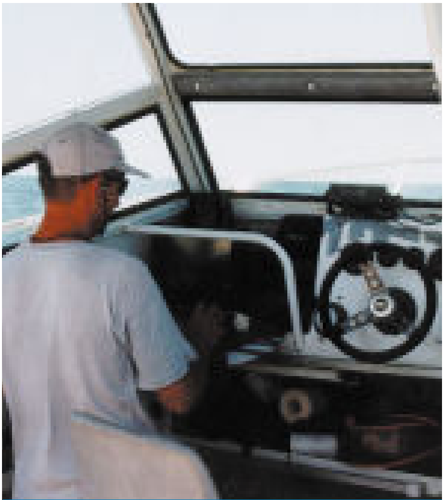
study were also observed with the stable isotope studies.

The dissipation of the Brisbane River sewage plume before reaching Hays Inlet/Pine Rivers is supported by the separate and distinct sewage plumes originating from Brisbane River versus Hays Inlet and Pine Rivers delineated in the stable isotope studies. In addition, the dispersal of dye into Waterloo Bay as well as Bramble Bay in 1973, was observed in the March 1998 sewage plume maps. At other times of the year the dispersal of plumes from the Brisbane River are restricted to Bramble Bay, as indicated by the stable isotope studies.

Bramble Bay is impacted the greatest by the Brisbane River discharge

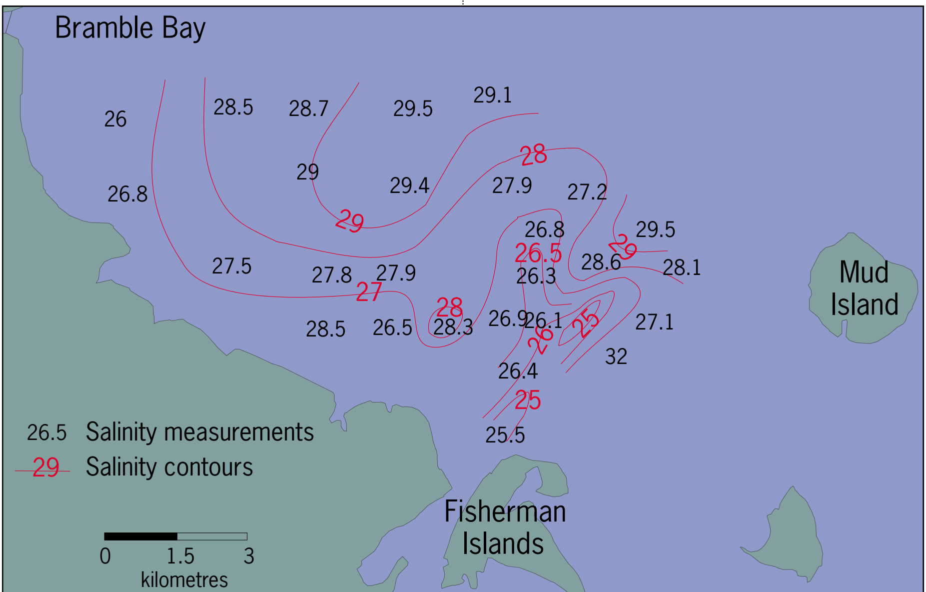
Salinity measurements trace sewage plume in Bramble Bay

The estuary is the zone in which riverine and oceanic waters combine, resulting in a gradient of salinity. Measurement of salinity changes and contours is a method of determining the dispersive patterns of riverine discharge into Moreton Bay and hence the associated sewage. An intensive survey of the salinity within and around the Brisbane River mouth was carried out in November, 1997. Salinity was determined using standard conductivity probes. At the time of sampling, at the bottom of the ebbing tide, winds were north moving to north-east. Despite this wind direction, the results demonstrate limited southerly dispersion of riverine discharge from the mouth of the Brisbane River. Instead, the plume was distributed northwards. Dispersal occurs predominantly into Bramble Bay with most of the Bay influenced by the freshwater discharge.



Field measurements of salinity

SINCLAIR KNIGHT MERZ



Salinity contours indicating a northward flowing plume from the Brisbane River mouth

Next section ▶

CHAPTER 12

Human Health Implications

PETER OLIVER

PETER OLIVER

PETER OLIVER

- Several human health issues

Turbidity

- High turbidity in foreshore areas exceeds limits for swimming

Toxicants

- Broad scale survey of toxicants
- Different toxicant guidelines exist
- Water sampling techniques devised
- Strong gradients in sediment toxicants: guidelines exceeded in Brisbane River
- Gradients in metal content of biota
- Persistent toxicants in biota, especially from Brisbane River

Lyngbya

- *Lyngbya* bloom in Deception Bay
- *Lyngbya* impacts both human and ecological health
- Nitrogen fixation in *Lyngbya* stimulated by iron and phosphorus
- Hypothesised link between *Lyngbya* and hydric soils

Faecal Coliforms

- Faecal coliforms high in Brisbane River
- Faecal coliforms can be flushed into the Bay after rain events

Bacteria

- High bacterial productivity in the Bremer River

Several human health issues

Turbidity
Toxicants
Lyngbya
Faecal coliforms
Bacteria

Health risks associated with water-based recreation have been identified to be a concern. Many people want to be able to swim and fish in certain parts of the river. These community-derived ecological values relate to issues such as toxicants, bacteria and faecal coliforms and also toxic algal blooms. Although much of the work undertaken during the study was aimed more at addressing environmental/ecological issues and not human health issues, results from several of the tasks had implications for human health in the region.

Water quality guidelines, such as those by ANZECC (Australian and New Zealand Environment and Conservation Council) and ANZFA (Australia and New Zealand Food Standard Authority), set out standards for specific contaminant concentrations in the seafood water column and sediment (e.g. turbidity, bacteria and faecal coliforms). These guidelines provide the limits for contaminants with respect to both the protection of aquatic ecosystems and for the health of humans in terms of consumption of biota and recreational use.

Toxicants are substances which cause deleterious effects to humans and biota, even at relatively low concentrations. Many substances which are considered toxicants were historically or previously used as pesticides and some were even used initially to control risks to human health such as disease vectors of malaria. Although many are now banned they still persist in the environment, particularly in the sediment of our waterways.

Faecal coliforms are the recommended bacterial indicators for assessing human health risk. Concentrations of faecal coliform are often elevated in regions receiving undisinfected sewage effluent or animal wastes. Bacteria are naturally present in the environment and perform many important functions, such as breakdown of organic matter. However, levels of bacteria may be elevated by human impacts on the system and these populations may include harmful bacteria.

There have been anecdotal reports that blooms of the toxic cyanobacterium *Lyngbya majuscula* in northern Deception Bay have been increasing in severity and frequency since 1992. These blooms have resulted in several ecological, social, as well as health impacts in the region, particularly for the fishermen in the region who first reported the blooms to researchers.

High turbidity in southern Moreton Bay

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Lyngbya on a fisherman's net at north Deception Bay

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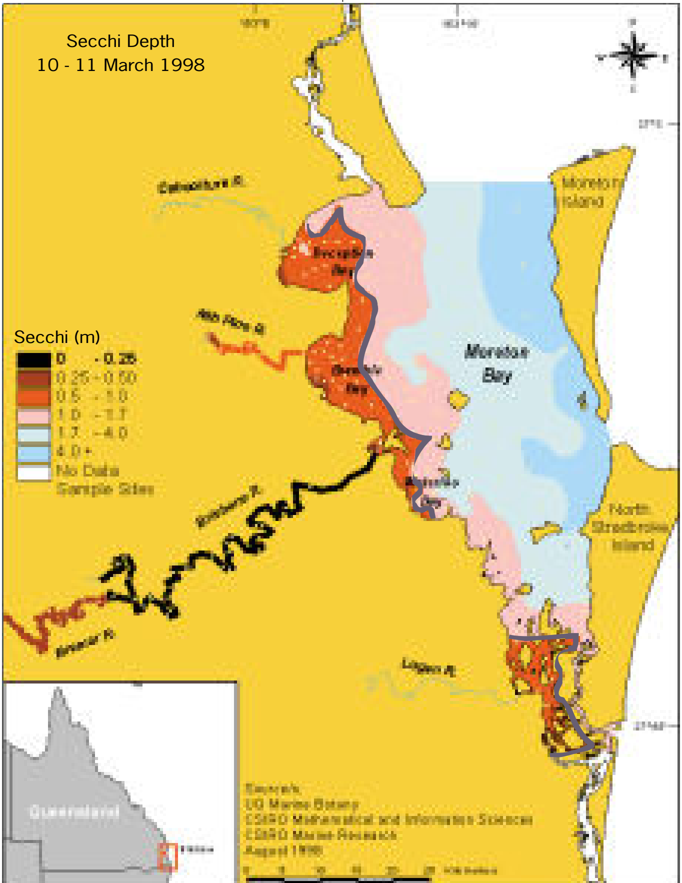
High turbidity in foreshore areas exceeds limits for swimming

One of the key elements in achieving the Healthy Waterways vision is safe swimming conditions in the river estuaries and Bay. Australian Water Quality Guidelines recommend a secchi depth of greater than 1.2 m for safe swimming conditions. From the secchi map generated in the March intensive water quality survey it is clear that the river estuaries and large areas of the western embayments are unsuitable for swimming as they exceed the turbidity limits for the region. This estimate of areas which are considered inappropriate for swimming by ANZECC guideline standards are conservative as they are based on a 1.0 m secchi depth contour. A 1.2 m secchi depth contour would result in the extension of the area considered unsafe for swimming further out into the Bay.



Map of secchi depth for March 1998 with blue line marking the 1.0 m secchi depth contour. ANZECC Guidelines recommend a secchi depth > 1.2 m, so areas to the west of the blue line represent a conservative estimate of regions unsafe to swim (to the west of the blue line).

Broad scale survey of toxicants

Substances that can harm living organisms are called toxicants. Many of these substances continue to be produced in our industrial society or have been generated unintentionally as byproducts. Some toxicants that end up in the natural environment are persistent, causing deleterious effects on biota or humans, even though they are present in low concentrations only. It is difficult to detect these compounds in water. However, because they persist in living tissue, they can accumulate in organisms to higher concentrations than in the surrounding environment. This process is termed bioaccumulation. By sampling organisms, detection of contaminants is more likely because of bioaccumulation.

The main objective of this work was to assess methods for biomonitoring which would allow the development of a monitoring strategy for toxicants. Sediment, water and biota samples from a number of sites were analysed for various organochlorine pesticides (OCs), polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins, polychlorinated dibenzofurans (PCDD/Fs) and also for heavy metals.

Sources and use of toxicants measured in the survey

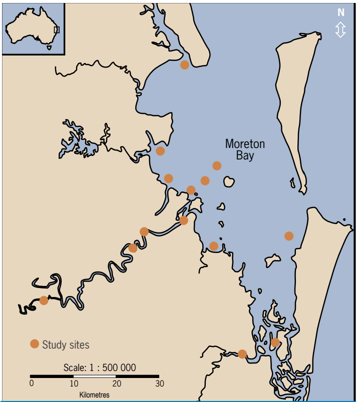
TOXICANT	SOURCES	USED FOR	PRODUCTION STATUS	QUANTIFICATION
Organochlorine pesticides (OC)				
Dieldrin	Agriculture, Industry, Buildings, Domestic	Control of: Fly Larvae, locusts, crickets, termites, grasshoppers, cockroaches, fleas, mosquitoes	Currently banned	GC/ECD (Gas Chromatography/ Electron Capture Detectors)
Heptachlor	Agriculture (sugar cane and banana plantations), Buildings	Control of: Ants, grubs, termites	Banned since 1995	GC/ECD (Gas Chromatography/ Electron Capture Detectors)
Hexachlor-benzene (HCB)	Agriculture, Contaminent in processes such as chlorine production, waste incineration and manufacture of chlorinated solvents	Pesticide and fungicide for ttreatment of seeds	Processes forming HCBs are numerous and ongoing	GC/ECD (Gas Chromatography/ Electron Capture Detectors)
DDT	Agriculture, Domestic	Control of: Crop and livestock pests, fles, lice mites, lawn grubs	Banned since 1987	GC/ECD (Gas Chromatography/ Electron Capture Detectors)
Polychlorinated biphenyls PCB				
Polychlorinated biphenyls (PCBs)	Technology, Industry, domestic, buildings	Insulators, hydrolic fluids, paints, plastics, adhesive, lubricants, sealants	Banned	GC - MS (Gas Chromatography Mass Spectrometry
Polycylic aromatic hydrocarbons (PAH)				
Benzo (a) pyrene	Incomplete combustion of organic material (e.g. untreated diesel exhaust gases, production of coke and aluminium, wood-fired stoves, boilers, forest fires	As creosote used as wood peservative in sawmills and timber impregnation plants	Processes forming PAHs are numerous and ongoing	ECD
Dioxins				
Polychlorinated dibenzodioxins and polychlorinated (PCDD/Fs)	Chemical reactions in industrial processes (e.g. pesticide & paper production), high temperature reactions (e.g.combustion engines, incinerators, iron and steel production)	Not produced intentionally. Formed as by-products when chlorinated compounds are manufactured or buried	Processes forming Dioxins are numerous and ongoing	HRGC (Gas chromatography) And HRMC (Mass Spectrometry)
Heavy Metals				
Lead, Copper, Cadmium, Zinc, Chromium, Arsenic	Atmospheric depositions, Urban stormwater & industrial sources, vehicle emissions, weathering of rocks, antifouling paints, mine sites, refining operations, waste disposal, sewage discahrge	Wood preservative Industrial processes Motor vehicle fuel	On - going usage.	ICP - MS (Inductively coupled plasma spectroscopy - mass spectrometry

Different toxicant guidelines exist

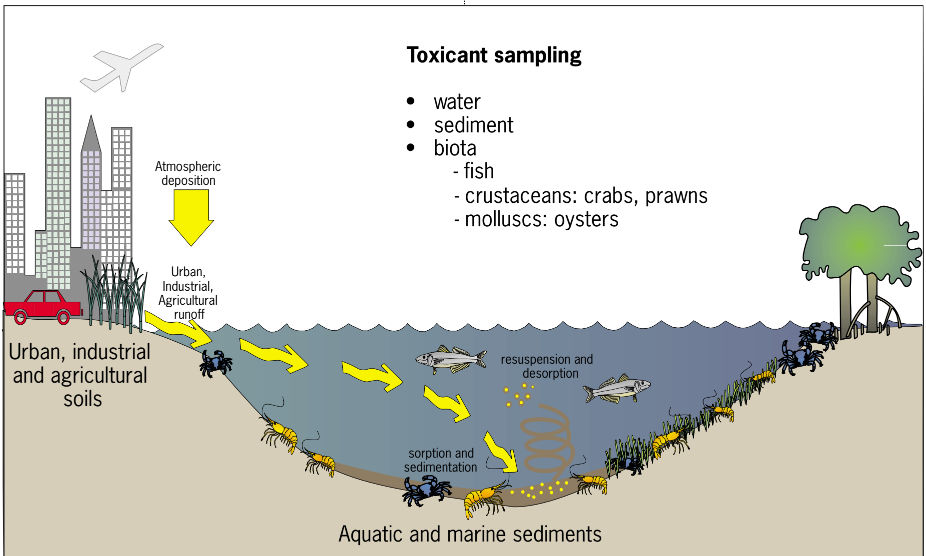
ANZECC Ocean Disposal Draft Guidelines (1998) provide limits for pollutants in sediment. Concentrations in sediment above screening levels are classified as 'moderately contaminated' and subject to acute toxicity testing. If the maximum levels are exceeded, the guidelines recommend that the sediment is potentially unsuitable for unconfined disposal at sea and subjected to sediment bioassay testing, including sublethal and bioaccumulation testing. If the sediment fails the testing, the sediment is recommended to be considered as 'highly contaminated' and 'unsuitable for unconfined sea disposal'.

ANZECC Water Quality Guidelines for Fresh and Marine Waters (1992) provide guidelines for the assessment of pollutant levels in water. This considers both the protection of the aquatic ecosystem and protection of human consumers of seafood. These guidelines also provide for the protection of food for wildlife from organic pollutant concentrations in water.

ANZFA (Australian New Zealand National Food Standard Authority) provides maximum permitted concentrations of toxicants in food. This is based on animal parts that are ordinarily consumed. Above these concentrations food is considered unfit for human consumption.



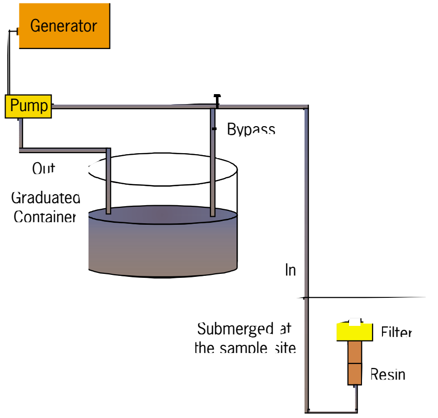
Map of study sites surveyed for toxicants in biota, sediments and the water column.



Conceptual model of movement of toxicants through the ecosystem. Sampling points within the system are marked.

Toxicants

Water sampling techniques devised



Schematic diagram of the sampler configuration for water sampling.

The use of solvent filled semipermeable membrane devices is an alternative method for monitoring the occurrence and concentrations of bioavailable organic pollutants. However, standard configurations of these devices are expensive and difficult to obtain. As an alternative, a simple passive sampling device (PESD) was developed using low-density polyethylene bags which have the ability to sequester organic pollutants from water. Initial results obtained showed the ability of PESDs to accumulate available hydrophobic pollutants such as OCs and PAHs and demonstrated great potential of this innovative sampling technique. As a result, more work is currently being undertaken to modify, calibrate and tune the PESD system and make it available for routine determination of pollutant concentrations in water.

Concentrations of various organic pollutants, especially dieldrin in all water samples collected from the Brisbane River exceeded the guideline for the protection of human consumers of fish and other aquatic organisms specified in the Australian Water Quality Guidelines for Fresh Water and Marine Waters by ANZECC (1992).

A water sampling device was developed specifically for this study to determine organic pollutants in water. This active sampling device enables the separation of toxicants associated with suspended or dissolved phases. Particles and associated pollutants are collected on filters while dissolved phase pollutants pass through the filter and are collected on a resin.

Passive sampling device (PESD) used to measure organic pollutants in water.

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Testing this technique during the study at two sites showed that the sampling system allows the determination of organic pollutants at very low levels in both phases. Results were consistent with those obtained from sediment samples in that overall levels of both PAHs and OCs were higher in water collected from the city site compared to the site near Breakfast Creek mouth. The development of this technique proved to be an important tool in assessing particle/dissolved distribution and hence the fraction of the bioavailable organic pollutants in the environment.

Comparison of ANZECC Guidelines for Fresh and Marine Waters with active sampling results (in ng L^{-1}; Nd = not detectable)

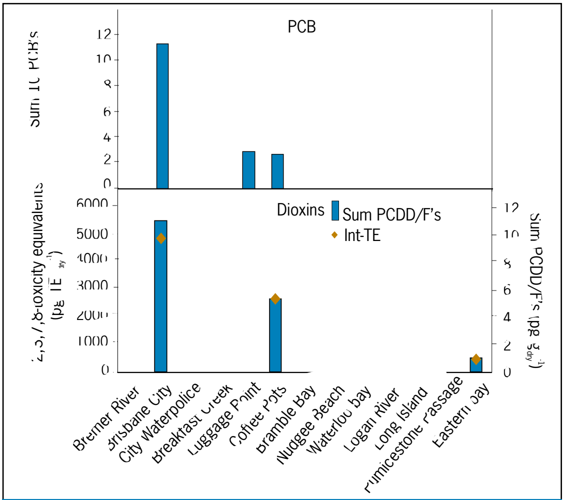
Compound	Protection of aquatic ecosystem	Protection for human consumers	Measured values	
			City	Breakfast Creek
Lindane	3	-	0.01-0.04	0.13
Aldrin	10	0.08	0.05-0.07	0.007
Heptachlor	10	0.3	0.05-0.08	Nd
Dieldrin	2	0.08	1.2-1.4	0.51
DDE	14	-	0.34-0.35	0.066
DDT	1	0.03	Nd-0.14	0.009
PAHs	3000	30	43-100	11
PCBs	1	-	-	-

Strong gradients in sediment toxicants: guidelines exceeded in Brisbane River

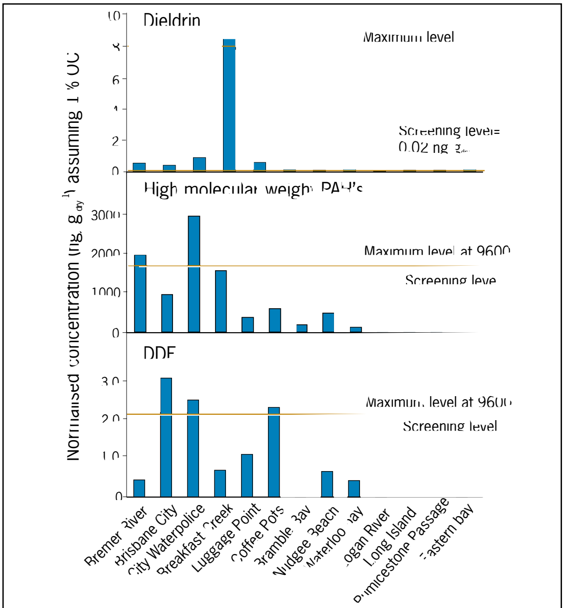
Sediment in aquatic environments acts as an important sink for many toxicants. Many of the organic pollutants tested were present at detectable concentrations in the sediment of the study area. In addition, west/east pollutant gradients were observed and the results clearly demonstrate that the eastern Bay is relatively unpolluted with organic contaminants while high levels are present in the Brisbane River.

With respect to the ANZECC Ocean Disposal Draft Guidelines (1998), sediment concentrations of dieldrin determined in the samples from the study area exceeded the screening levels at all sites except Eastern Bay. Concentrations in sediment from the Breakfast Creek mouth even exceeded maximum levels. At various sites DDE, DDD, DDT and PAH levels exceeded the ANZECC screening levels.

The trend of decreasing contaminant concentration in sediment with distance from the city was also noticeable for dioxins and PCBs. 2,3,7,8-tetrachlorodibenzodioxin, the most toxic PCDD/F and one of the most toxic compounds known to humans, was detected in the sediment samples from the city and Coffee Pots/mid Bay sites. Results of the relatively non-specific PCB testing indicate that PCB concentrations in the sediment also exceeded at least the screening levels in sediment of the Brisbane River.



Concentration of PCDD/Fs expressed as 2,3,7,8-TCDD equivalents (TE) and PCDDs in sediments from three study areas.

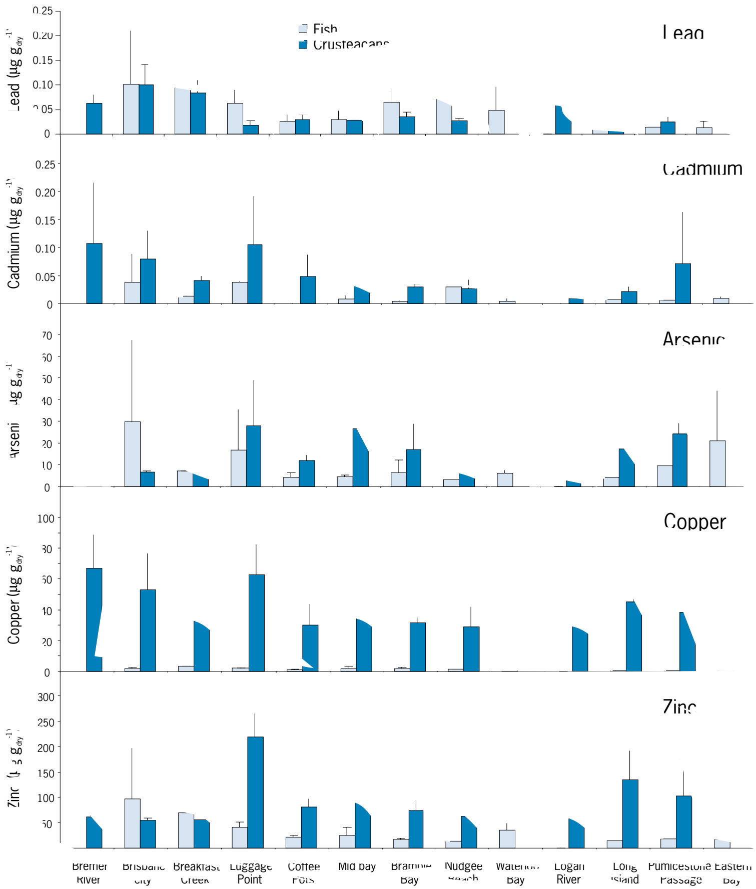


Comparison of normalised dieldrin, PAH and DDE levels in the sediments with screening and maximum levels marked as per the ANZECC Guidelines.

Gradients in metal content of biota

Heavy metals enter estuarine and marine waters via several paths which can be separated into riverine influx, atmospheric deposition and anthropogenic activities. Because organisms tend to accumulate heavy metals from the environment (bioaccumulation) they can become toxic above certain threshold concentrations.

Although west-east gradients were not as pronounced, concentrations of most heavy metals were higher at western sites compared to the eastern Bay. Most heavy metal concentrations in biota did not exceed the levels specified in the Australian National Food Standard. However, copper concentrations were found to exceed these standards in crab and prawn samples from some western sites.

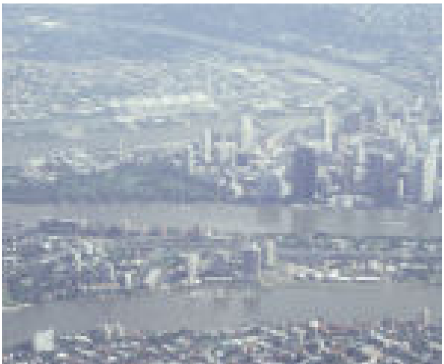


Mean concentration of heavy metals in muscle tissue of fish and crustaceans. Concentration of metals, especially copper, were generally higher in crustaceans

Persistent toxicants in biota, especially from Brisbane River

Results from biota samples analysed for organochlorine (OCs) pesticides again reflect west to east gradients similar to results in sediment, with highest dieldrin and DDT concentrations found in biota from both Brisbane and Bremer River. DDT concentrations in a number of biota exceeded levels specified for the protection of food for wildlife as documented by ANZECC (1992). However, with respect to dieldrin and DDT, biota was found to be within limits specified in the ANZFA guidelines (1998), and therefore safe for human consumption.

PAH concentrations in biota were often below the quantification limits. When compared to high sediment PAH concentrations these results indicate the capability of the organisms to metabolise or biotransform PAHs. In addition, this biotransformation capacity seems to be greater in organisms which are regularly exposed to higher PAH concentrations (e.g. Brisbane River). Since biotransformation of PAHs is known to result in production of carcinogenic products, the use of biomarkers for assessing PAH gradients in the study area is recommended.



Highest concentrations of toxicants in biota were identified at the Brisbane River Site.

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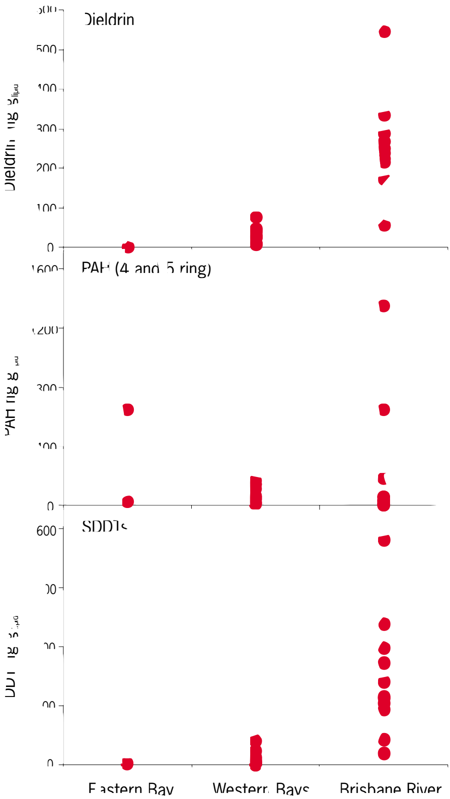
With respect to biomonitoring, it was not possible in the scope of this study to assess whether the use of biota is feasible since large variations between species from one site and within a sampling area exist. More data are necessary to estimate the cause of these variations.



Concentrations of various organochlorine pesticides in biota samples. Results from Waterloo Bay, Bramble Bay and Nudgee Beach have been combined into Western Bays.

Lyngbya bloom in Deception Bay

Microscopic view of *Lyngbya majuscula* (x40)

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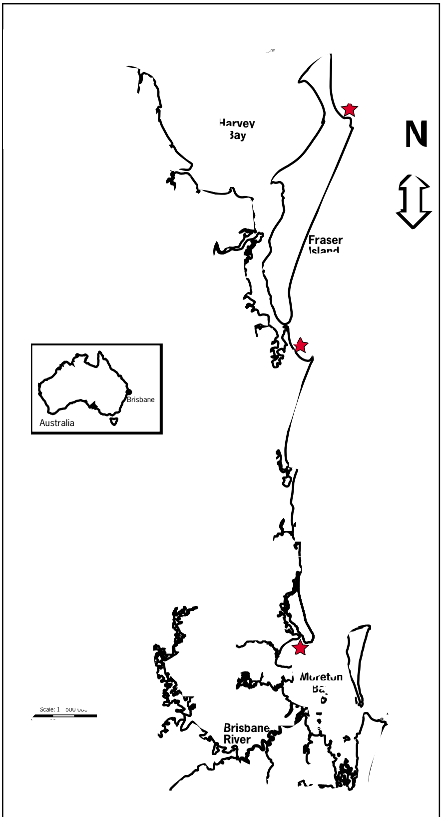

Map of south-east Queensland coast. Red stars denote regions where *Lyngbya* has been recorded

There have been anecdotal reports of blooms of a toxic cyanobacterium in northern Deception Bay since 1992. This cyanobacterium, *Lyngbya majuscula* ('Mermaid hair'), is a filamentous species forming strands of 10-30 cm long filaments, which grow loosely attached to seagrass, macroalgae and rock outcrops. *Lyngbya* possesses a suite of toxins and is found in sub-tropical and tropical estuarine and coastal waters worldwide. Previous blooms of *Lyngbya* have been reported in such areas as Hawaii, Mozambique, Philippines, and Curacao. Blooms in Hawaii have been recorded since 1971, where it is referred to as 'Stinging Limu'.

In the summer of 1996-97, a large bloom of *Lyngbya* was identified in northern Deception Bay. The bloom covered an area of approximately 7 km^2, mostly in water depths < 3 m in an area with sandy sediment. *Lyngbya* was found attached to the seagrass *Zostera capricorni* and to benthic green algae (*Udotea argentea* and *Enteromorpha prolifera*). In the summer of 1997-98, another large bloom of *Lyngbya* occurred in the northern Deception Bay region, beginning in December and extending through the summer. Biomass of *Lyngbya* fluctuated throughout the summers, with occasional disappearances reported following wind events.

Lyngbya impacts both human and ecological health

There have been a variety of human and ecological health impacts associated with the *Lyngbya* blooms. Human health issues associated with *Lyngbya* include severe contact dermatitis causing skin to blister and peel off, eye irritation and respiratory distress. Symptoms are highly variable between individuals, but have been widely reported by fishermen working in the area and others who come into contact with the *Lyngbya*. Asthma-like respiratory distress reported by fishermen working with crab pots or ropes were most likely due to the dusty powder which forms when *Lyngbya* dries. During and following the blooms large wracks of decaying *Lyngbya* gather on beaches in the region. These decaying mats emit a putrid odour necessitating the removal of the decomposing material by local authorities in the Deception Bay region.

There have been a number of localised ecological impacts in the south-east Queensland region associated with *Lyngbya* blooms. Areas of seagrass loss in northern Deception Bay correlated to the areas of *Lyngbya* blooms. Declines in crab and fish harvests in years of *Lyngbya* blooms have not yet been quantified. However, studies in Egyptian aquaculture farms have linked *Lyngbya* to detrimental effects on mullet. Initial research during the *Lyngyba* blooms in Deception Bay also reported decreased oxygen in the water column and proliferation of the bacteria, *Beggiatoa.* The high rates of nitrogen fixation, particularly associated with peak bloom biomass, is likely to have resulted in significant localised input of bioavailable nitrogen following the release of organic and inorganic nitrogen during the decay process.

Severe dermatitis following *Lyngbya* contact

PETER OLIVER

Healthy seagrass beds in northern Deception Bay prior to *Lyngbya* bloom

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Seagrass beds in northern Deception Bay following settling of *Lyngbya* bloom

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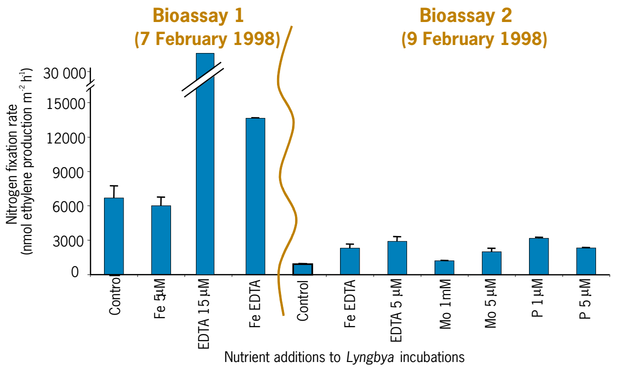
Nitrogen fixation in *Lyngbya* stimulated by iron and phosphorus



Effects of phosphorus (P), iron (Fe), EDTA and molybdenum additions on nitrogen fixation rates in *Lyngbya*. Nitrogen fixation was stimulated by iron and EDTA + Iron.

Many cyanobacteria, including *Lyngbya*, are able to take gaseous nitrogen (N_2) that is dissolved in seawater for their own cellular needs, through a process called nitrogen (N) fixation. The enzyme nitrogenase reduces nitrogen gas to ammonia (NH_3) which can then be incorporated into amino acids and other organic compounds. The fixed N is then made available upon the death or lysis of the cyanobacterial cells.

Rates of nitrogen fixation in *Lyngbya* were determined using the acetylene reduction fixation assay under different light conditions and various nutrient additions. The highest rates of N fixation were identified at the height of the bloom when incubated in light. The potential contribution to the N input in the 7 km^2 bloom area was calculated to be approximately 8 kg N d^{-1}. The transient nature of blooms means that the amount of bioavailable nitrogen *Lyngbya* is contributing to the region could be significant but sporadic and could potentially have significant, localised impacts.

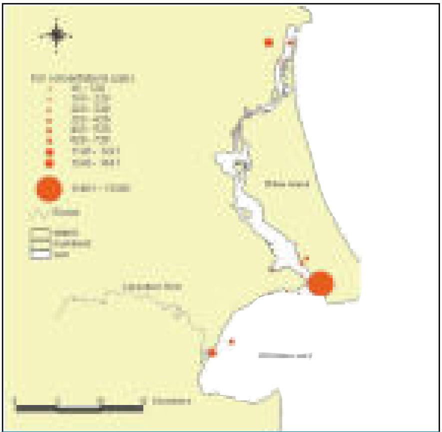
In order to determine factors regulating N fixation in *Lyngbya*, N fixation was measured under various nutrient additions. The effects of these different nutrient additions (iron, Fe; molylodenum, Mo; phosphorus, P) on N fixation were measured in order to identify factors controlling growth and/or formation of blooms. The largest stimulation (4-fold increase) of N fixation occurred in response to the addition of 5µM FeEDTA (iron and a chelating agent). This is consistent with previous *Lyngbya* research (Gross, E.D. and Martin, D.F., 1996, J. Aquatic Plant Manage, 34) and indicates an Fe dependence in cyanobacteria (refer to box). The low stimulation found with Fe additions demonstrates the importance of introducing Fe in the bioavailable form (EDTA is an Fe chelator). Stimulated rates of N fixation were also identified with the addition of EDTA alone which may be a result of chelation of ambient iron in the site water (making it bioavailable). These results, in combination with high levels of total iron identified coming from Pumicestone Passage, indicate that iron may be a contributing factor to blooms of *Lyngbya* in northern Deception Bay. Stimulated rates of N fixation were also identified in response to additions of P (refer to box). This indicates that *Lyngbya* blooms may be co-limited by Fe and P and the availability of both nutrients within the region should be carefully investigated.

Iron (Fe) is an essential cyanobacterial nutrient. It is a component of ferrodoxin and the enzyme, nitrogenase. Ferrodoxin is a primary constituent of photosystem I which provides energy for nitrogen (N) fixation, while nitrogenase is the enzyme which actually fixes nitrogen gas to ammonium. Phosphorus (P) is a necessary component of ATP, the energy source in most reactions in organisms, and in phospholipids.

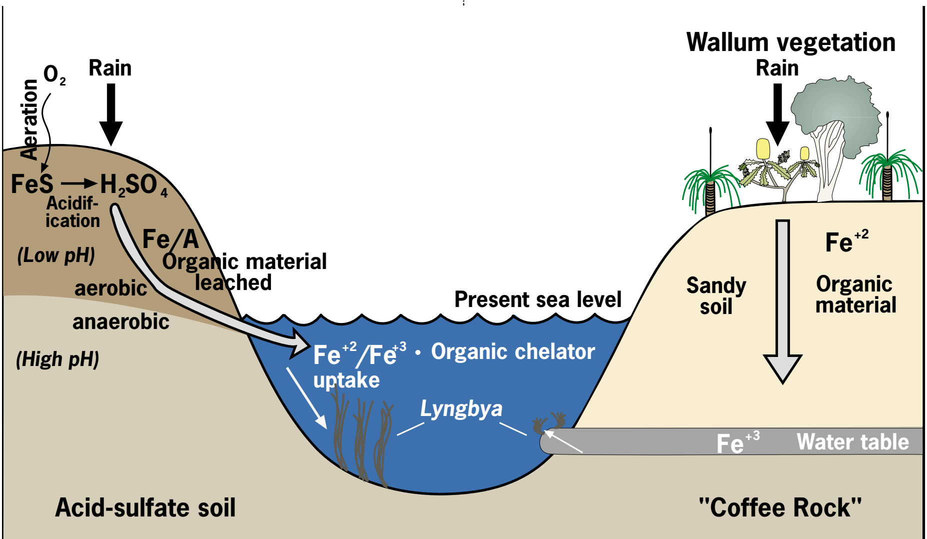
Hypothesised link between *Lyngbya* and hydric soils

The northern Deception Bay region is characterised by low ambient water column and sediment nitrogen (N) and phosphorus (P) concentrations. Initial surveys of the region found higher total metal concentrations, particularly iron (Fe), in groundwater loads in the southern Pumicestone Passage area than in other parts of Moreton Bay.

Similarities in habitat characteristics in the regions where *Lyngbya majuscula* has been reported (northern Deception Bay and Fraser Island) include: clear oceanic waters, shallow water with high light availability, mobile sandy sediments, attachment to the benthos (either plants or rocks), and proximity to acid soil leachate or coffee rock. These similarities and the data on total iron concentrations led to the hypothesised link between *Lyngbya* blooms and iron. Other possible triggers of *Lyngbya* outbreaks include increases in concentrations of nutrients such as P, and trace metals such as molybdenum, needed for the enzyme nitrogenase, and increases in organic substances such as humic acids that may act as chelators for trace metals.



Iron concentrations (ppb) in Deception Bay and Pumicestone Passage. Highest concentrations were recorded at mouth of Pumicestone Passage.



Conceptual model of hypothesised factors influencing growth and proliferation of *Lyngbya* in Deception Bay and at Fraser Island

Faecal coliforms high in Brisbane River

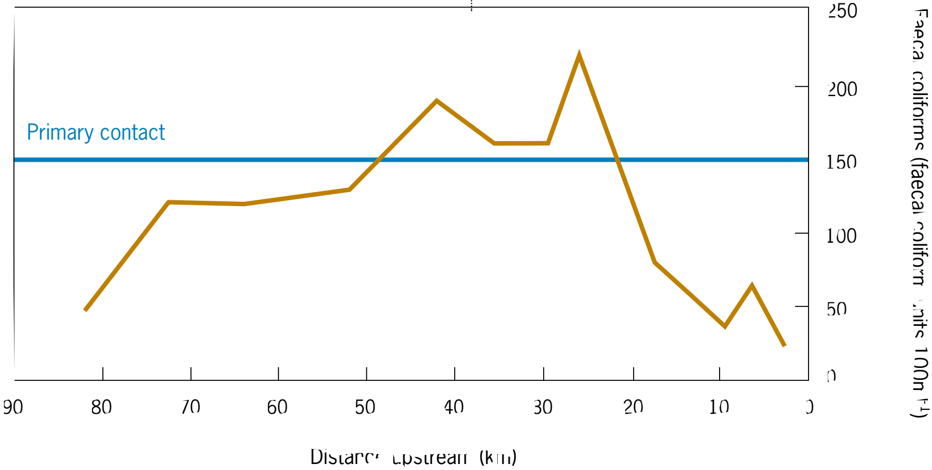
Faecal coliforms are naturally occurring bacteria in the intestines of mammals and birds. Their presence is used as an indicator of contamination by sewage waste in water quality monitoring and is the recommended bacterial indicator for assessing risk to human health. Although faecal coliforms are not pathogenic, their presence is an indication that pathogenic bacteria and viruses may also be present.

Human health indicators were not specifically addressed within Stage 2, with the monitoring program development focussing more on ecological health, however, EPA possesses a large database of results from ongoing faecal coliform monitoring. ANZECC guidelines recommend less than 150 faecal coliforms per 100 ml for primary contact (e.g. swimming) and less than 1000 faecal coliforms per 100 ml for secondary contact (e.g. boating).

Sewage discharges are the predominant source of faecal coliforms in waterways, particularly sewage treatment plants where effluent is not disinfected. However, stormwater runoff may also contain high levels of faecal coliforms from animal faeces. Monitoring by EPA indicates that urban creeks and estuaries have fairly high levels of faecal coliform contamination. This is particularly true for the Brisbane River where many reaches have levels that exceed the primary contact level.

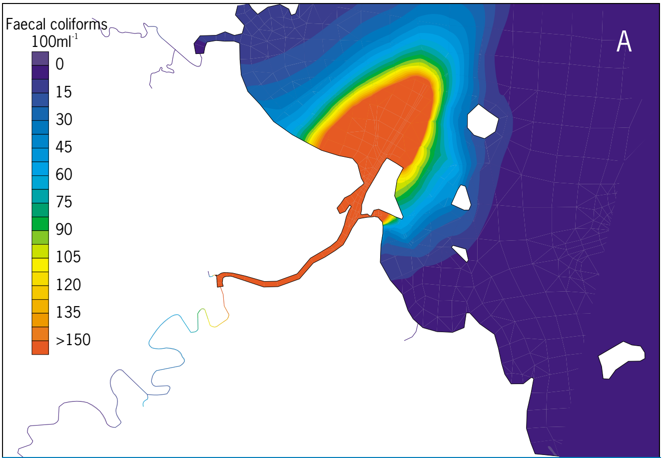
During dry weather, most urban waters contain faecal coliforms, but many creeks would meet primary contact criteria. Following rain events, EPA data suggests few urban creeks and estuaries would meet primary contact criteria. Even regions of Moreton Bay would suffer some level of contamination from river and creek plumes.

Outputs from the receiving water quality model also support this suggestion, with faecal coliform plumes predicted to extend beyond Mud Island even during dry periods (primary contact guidelines). Although recovery periods vary for different regions, recovery for the Bay regions would most likely be rapid.

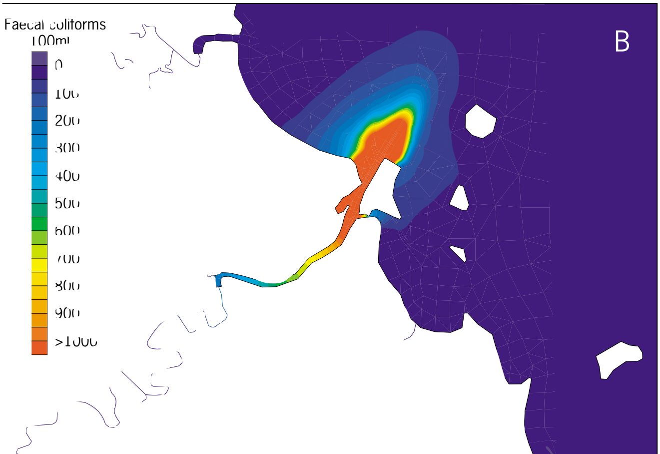


Faecal coliform concentrations in the lower reaches of the Brisbane River. Concentrations between 20 km and 50 km upstream, exceed primary contact level recommended by ANZECC Guidelines.

Faecal coliforms can be flushed into the Bay after rain events



Predicted faecal coliform concentrations per 100 ml near the Brisbane River mouth. The red area indicates the region where primary contact is not recommended (>150 faecal coliform units per 100 ml).



Predicted faecal coliform concentrations per 100 ml near the Brisbane River mouth. The red area indicates the region where secondary contact is not recommended (>1000 faecal coliform units per 100 ml).

Faecal coliform scenarios were generated from the receiving water quality model for an assumed average year (1997). Although the faecal coliform routines have been shown to be producing valid output, because the program does not include a salinity factor (which may result in greater death rates), estimates of faecal coliform numbers may be an overestimation of actual numbers. Despite this, it is clear that the faecal coliform contour maps for Moreton Bay are dominated by the undisinfected sewage treatment effluent from the Luggage Point and Gibson Island plants. The diagrams represent regions (in red) which are considered unsuitable for activities considered as primary contact (A) and secondary contact (B).

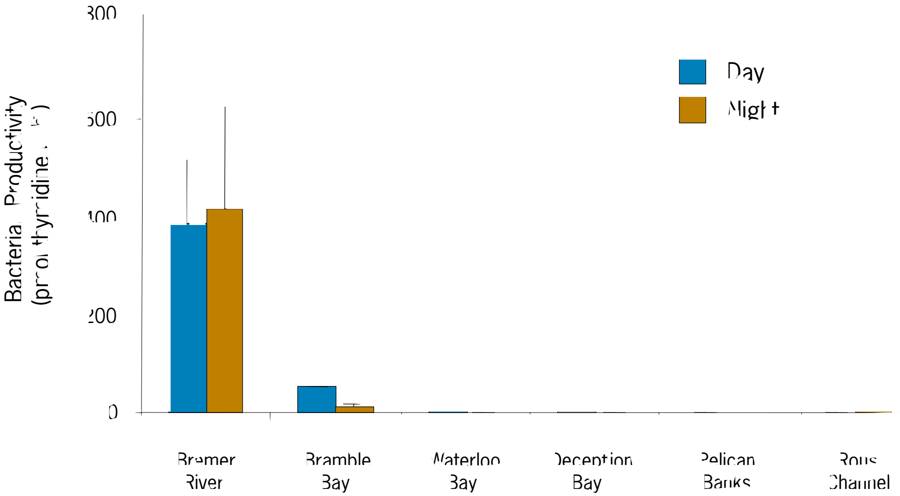
Bacteria

High bacterial productivity in the Bremer River

Bacteria are single celled microorganisms forming a natural component of the phytoplankton community. They have rapid rates of cell production and turnover and therefore productivity can be determined, on short time scales, by the rate of DNA synthesis. Heterotrophic bacterial DNA synthesis is measured by the rate of ^{3}H-thymidine (a precursor molecule of the cell genetic material) incorporation. Lowest levels of productivity were detected during the day at all Moreton Bay sites with the exception of Bramble Bay. Here, higher bacterial productivity may have been stimulated by exudation of organic substances from the diatom bloom.

In the Bremer River, bacterial productivity rates were over three orders of magnitude greater than at any other site in both day and night sampling. High rates of productivity are likely to result from very high external nutrient loadings. These high levels of productivity were consistent with high uptake rates of nitrogen and low autotrophic productivity in the Bremer River. This heterotrophic dominated system is an indication of poor ecological health.

Although the composition of these bacterial populations were not a focus of the study, their presence and high rates of production, particularly in the Bremer River, may have implications for human health.



Bacterial productivity at the sample sites. Productivity was lowest at all bay sites and highest in the Bremer River.

CHAPTER 13

Moreton Bay Biota

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CHRIS ROELFSEMA

- High biotic diversity

Plankton

- Plants = phytoplankton; animals = zooplankton
- Phytoplankton = diatoms, dinoflagellates and other flagellates
- Zooplankton = copepods, shellfish larvae, ciliates and polychaetes
- Zooplankton grazing determined by various methods
- Zooplankton grazing affects phytoplankton biomass

Benthic Microalgae

- Benthic microalgae = pennate diatoms, dinoflagellates and cyanobacteria
- Benthic microalgae ubiquitous
- Benthic microalgae productive

Macroalgae

- Diverse red, green and brown macroalgae
- Macroalgae on rocks, mangroves and seagrass
- Nuisance green macroalgae in Bay

Corals

- Unique coral assemblages
- Historical record of floods from coral cores

Seagrass

- Seagrass supports dugong, sea turtle, prawns and fisheries
- Variable seagrass communities
- Seagrass distribution patterns distinguished by remote sensing
- Worm digging disrupts seagrasses
- Intensive cultivation grazing by dugongs

Mangroves

- Mangrove communities dominated by grey mangrove
- Mangroves (and salt marshes) throughout river estuaries and Bay
- Mangroves: nursery and habitat

Fauna

- Diverse assemblages: not an emphasis of the study

High biotic diversity

Moreton Bay is a subtropical environment, located in a geographical overlap between the tropical and temperate latitudes. The prevailing conditions allow for species co-existence from each of these zones, which together form a unique framework for examination of ecosystem dynamics.

Moreton Bay supports a broad diversity of taxonomic groups. This includes the primary producers, phytoplankton, macroalgae, seagrasses, mangroves and corals. These support a diverse assemblage of faunal groups of taxonomic and biogeographic interest which occupy and feed in the habitats. The factors maintaining these habitats are becoming increasingly understood as the role of the factors in controlling their growth are examined.

The comprehensive array of environmental conditions provides the opportunity for a diverse faunal and floral assemblage to establish. The variety of habitats on a broad scale, estuaries, coastlines and open water environments, and on a smaller scale substrate available for inhabitation including, mud, sand, rocky outcrops and the structural substrate provided by the organisms which inhabit these (e.g. mangrove pneumatophores, seagrass leaves), provides opportunities for establishment of a rich diversity of fauna and flora.

Phytoplankton

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Macroalgae

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Mangrove

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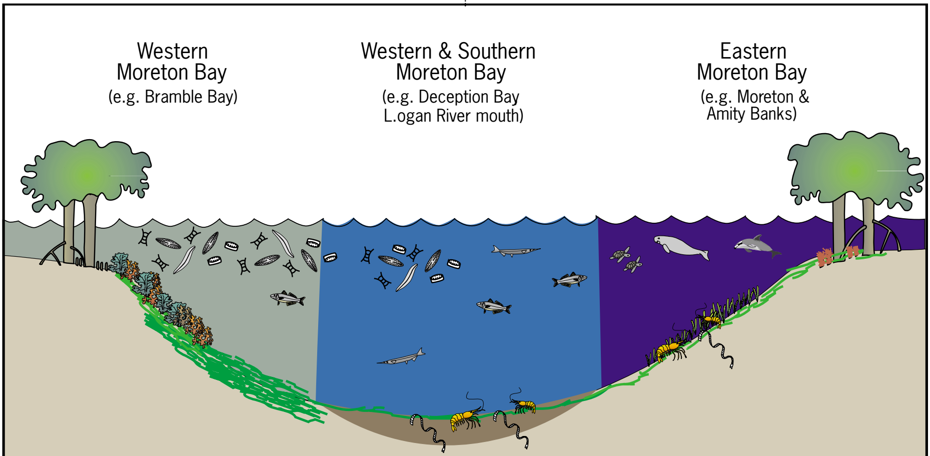


Conceptual model depicting the diversity and distribution of biota in Moreton Bay.

Plants = phytoplankton; animals = zooplankton

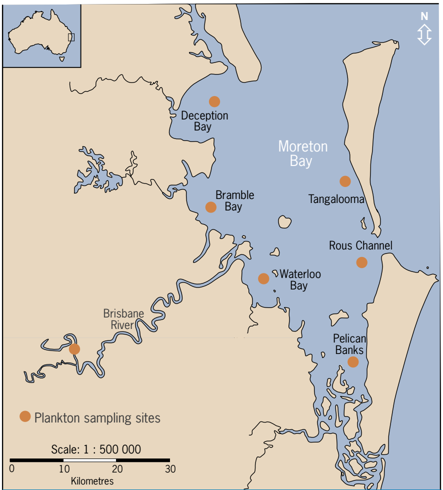
'Plankton' is a term coined in the 19th Century by oceanographers to describe microscopic aquatic organisms which are carried passively by ocean currents. The definition also includes organisms which inhabit the water column for only part of their life. The term now also applies to different trophic groups of plankton (e.g. marine plants: phytoplankton and marine animals: zooplankton) and different size groups (picoplankton (0.1 – 1.0 µm) to megaplankton (> 1µm).

Phytoplankton are very small (0.1 µm – 2 mm) unicellular plants which can be photosynthetic, motile, single celled or chains of cells and are important ecologically and economically. While water motion controls their large scale movements, the distribution of species is primarily determined by physical and chemical environmental factors. They form the basis of most marine food webs and have a significant influence on nutrient cycling and hence water quality. Because they are so small they frequently go unnoticed to a casual observer until a 'bloom' occurs, when physical conditions concentrate cells to very high levels or increased light and/or nutrient availability allows the growth of a single species over others, resulting in cell concentrations so dense that water discolouration and a decline in ecosystem health may occur. Nutrient and light availability are 'bottom-up' controls on phytoplankton productivity and biomass.

Zooplankton are non-photosynthetic protist or animal plankton which have heterotrophic nutrition (i.e. they require carbon already fixed into organic molecules). Although often capable of weakly directed swimming movements, their large scale (> 1 km) distribution is dictated primarily by water motion. Zooplankton include single celled protists, microscopic animals, jellyfish and larvae of fish and shellfish which may spend only a part of their life as plankton. Zooplankton graze on phytoplankton providing 'top-down' control on phytoplankton biomass. The role of this interaction in controlling phytoplankton populations varies according to the dominance of bottom-up controlling mechanisms (e.g. light and nutrients).

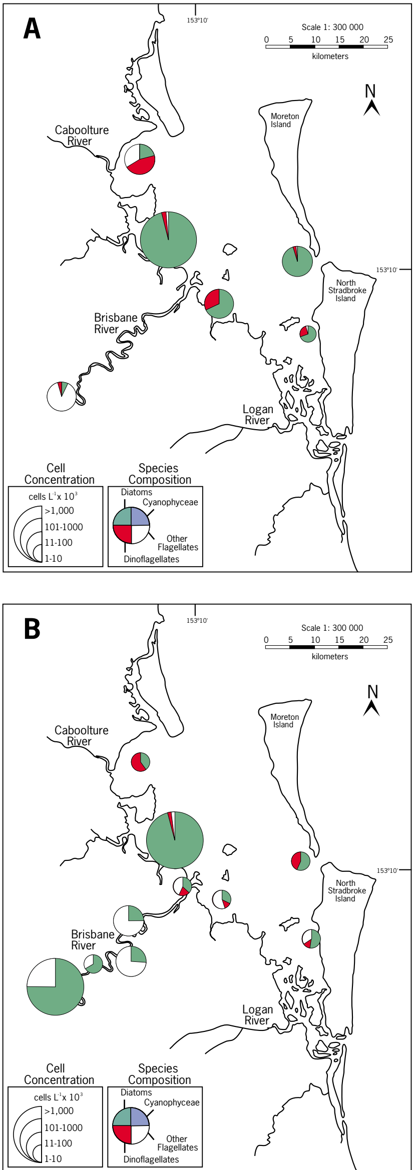
Plankton size fractions

Because of the difficulty in collecting and studying mixed communities of very small organisms in the natural environment, plankton are frequently classified according to size. Both phytoplankton and zooplankton are collected from the water by towing nets with different mesh sizes through the water which collect and concentrate the plankton for later microscopic examination. Collection of Moreton Bay plankton involved three different net mesh sizes: >20 µm, >64 µm and >200 µm. For phytoplankton nutrient and productivity experiments, whole water samples were collected, large zooplankton were filtered out, and the responses of different size fractions of phytoplankton to nutrient addition, were determined by filtering the phytoplankton sample onto different sized filters (generally 1, 3 and 10 µm pore sizes).



Plankton sampling sites

Phytoplankton = diatoms, dinoflagellates and



Phytoplankton community composition and abundance in A) September and B) July. Generally diatoms dominated in the Bay sites and the rivers were dominated by flagellates.

Diversity and biomass of Moreton Bay phytoplankton was broadly related to water quality. Generally, lowest community diversity was found in association with poor water quality (high nutrients and turbidity) as the Bremer River was dominated by freshwater flagellates and Bramble Bay was dominated by 1-3 diatom species. Highest phytoplankton community diversity was found in the clean oceanic water of Rous Channel in eastern Moreton Bay. Other western Bay sites contained an intermediate level of diversity. Thus, there is the potential for phytoplankton diversity to be utilised as an indicator of changes in ecological health.

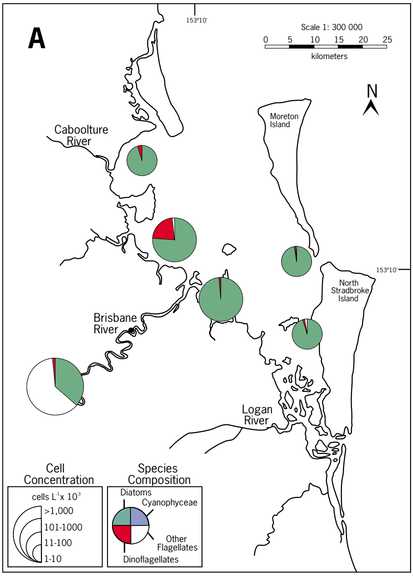
The phytoplankton community of Moreton Bay is typical of a subtropical estuarine community. In winter, however, it may become more typical of the temperate neritic (coastal) community identified in New South Wales (Heil, C.A. et al, 1998, Moreton Bay and Catchment). To date, more than 145 phytoplankton species have been reported from Moreton Bay, including diatoms (Bacillariophyta), dinoflagellates (Dinophyta), cyanobacteria (Cyanophyta) as well as other small flagellate groups (e.g. Cryptophyta, Chlorophyta and Euglenophyta).

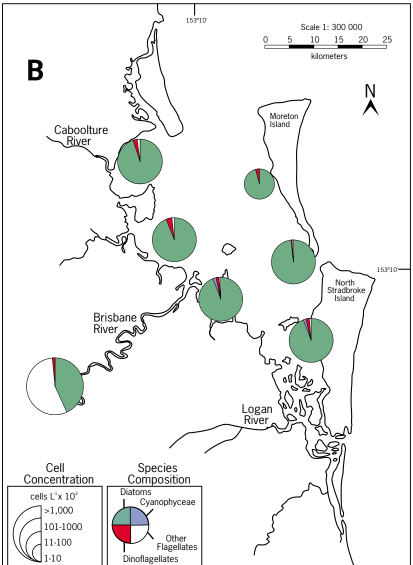
Diatoms are photosynthetic phytoplankton which frequently form chains of cells and are distinguishable by their often elaborate siliceous skeletons, the morphology of which is used for species identification. Because of their siliceous skeletons, diatoms have a nutritional requirement for silica (refer to Chapter 9). Diatoms were the dominant group of phytoplankton in the Bay, representing up to 95% of the phytoplankton population. The Bremer and Brisbane River phytoplankton community had a much smaller percentage of diatoms and instead a predominance of heterotrophic forms. This community structure is suggested to result from reduced light penetration from high concentrations of suspended solids.

other flagellates

Dinoflagellates (dinos = whirling) are the second most dominant phytoplankton group in Moreton Bay. Dinoflagellates are motile phytoplankton which possess two or more flagella enabling them to swim at speeds up to 1 m hr^{-1}. Approximately 2% of dinoflagellates worldwide are toxic and are responsible for toxic 'red tides' which can result in shellfish toxicity as well as shellfish, fish and mammal (including human) mortality. The toxic dinoflagellate *Dinophysis caudata* responsible for diarrhetic shellfish poisoning, has been identified in Moreton Bay since the 1940's (Wood, E.J.F., 1954, Aust J. Fresh. W. Mar. Res. 5) and occurs year round primarily in the north-eastern Bay. It may be of concern because of its bloom potential associated with sewage derived nutrients. Approximately half of the dinoflagellate species are photosynthetic (as are most other phytoplankton groups) and therefore have pigments which allow them to capture energy from the sun to convert carbon dioxide into organic carbon molecules (photosynthesis). The other half, however, are heterotrophic and ingest fixed carbon either in dissolved form or as whole prey organisms. *Noctilica scintillans* a bioluminescent, heterotrophic dinoflagellate which is a voracious obligate grazer of other diatom and dinoflagellate species, may have deleterious impacts through grazing on zooplankton and fish eggs when blooms occur.

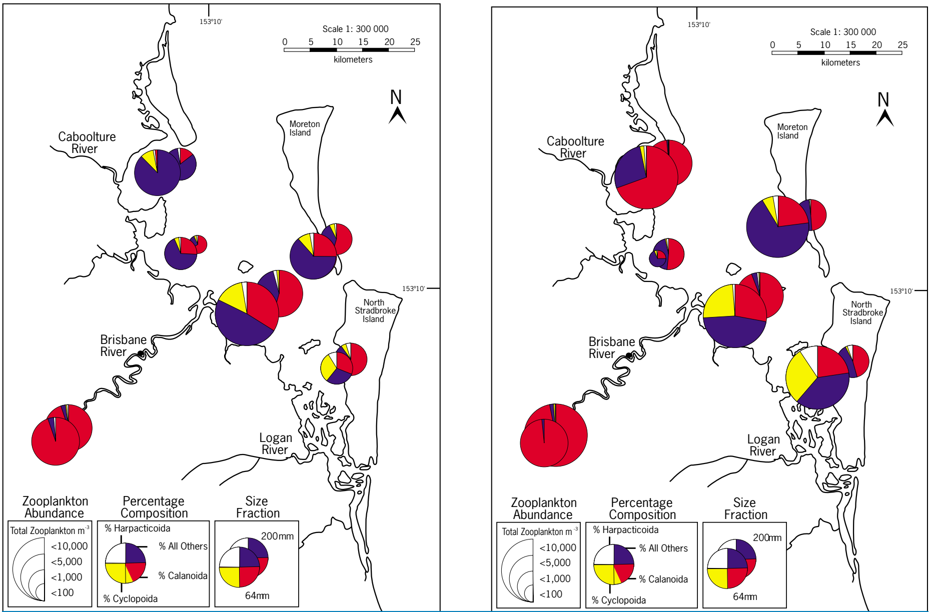
The other flagellate groups found in Moreton Bay are the Cryptophyta, which are less common in Australian tropical oceanic waters; Prymnesiophytes, including the more commonly known coccolithophores which produce intricate calcareous plates; Chrysophytes which are more commonly freshwater inhabitants and which frequently form siliceous resting stages. A small unidentified dinoflagellate dominated the phytoplankton community in the Bremer River. Outside of the Brisbane River, flagellates generally represented a low proportion of the phytoplankton community.





Phytoplankton community composition and abundance A) February day and B) February night. Diurnal changes of community composition occurred predominantly at Bramble Bay.

Zooplankton = copepods, shellfish larvae,



Zooplankton community composition and abundance of the > 64 μm and > 200 μm size fractions in September A) day and B) night. The communities were dominated by the Calanoid copepods in the river and western Bay sites particularly in the greater than 200 μm size fractions while other zooplankton (excluding copepods) dominated Bay sites.

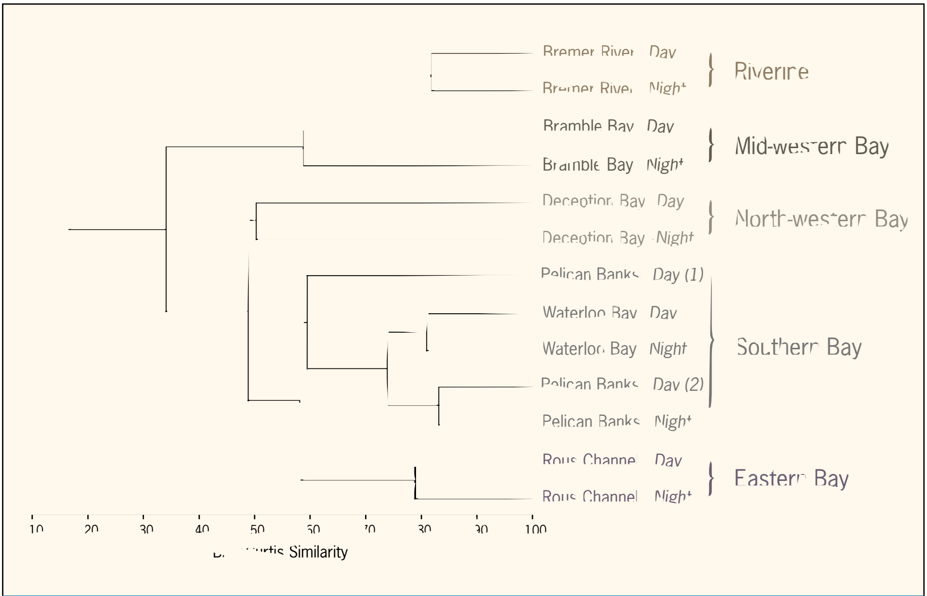
The zooplankton community of Moreton Bay includes copepods, shellfish larvae, ciliates and polychaetes. Copepods are small crustaceans which frequently dominate the coastal and oceanic zooplankton community. Ciliates are single celled zooplankton and although extremely small are an important link in the planktonic food web as they consume very small organisms such as bacteria, which are unavailable to other zooplankton. Polychaetes are annelids (segmented worms) bearing setae (bristles) on each segment which serve a variety of functions including assistance with swimming.

Zooplankton community at Bremer River was dominated by calanoid copepods (x100)

TOM GORRINGE

Zooplankton are highly sensitive to environmental conditions such as food and water availability and water clarity, and therefore their community composition may also be utilised as a biological indicator of ecological health. Zooplankton community diversity increased and the abundance decreased from western to eastern Moreton Bay, a trend consistently observed in the 64 μm and 200 μm size fractions. The increase in the diversity from west to east was accompanied by a relative increase in the proportion of larval forms and a decrease in the copepod population. Lowest zooplankton diversity occurred in the Bremer River. Here almost a monoculture of copepods

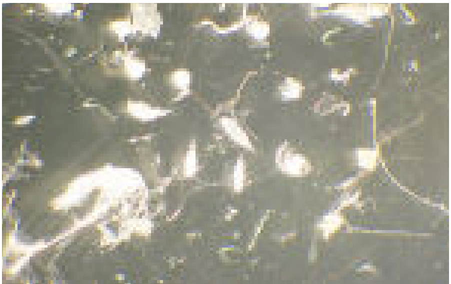
ciliates and polychaetes



Similarity in zooplankton species composition at six sites for day and night. Riverine and eastern Bay sites are mostly distantly related.

(consisting of two genera of Calanoid copepods: Glodioferens and Sulcanus) was identified.

Based on this west to east zooplankton community gradient, Moreton Bay can be divided into approximately five regions 1) Bremer River; 2) Deception Bay; 3) Bramble Bay; 4) the southern Bay (Waterloo Bay and Pelican Banks); and 5) Rous Channel. Deception and Bramble Bays have a similar zooplankton diversity and both experience large seasonal and possibly diurnal changes in biomass. However, total abundance was much lower in Bramble Bay. Periodically, Deception Bay experiences large blooms of *Catostylus mosaicus*, a large jellyfish that swarms Moreton Bay in winter and spring. Careful monitoring may be necessary as consumption of the zooplankton by *C. mosaicus,* under bloom conditions, may be significant and the decay of copious mucus secretions may potentially



Diverse zooplankton assemblage at Rous Channel (x100)

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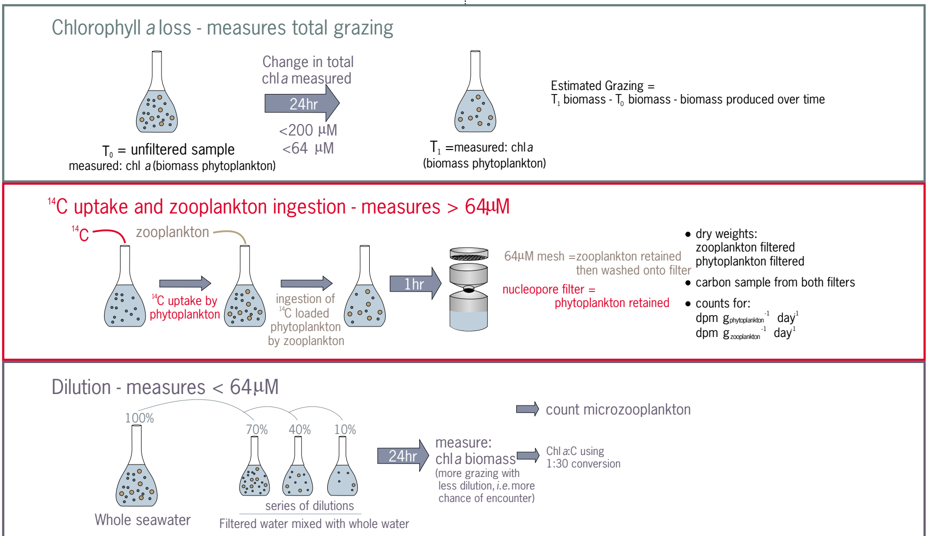
stimulate microbial activity. Southern Bay sites had similar abundances of total zooplankton to western Bay sites although a larger proportion of barnacle nauplii (very early larval stage) were found here. At Rous Channel, the presence of diverse zooplankton larvae in a range of developmental stages led to an overall greater diversity when compared to other sites.

Zooplankton grazing determined by various methods

Grazing by zooplankton can be an important regulator of phytoplankton biomass and productivity. Zooplankton grazing rates in Moreton Bay were determined by 3 different methods. The first of these is a straightforward procedure based on the loss of phytoplankton biomass over time in a water sample with both phytoplankton and zooplankton communities present. The chlorophyll *a* in phytoplankton is ingested by zooplankton and the decline in this pigment (measured by fluorescence), from a water sample over time, gives an estimate of the amount of phytoplankton grazed by zooplankton. Although there are other causes of chlorophyll disappearance, this method provides a simple technique for determining site and temporal variations of grazing rates. In the second method, phytoplankton are incubated with the radioactive carbon isotope ^{14}C which is incorporated into their biomass by photosynthetic carbon fixation. Zooplankton graze this ^{14}C labelled phytoplankton and ingest the carbon isotope. The amount of ^{14}C in the zooplankton is then determined and related to the amount of ^{14}C in the phytoplankton allowing calculation of zooplankton ingestion rates. The final method (the Landry and Hasset technique: Landry, M.R and Hasset, R.P, 1982, Marine Biology, 67) measures zooplankton grazing by diluting natural populations of phytoplankton and zooplankton with filtered seawater containing no phytoplankton (typically 70%, 40% and 10% dilution). As the plankton are diluted, the chance for an encounter between an individual phytoplankton and zooplankton is reduced and the technique therefore also assumes that grazing rates will also decline. Chlorophyll *a* loss, over time, is again used as a measure of phytoplankton decline. Additionally, counts of microzooplankton abundance were determined.

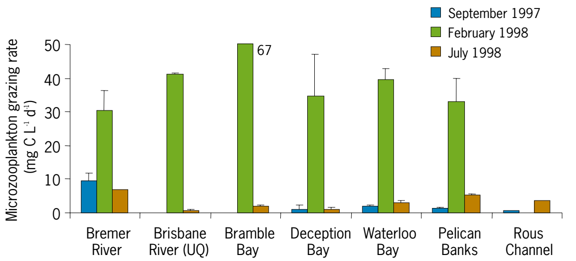


Methodology for determining zooplankton grazing on phytoplankton outlining 3 different procedures. A) Chlorophyll *a* reduction over time B) ^{14}C uptake by phytoplankton and zooplankton ^{14}C ingestion and C) Landry and Hasset technique in which samples are diluted with filtered seawater and chlorophyll loss over time is determined.

Zooplankton grazing affects phytoplankton biomass

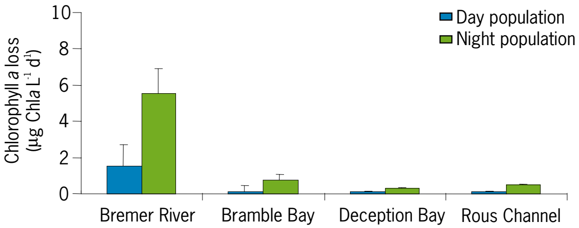
Herbivorous zooplankton grazing can be an important control of phytoplankton biomass (top-down control) as well as providing crucial links in the food web. All zooplankton grazing techniques indicated that microzooplankton (zooplankton < 64 µm) were responsible for the most significant portion of the herbivorous grazing at all sites. The dilution technique determined that microzooplankton can consume 10-100% of the total phytoplankton productivity and biomass per day. Ciliates dominated the micrzooplankton community and therefore accounted for the majority of this grazing.

If the zooplankton grazing rate is greater than the growth rate of the phytoplankton, there will be a decrease in phytoplankton biomass. In general, there is a greater proportion of phytoplankton biomass grazed by zooplankton moving from western to eastern Bay. This is in part due to high standing stock (or blooms) of phytoplankton in the Bremer River and Bramble Bay that the resident zooplankton populations are unable to keep up with. At the more oligotrophic eastern Bay sites, the zooplankton are better able to control the phytoplankton populations.



Microzooplankton grazing rates in September, February and July. Grazing rates were highest in February at Bramble Bay. In September and July grazing rates were highest in the eastern and southern sites.

Grazing rates were highly variable, both spatially and temporally. However, zooplankton grazing rates were uniformly an order of magnitude higher at all sites in summer, which corresponds to peak water temperatures as well as phytoplankton abundance and productivity.



Zooplankton grazing during the day and night. Grazing rates were highest at night.

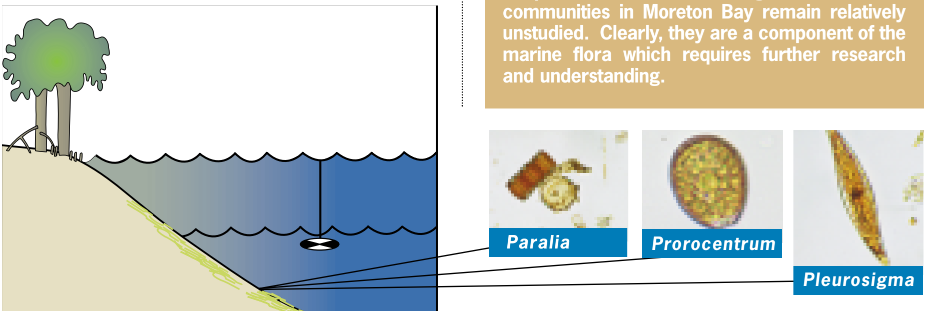
Night-time populations exhibited higher grazing rates on phytoplankton than day-time populations at all sites, as determined by chlorophyll *a* loss. This may be due to the migration of demersal (bottom-dwelling) zooplankton into the water column at night. Bramble Bay was the only site with substantially higher rates of grazing during the day, as compared to night. This may have been driven by the diatom bloom which dominated the phytoplankton community at Bramble Bay.

Benthic microalgae = pennate diatoms, dinoflagellates and cyanobacteria

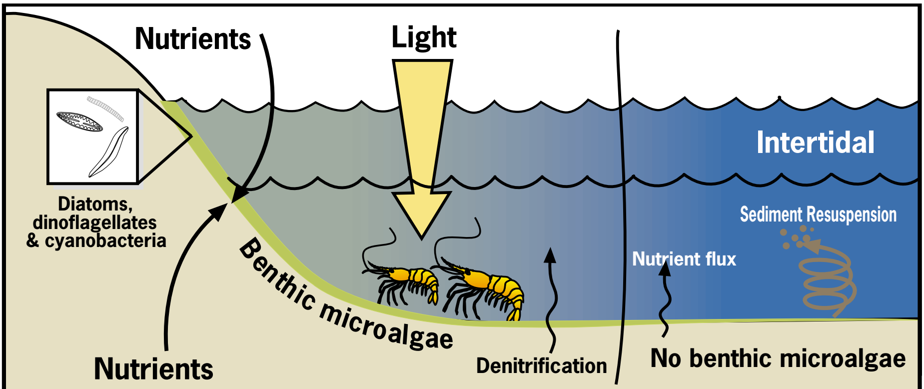
Benthic microalgae (BMA) are single-celled microscopic plants (primarily diatoms and dinoflagellates) and cyanobacteria which inhabit the top 0-3 cm of aquatic sediment. Their biomass can be detected and quantified by chlorophyll *a* analysis using the same method described previously for determination of phytoplankton biomass in the water column (refer to Chapter 9). Although they are so small that single cells cannot be seen by the naked eye, BMA may become so concentrated at the sediment surface that the sediment appears green due to chlorophyll *a*. BMA can migrate through the sediment to depths of over 3 cm.

Ecological significance of benthic microalgae

Benthic microalgae (BMA) are ecologically significant in coastal marine environments from corals reefs to estuaries. They are a major food source for benthic feeders such as prawns and other crustaceans, bivalves and polychaete worms. Suspension feeders, such as polychaete worms and oysters, may also graze on them when they are resuspended into the water column due to current or tides. BMA excrete polysaccharides which bind the sediment and minimise the influence of overlying water movements. This results in an increase in sediment stability reducing the potential for sediment erosion and resuspension. BMA communities also modify nutrient exchange, particularly nitrogen, between the water column and sediments and hence may play an important role in regulating water quality. Despite these crucial ecological roles, BMA communities in Moreton Bay remain relatively unstudied. Clearly, they are a component of the marine flora which requires further research and understanding.



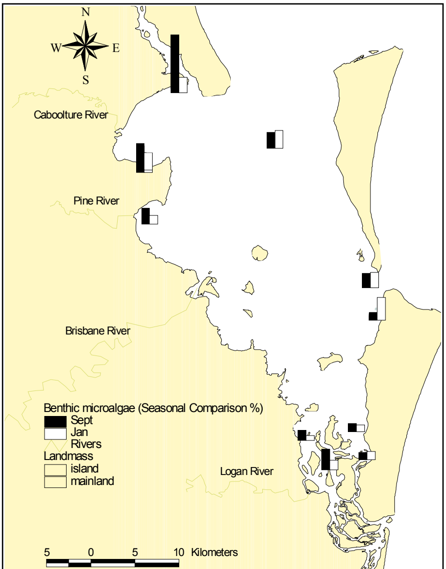
Examples of Moreton Bay benthic microalgae.



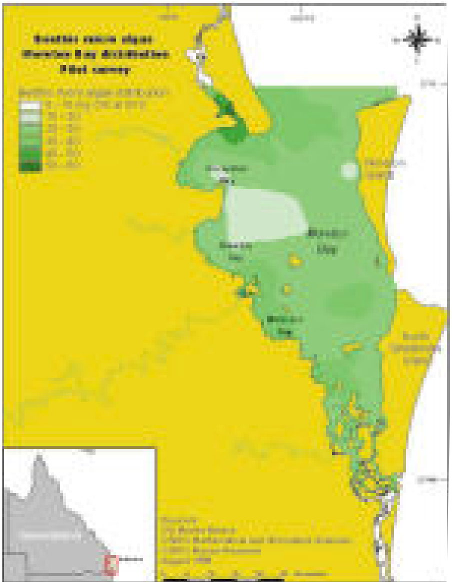
Conceptual model depicting the ecological role of benthic microalgae. BMA are important for nutrient absorption, sediment binding and contribute to the benthic food webs.

Benthic microalgae are ubiquitous

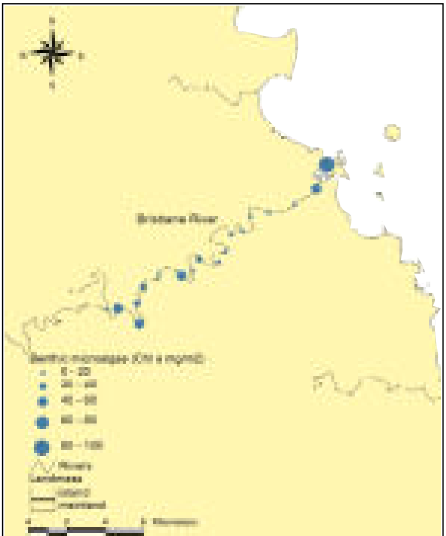
A comprehensive survey of chlorophyll *a* content of Moreton Bay sediments has shown that benthic microalgae (BMA) are ubiquitous, although concentrations vary greatly between sites. Concentration 'hot spots' characterised by extremely high chlorophyll *a* concentrations were identified in the northern Bay, particularly at the southern end of Pumicestone Passage and at the mouth of the Brisbane River. Lowest concentrations were found in the middle reaches of the Brisbane River where the turbidity maximum occurred, and in the central Bay. The survey also involved a seasonal component with biomass measurements taken in September and January. Seasonal variation of BMA biomass was only observed at western Bay sites, with the highest values in September.



Seasonal variation of benthic microalgal biomass. The greatest seasonal variation occurs in the western Bay.



Benthic microalgal distribution and concentration as determined by sediment chlorophyll *a* concentrations. The highest concentrations were found at the mouth of Pumicestone Passage and the lowest concentrations were recorded in central Bay



Intertidal benthic microalgal abundance in the Brisbane River. The greatest abundance occurred at the River mouth. Very low concentrations were recorded in the lower reaches of the river.

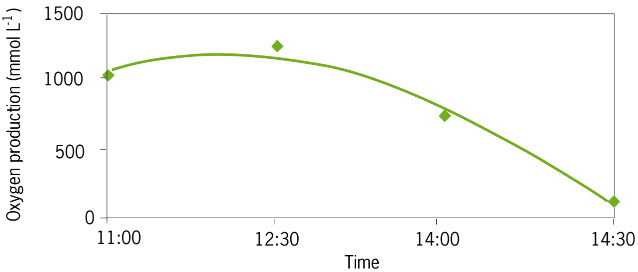
Benthic microalgae productive

Benthic microalgae (BMA) may be the most productive marine plants within Moreton Bay. This was determined from the rate of oxygen evolution. Oxygen is a product of photosynthesis and therefore, the rate at which oxygen is produced indicates the rate of photosynthetic carbon incorporation (productivity). The highest rates of BMA productivity were found in the middle of the day and decline rapidly by mid-afternoon. Extrapolation of this data indicates that BMA have a bay-wide productivity greater than that of mangroves, seagrasses and macroalgae despite their significantly lower biomass.

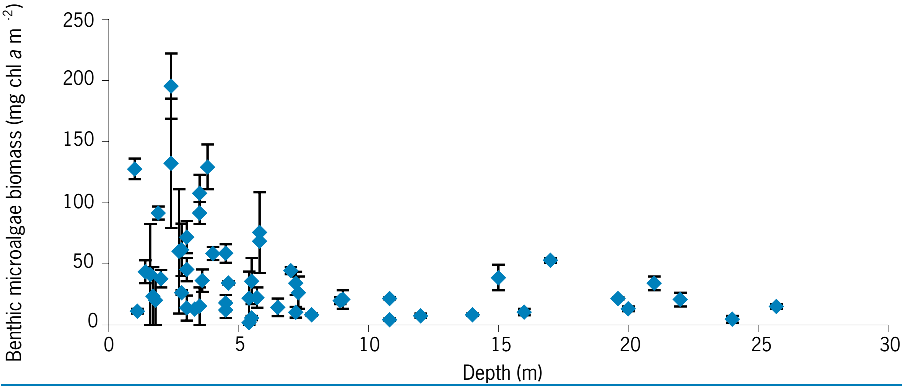
Productivity and biomass of marine plants

	Areal extent (Km^2)	Biomass (tC)	Productivity (tC yr^{-1})
Benthic microalgae	315	1 800	520 000
Mangroves	103	2 300 000	59 000
Seagrasses	181	11 000	36 000
Macroalgae	106	820	20 000

Based on biomass spatial distribution maps, and biomass depth profile, high rates of productivity by BMA appear to be primarily concentrated in the shallow coastal regions. Although benthic microalgae are ubiquitous and observed at all sampling sites, the greatest biomass was observed at depths of less than 5 m. In these shallow regions high BMA productivity may form the basis of the coastal food web and may also have a significant influence on sediment biogeochemistry through nutrient processing.



Oxygen production of benthic microalgae. The greatest rate of production occurred in the middle of the day followed by a rapid decline.



Benthic microalgal biomass as a function of depth. Abundance was greater and also more variable at shallower depths.

Diverse red, green and brown macroalgae

Macroalgae, including the red algae (Rhodophyta), green algae (Chlorophyta) and brown algae (Phaeophyta), are widely distributed within Moreton Bay. Less than 100 macroalgae species were observed in this study from a survey encompassing a total of 1000 sites. A total of 285 species have been identified in the bay from a total of 1900 records (HERBRECS, Queensland Herbarium data base). Temporal variability of species diversity may account for the majority of the discrepancy in species numbers (lower values) observed in this survey.

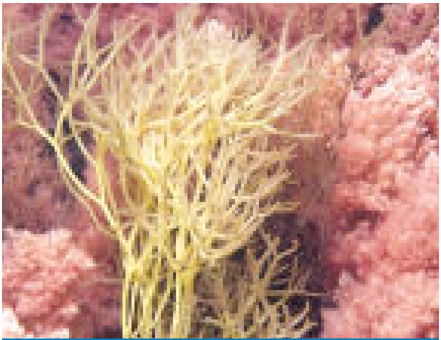
Rhodophyta are the dominant group within Moreton Bay including *Hypnea spp.*, *Gracilaria spp.*, *Laurencia spp.* and *Asparagopsis taxiformis*. Phaeophyta are the second most dominant group including *Dictyota spp.*, *Lobophora spp.*, *Padina spp.* and *Sargassum spp.* Chlorophyta, have the fewest number of species within the bay, dominated by *Caulerpa spp.*, *Udotea spp.* and *Ulva lactuca* (sea lettuce).

The total areal coverage of macroalgae is estimated at greater than 106 km^2 and includes a variety of substrates such as rocky outcrops, mangrove trunks and pneumatophores, seagrass beds or anchored in the sediment. Although this represents an areal coverage of 13% of the Bay, the contribution of macroalgae to the baywide nutrient pools was relatively minor.

Rocky outcrops at Redcliffe support the highest species diversity and biomass of macroalgae in the bay. The eastern Bay generally has a low species diversity and biomass due to low availability of suitable substrate. However, high species diversity can be found at Crab Island, a mangrove island which supports a large bird rookery. The combination of high substrate availability (mangrove pneumatophores) and elevated nutrient input (from birds) may contribute to high species diversity. Seasonal variations in macroalgae biomass were not observed at either site, Crab Island or Redcliffe.

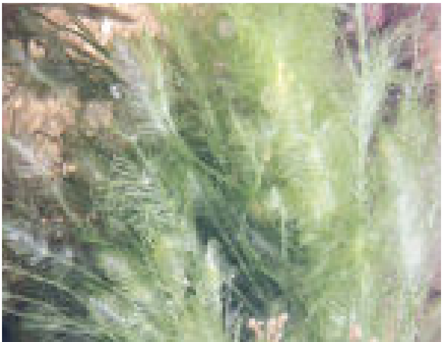
Brown macroalgae

CHRIS ROELFSEMA



Brown macroalgae penetrating through red macroalgae

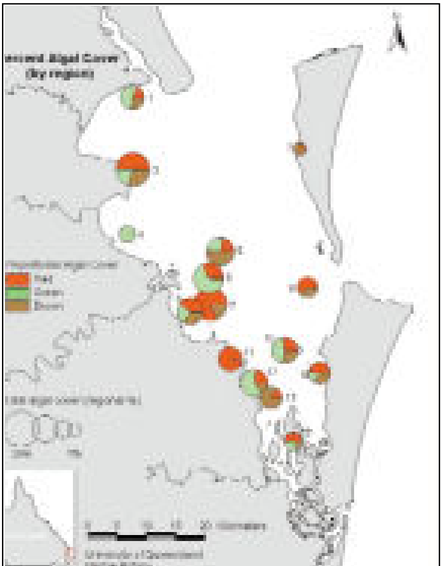
CHRIS ROELFSEMA



Green macroalgae with red macroalgae attached at the base.

CHRIS ROELFSEMA

Macroalgae on rocks, mangroves and seagrass



Macroalgae abundance and distribution map. The greatest abundance can be found at Redcliffe and Crab Island

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Macroalgae mat on mangrove pneumatophores.

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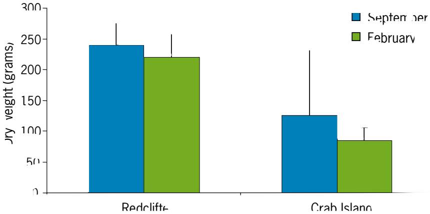
Diverse macroalgae community attached to rocky substrate.



Seasonal comparison of macroalgae biomass at 2 sites. No significant seasonal variation occurs at either site.

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Macroalgae on mangrove pneumatophores at Crab Island.

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Brown macroalgae.

Nuisance green macroalgae in Bay

Several locations in Moreton Bay have large populations of nuisance green macroalgae. *Caulerpa taxifolia* has been recorded in the Bay since 1946 (Cribb, A.B., Pap., 1958, Dep. Bot. Univ. Qld), however, expanding populations of this algae have recently become evident at One Mile Harbour, Adams Beach and Pelican Banks off North Stradbroke Island, and also at Redcliffe and Pumicestone Passsage. *Caulerpa taxifolia* occupies the same niche as seagrasses, and because of the expanding populations, they are frequently found competing with seagrasses for substrate and light availability. However, unlike seagrass, *Caulerpa spp.* are not a food source for dugongs and turtles and they have little or no root system to provide sediment stability. Their occupation and increasing distribution within this environment is therefore of concern and should be carefully monitored. *Ulva lactuca* (sea lettuce) blooms have also been identified in Bramble Bay at Hays Inlet. *Ulva lactuca* requires a rocky substrate and its growth is rapidly stimulated by elevated nutrients. Its proliferation is most likely a result of high nutrient loads, particularly from sewage inputs into Bramble Bay.

***Ulva* bloom in Bramble Bay**

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Northern Bramble Bay and Hays Inlet. Blooms of the nuisance green macroalgae *Ulva lactuca* occur here (as indicated)

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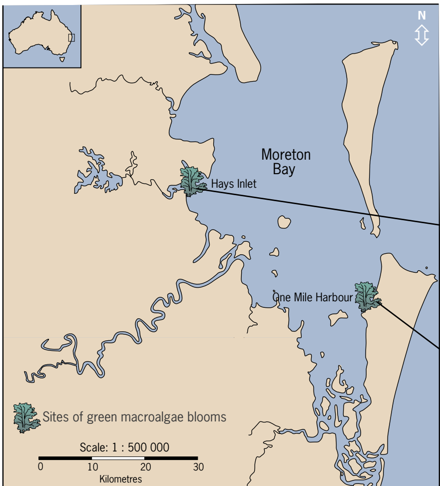
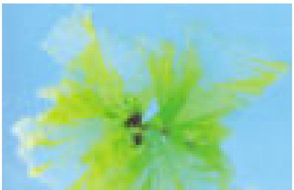
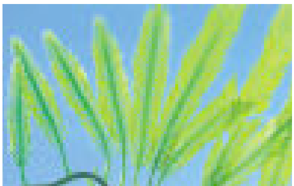


Sites of green macroalgae blooms at Hays Inlet and One Mile Harbour



Ulva lactuca



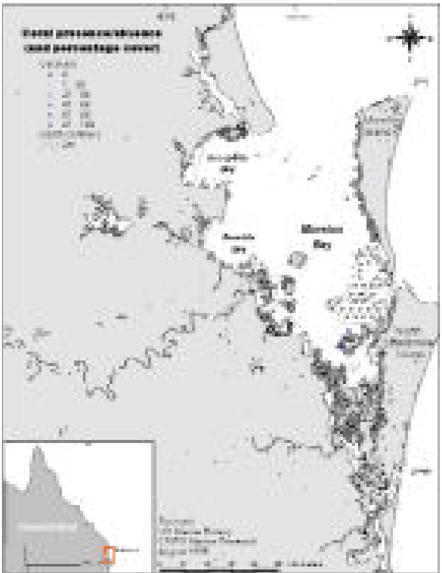
Caulerpa taxifolia

CRIBB, A.B., 1996 SEAWEEDS OF QUEENSLAND; A NATURALIST'S GUIDE

Unique coral assemblages

Corals are broadly distributed throughout Moreton Bay. They can be found on the mainland coast at Wellington Point and Cleveland, on the islands of Waterloo Bay (Peel, Mud, St Helena, Green and King Island), on Goat Island and at Myora off North Stradbroke Island. Most corals occur at depths less than 3 m, with their seaward limit determined by the extent of a hard substrate. They are often patchy and interspersed amongst seagrasses and sandy substrates.

Moreton Bay supports a unique assemblage of corals which represent a biogeographical overlap of tropical and sub-tropical species. Forty species are known to currently occur within the Bay. In general there is a gradient from a dominance of *Favia speciosa* (a massive coral) in the south west Bay to *Acropora digitifera* (a branching coral) in the north eastern Bay. *Alclonium sp.* is the dominant soft coral species in the south-west while *Xenia sp.* and *Sarcophyton sp* predominate in the north-east. The formation of artificial substrates at the Amity rock wall and Tangalooma Wrecks combined with near to oceanic water quality has allowed the establishment of the only live colony of *Pocillopora damicornis* in Moreton Bay (Johnson, P.R., and Neil, D.T., 1998, Moreton Bay and Catchment).



Coral distribution map. The greatest abundance of coral occurs at Myora, Peel Island and the bordering islands of Waterloo Bay.

Corals are strongly influenced by the stresses created by riverine discharge, more specifically, the associated sediments, nutrients and freshwater. In addition, Moreton Bay corals have been seriously impacted through dredging removal for lime making and boat anchor damage.

Flinders Reef, just north of Moreton Island, supports an unusually high diversity of coral with 119 species. As this reef is not exposed to the flooding and sedimentation events faced by the populations in the Bay, it is likely that this reef provides larvae for recruitment into Moreton Bay following catastrophic events (Johnson, P.R., and Neil, D.T., 1998, Moreton Bay and Catchment).

Coral reef - Moreton Bay

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Coral heads

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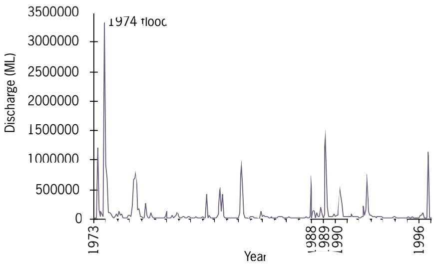
Historical record of floods from coral cores

There is difficulty in identifying environmental changes which have affected marine biota over time, with which to compare present measurements, owing to the lack of data. Corals are excellent historical archives as skeleton features represent environmental conditions at the time of deposition. This skeletal material can be accurately dated, and as corals are long lived, allows dating over extended periods.

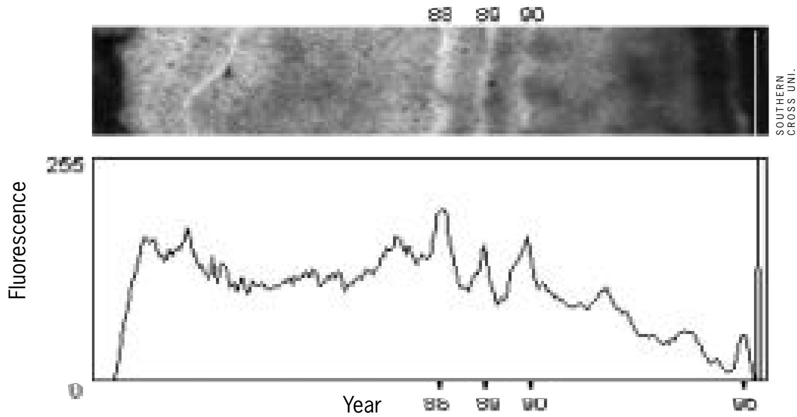
Coral cores are dated using annual banding techniques. This is a procedure similar to that of tree banding in which a pair of high density (summer growth) and low density (winter growth) bands are representative of a single years growth. With a known time of collection and a clear banding pattern, rings are counted from the outer coral core and bands are assigned in years.

Flourescence bandings, which are detected under UV light, provide information on environmental conditions at the time in which the coral skeleton was laid down, extended and thickened. In particular, bandings are affected by the inclusion of humics (black organic substances resulting from microbial decomposition), derived from river run-off. High fluorescence zones within a core can be correlated to the visible banding patterns in order to date an event.

Cores of *Psammacora superficialis* (a large, slow growing coral with a fine grained skeleton) from Moreton Bay were compared to known dates of local flood events. Banding patterns of this species were clearly evident and enabled dating where peaks of fluorescence occurred to the years 1988, 1989 and 1990. During these years, annual discharge from the Brisbane River peaked.

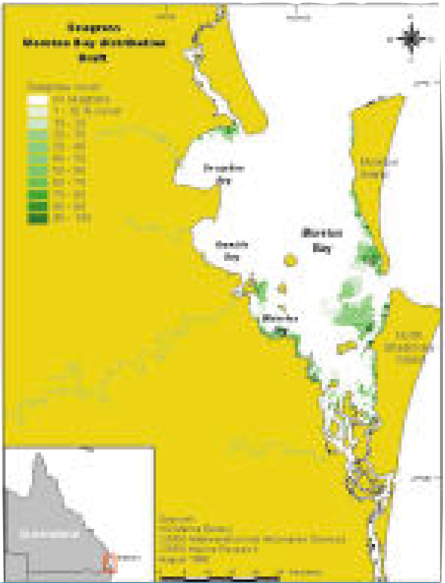


Annual discharge from the Brisbane River. Distinctive peaks of discharge occurred, including the years 1988, 1989 and 1990.

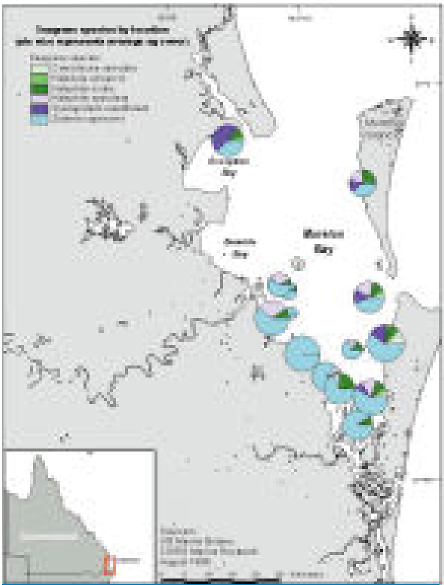


Fluorescence bandings on a coral core. Distinctive fluorescence peaks were recorded in the years 1988, 1989 and 1990 correlating to peaks of river discharge.

Seagrass supports dugong, sea turtle, prawns and fisheries



Seagrass coverage map. The greatest coverage occurs in eastern Bay, Waterloo Bay and northern Deception Bay.



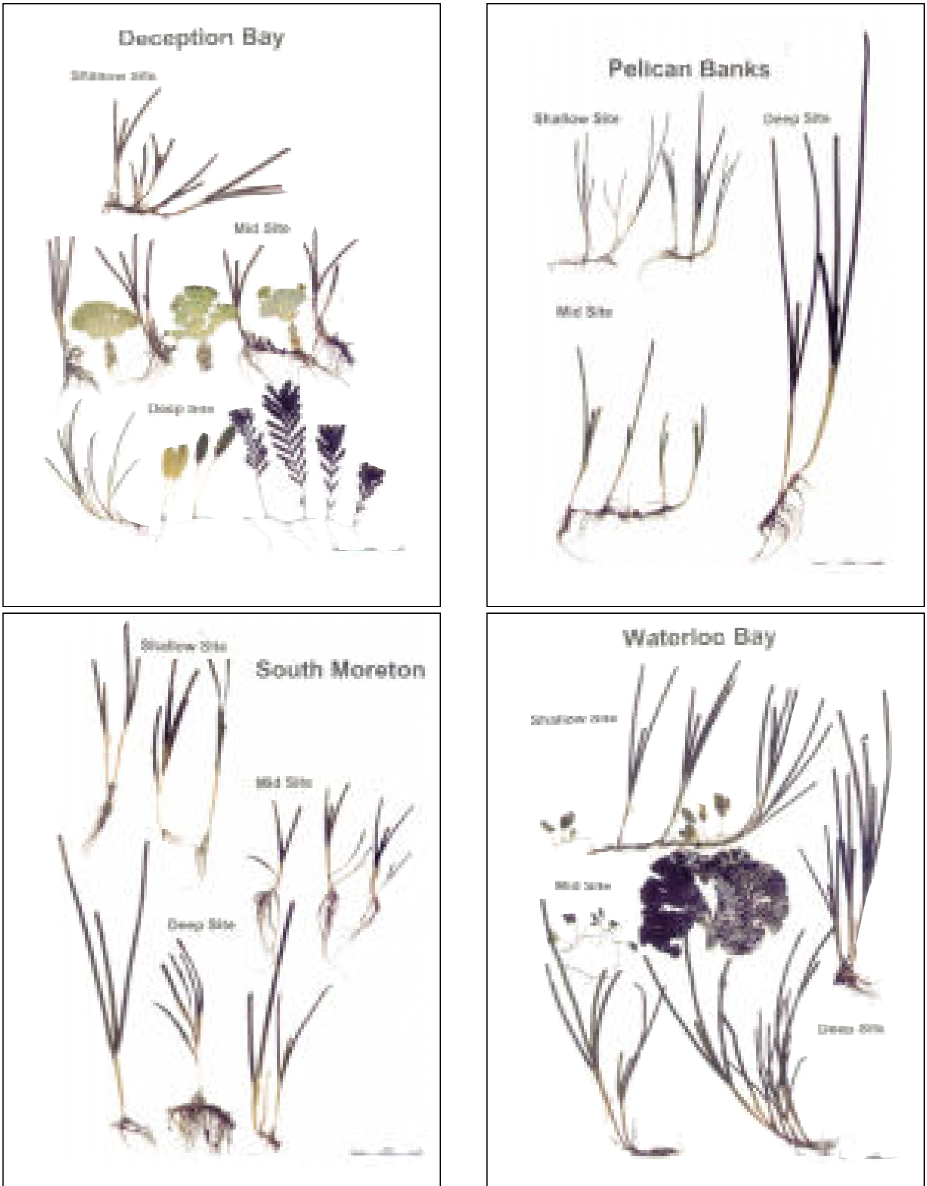
Seagrass species distribution map. The Bay is dominated by *Zostera capricorni* and the greatest diversity can be found in the eastern Bay.

Ecological role of seagrasses

- Habitats and nursery for commercially important marine organisms
- Food for dugongs and sea turtles
- Nutrient cycling and high nitrogen fixation
- Sediment trapping and stabilisation

Conceptual model depicting the ecological role of seagrass beds.

Variable seagrass communities



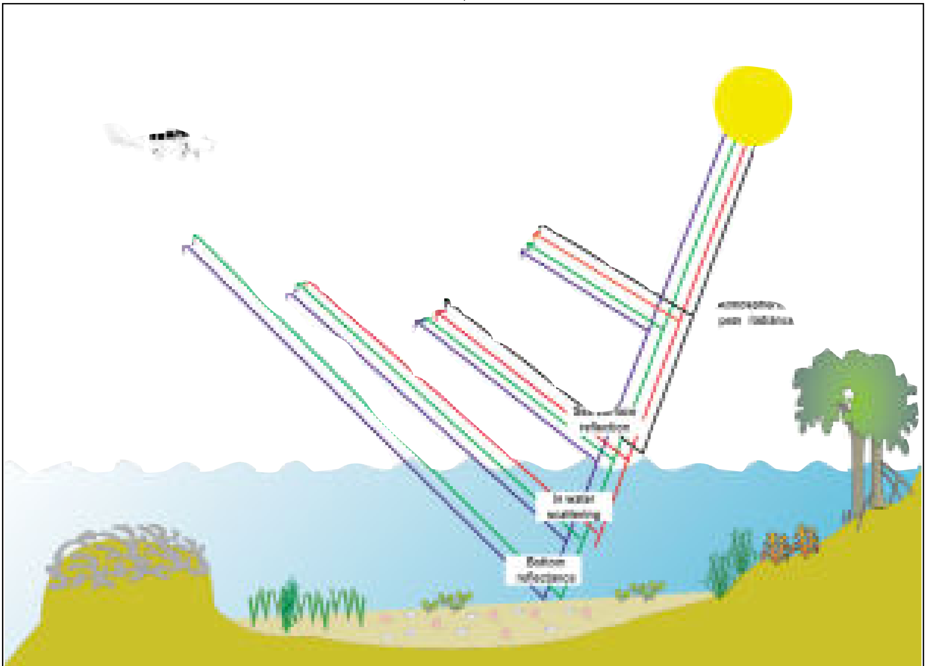
Pressed seagrasses (*Zostera capricorni*, *Halophila ovalis* and *Halophila spinulosa*) and macroalgae (*Udotea argentea* and *Lobophora variegata*) from 4 Moreton Bay sites. *Z. capricorni* remains dominant although morphology and diversity varies with site and depth.

Seagrass distribution patterns distinguished by remote sensing

Marine substrate and vegetation (e.g. seagrasses) reflect light emitted from the sun, which is composed of different wavelengths. Reflection patterns of the wavelengths depend on the absorption and scattering properties of the atmosphere, water and the type of substrate or vegetation. This results in a distinctive spectral signature characteristic for the substrate being examined.

Remote sensing the marine environment, from sensors mounted on aeroplanes or from satellites, detects a spectral signature for the substrate. The signature detected by the sensors is presented as an image for the range of substrates or vegetation types in the field of view. As the spectral signature for the substrate types are initially determined on the ground, analysis of the image enables characterisation of the substrate or vegetation type.

The result of remote sensing is an image which enables mapping of the spatial distributions of, for example, seagrasses. While ground work and manually obtained biomass values provide valuable information on small scale fluctuations, remote sensing provides the opportunity to rapidly obtain information over large areas. This may be of particular advantage in areas which are difficult to access.



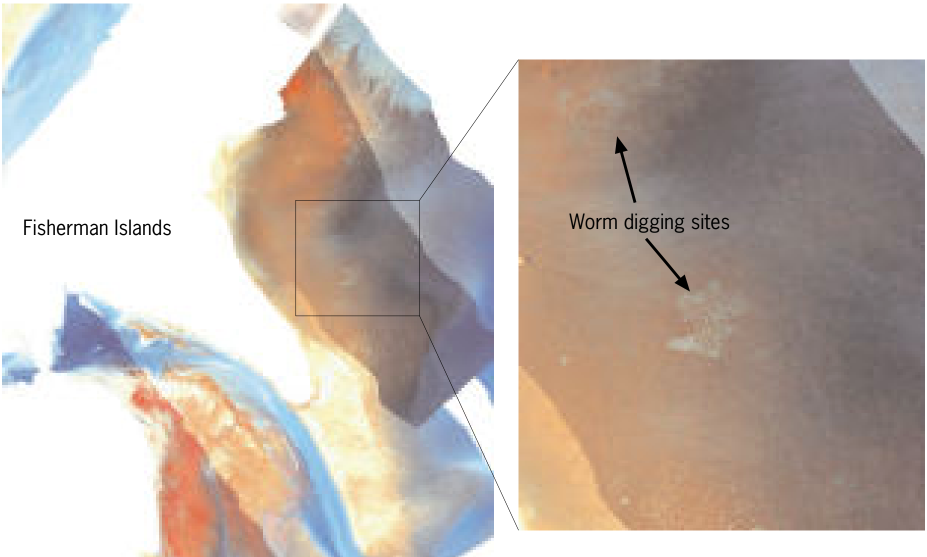
Theory behind the remote sensing technique. Light emitted from the sun is selectively absorbed by the atmosphere, water surface, water column and bottom substrate (sediment, seagrass, benthic algae, corals and mangroves

Worm digging disrupts seagrass

Commercial worm digging, operating under license conditions, occur in some seagrass beds located on the western side of Moreton Bay. Images produced from remote sensing of the region to the south of Fisherman Islands indicate areas where seagrass beds have been physically disrupted. Bare patches are clearly seen as a matrix of squares plots which result from worm digging on these shallow flats. The areal coverage of these patches can be readily determined from the images. Recovery of the seagrass beds in worm digging sites depends on the species present, existing environmental conditions and the extent of the disturbance. Recovery of the habitat can be monitored using the remote sensing technique.

ENVIRONMENTAL PROTECTION AGENCY

Digging for worms at Fisherman Islands



Remote sensing images (CASI - Hyperspectral sensor) taken of Fisherman Islands and the surrounding seagrass banks. A matrix of patches are visible where digging for worms occurs.

Moreton Bay Biota

Intensive cultivation grazing by dugongs

Dugongs are the only strictly marine mammal herbivore and are almost entirely dependant on seagrass as a food source. Small successional species are favoured (e.g. *Halophila ovalis* and *Halodule uninervis*) as they have low fibre content and high nutrient content. In the sediment, associated with the roots of these species, there are nitrogen fixing bacteria which convert biologically unavailable nitrogen (N) gas into the biologically usable form, NH_3. The seagrasses exude carbon compounds which increase the source of energy substrates for heterotrophic bacteria which fix N in the sediments. They also leak gas through their roots providing the oxygen required by bacteria for metabolism of the carbon compounds. The result of this is an energy source provided to the bacteria to stimulate N fixation. This is a mutually beneficial relationship as bacterial and seagrass productivity are promoted by the other.

The destructive nature of the grazing habits of dugongs leads to an increase in the availability of organic matter and provides added aeration for bacterial metabolism of the organics within the sediment. As a consequence, N fixation rates are stimulated, increasing the availability of nutrients for re-colonisation of the fast growing pioneer seagrass species. Later successional stage climax species (e.g. *Cymodocea serrulata*) are prevented from colonisation as continued grazing pressure promotes the presence of fast growing, colonising species (i.e. *H.ovalis* and *H. uninervis*). Cultivation grazing is a term which describes this process whereby growth of early successional stages is stimulated by grazing and climax species are prevented from establishing, therefore dugong food species are maintained.

An ungrazed *Cymodocea serrulata* seagrass bed. Ungrazed seagrass develop a dense leaf canopy.

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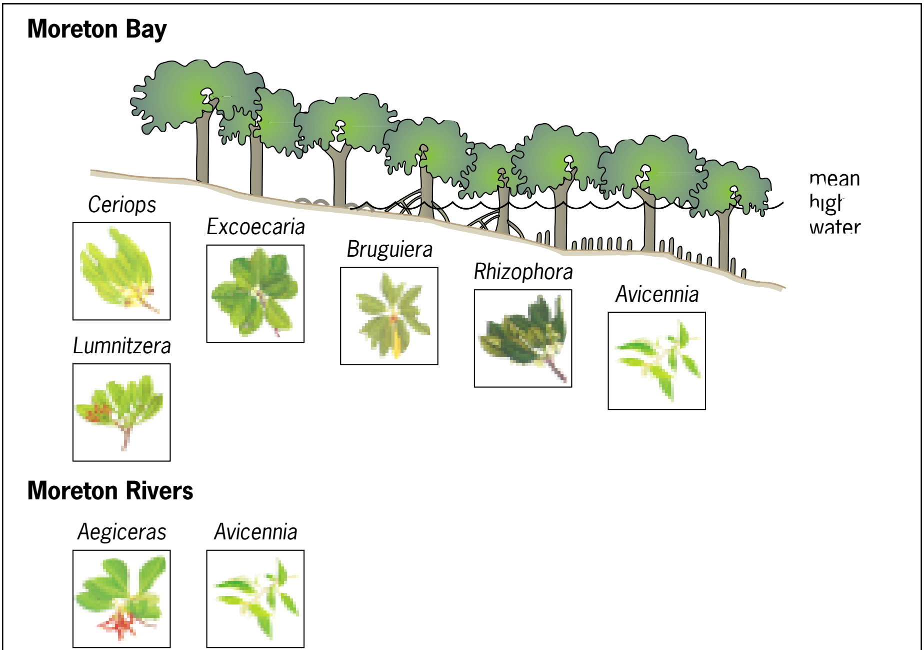
Dugong grazing trail in a *Halophila ovalis* seagrass bed. Grazing removes most seagrass biomass within the feeding trail.

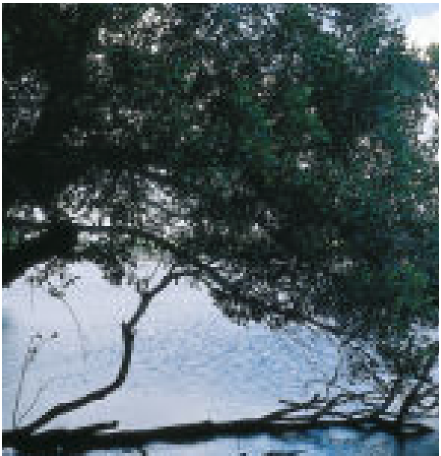
CHRIS ROELFSEMA

Mangrove communities dominated by grey mangrove



Theoretical mangrove species' depth distribution. Species are variably tolerant to tidal submersion and only two Moreton Bay species can be found in the rivers. (Abal, E.G., et al, 1998, Moreton Bay and Catchment)

LOVELOCK 1993



***Avicennia marina*: grey mangrove**

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***Avicennia marina* fruits.**

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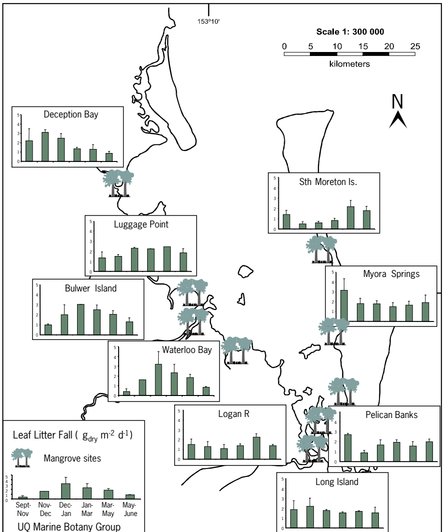
Ecological role of mangroves

- Protection of coastlines
- Sediment trapping
- Habitat for commercially important species
- Nutrient cycling

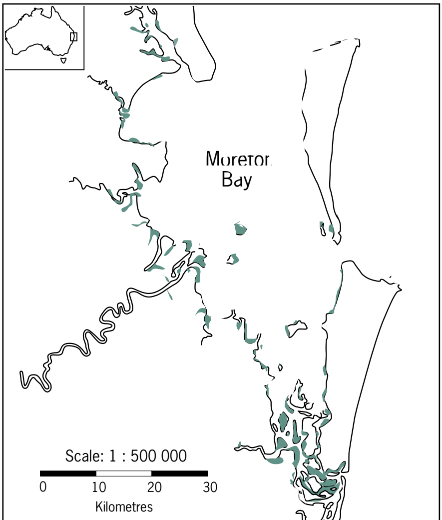
Mangroves (and salt marshes) throughout river estuaries and Bay

There are extensive mangrove forests throughout Moreton Bay but particularly in the southern Bay where diversity and extent are greatest. Thin stands of mangrove forests can still be found along the banks of many of the rivers. Although it has been suggested that mangroves penetrate further up the river now than in the past, historical records show presence of *Avicennia marina* in the upper reaches of the Brisbane River early this century.

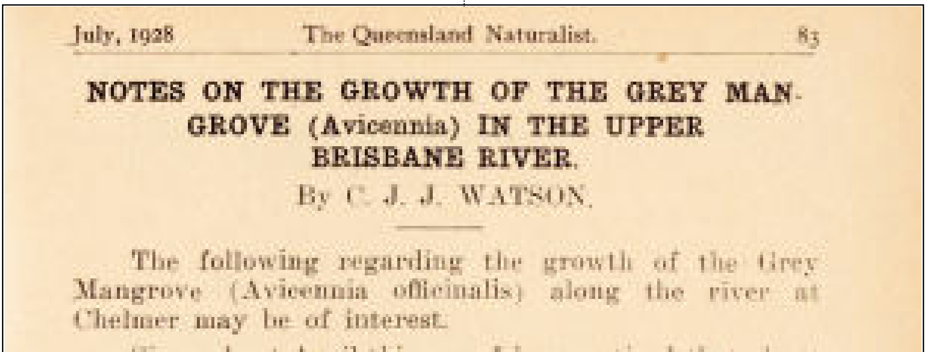
Leaf litter fall was measured at nine sites throughout the Bay and at the mouths of several rivers. No difference between sites in terms of average leaf litter fall was observed (which is often used as an estimate of productivity) over the nine month sampling period.



Mangrove leaf litter fall. There was no consistent seasonal or site variation in the rate of leaf loss.



Mangrove distribution map. The southern region of the Bay has the most extensive and varied mangrove forests.


July, 1928 The Queensland Naturalist. 83

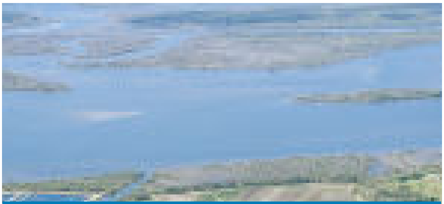
NOTES ON THE GROWTH OF THE GREY MANGROVE (Avicennia) IN THE UPPER BRISBANE RIVER.

By C. J. J. WATSON.

The following regarding the growth of the Grey Mangrove (Avicennia officinalis) along the river at Chelmer may be of interest.

Historical documentation of mangrove extension into Brisbane River. *Avicennia marina* has extended into upper reaches of river since at least 1928 (Watson, C.J.J., 1928, The Qld Naturalist).

Mangroves: nursery and habitat



Aerial view of the hail damaged sites. Defoliation led to a loss of habitat for fish species.

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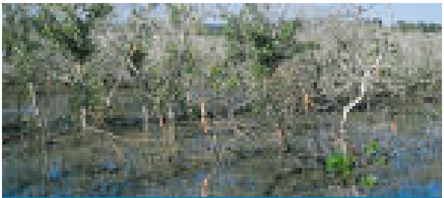
Mangrove forests are recognised worldwide as an important habitat and a nursery area particularly for juvenile fish, crabs and prawns. It has been suggested that the use of mangrove forests by these animals is based predominantly on two ecosystem functions. Firstly, mangrove detritus is an important food source and second, the structural complexity of pneumatophores and fallen branches and the shading provided by overhead foliage reduces the risk of predation thus favouring juveniles. To date, there is limited understanding of the specific contribution by mangrove forests in terms of food provision and predator protection in accommodating the various taxa found in mangrove forests.



Damage to southern Moreton Bay mangroves. Most species struck have limited and slow capacity for recovery.

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A unique opportunity to examine the ecological role of mangroves occurred when a hail storm swept through southern Moreton Bay in September of 1997 resulting in complete defoliation of the mangrove forests in its direct path. Either side of the swathe, trees experienced some level of defoliation and damage. *Avicennia marina* may recover through lateral sprouting, however, this region is dominated by other species. Therefore, little recovery of the canopy occurred over the following months. This natural event provided a unique opportunity to assess the importance of overhead foliage (shading) and the detrital-based food web to the use of mangrove forests by crabs and fish.

Hail damage to southern Moreton Bay mangroves. Only *Avicennia marina* trees recovered.

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Pink mangrove lobster. Mangroves are an important habitat for many faunal species

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Surveys of the areal extent, degree of damage to trees and the influence this had on crab and fish populations were carried out approximately 6 months after the hail storm. Crab activity, measured as rates of leaf removal from the sediment were similar at control and hail damaged sites, a surprising finding given that Sesarmid crabs rely largely on mangrove leaves as a food source. The number of juvenile fish, however, was significantly lower at damaged sites and this was not related to physical (e.g. temperature and salinity) or chemical (e.g. sediment exchangeable ammonium or phosphate availability) factors. Instead, this suggests that protection provided by the shading effects of foliage is an important factor in the use of the mangroves by fish. However, the remaining structural complexity may have provided protection for feeding fish.

Fauna

Diverse assemblages: not an emphasis in the study

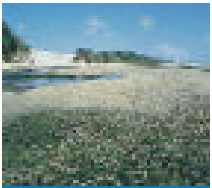
Moreton Bay supports diverse fauna of economic and ecological importance. Examination of all of these groups and their ecological role was beyond the scope of this study but is covered elsewhere (refer to further reading list).

Many infaunal groups are important for nutrient recycling processes within the sediment and water column and between these substrates. Animal burrowing, predominantly by marine worms, rework sediments providing a means for permeation of oxygen rich water (bioirrigation), facilitating nitrification and subsequently, denitrification. The contribution of bioirrigation to sediment and water column exchange was inferred in this study from conservative tracer studies (radon flux) indicating that the greatest bioirrigation occurs in the sewage impacted muds on the western side of the Bay. Dugongs also play an important role in the nutrient cycling processes of seagrass beds particularly in the nitrogen (N) cycle where 'cultivation grazing' stimulates N fixation (previous section, this chapter).

Invertebrate and fish community distribution in the Bay reveals three 'hot-spots' of diversity. The first of these radiates from the mouth of the Brisbane River, the second occurs at the northern end of North Stradbroke Island and the third at Tangalooma and Middle Banks on Moreton island. A shift of community composition from western to eastern Bay, manifests as an increasing presence of cleaner water reef species (Davie, J.F., Hooper, N.A., 1998, Moreton Bay and Catchment).

Dugong mother and calf in Moreton Bay. Large seagrass banks in the eastern Bay are an important food source for dugongs.

ENVIRONMENTAL PROTECTION AGENCY



Soldier crabs on tidal seagrass flats, North Stradbroke Island.

ENVIRONMENTAL PROTECTION AGENCY

There are two species of sea turtle in Moreton Bay, the green turtle (*Chelonia mydas*) and the loggerhead turtle (*Caretta caretta*). Early to mid this century the green turtle population experienced drastic declines resulting from capture of females for canned turtle soup. Although they have recovered, the turtles are again under threat from entanglement incidents and boat kills. In addition, declining water quality has been linked with the increasing number of incidents of fibropapilomas (external cancerous growth) (Limpus, C.L., et al, 1994, Memoirs of the Queensland Museum, 6).

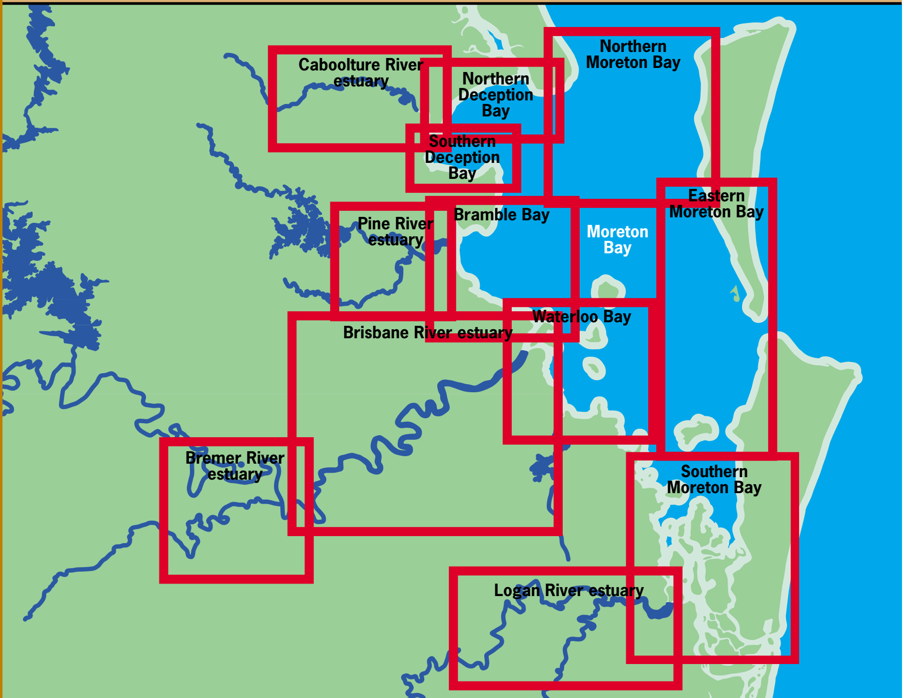
There are two species of dolphin found in the Bay. The rare Indo-Pacific humpback dolphin (*Sousa chinensis*) inhabits the more turbid and sheltered waters within close proximity to mangrove forests and within river estuaries. Although some habitat overlap may occur, the common bottlenose dolphin (*Tursiops truncatus*) generally inhabits the oceanic waters of the eastern bay. Dolphins are also under threat from accidental capture and decline in prey via habitat loss and overfishing. This is of particular concern for the rare humpback dolphin. (Hale, P., et al., 1998, Moreton Bay and Catchment).

Moreton Bay's largest marine mammal, the humpback whale, occasionally visits the Bay during migration between Hervey Bay and Antarctica for breeding and birth. It is believed that these animals play very little role in the ecology of the Bay, owing to the infrequency of their visits.

Next section ▶

CHAPTER 14

Functional Zones



- Overall conceptual model

River estuaries: moderately to highly impacted

- Caboolture River estuary
- Pine River estuary
- Logan River estuary
- Brisbane River estuary
- Bremer River estuary

Moreton Bay: highly impacted to relatively pristine

- Northern Deception Bay
- Southern Deception Bay
- Bramble Bay
- Waterloo Bay
- Southern Moreton Bay
- Eastern Moreton Bay
- Northern Moreton Bay

Moreton Bay and river estuaries

- Functional zones defined

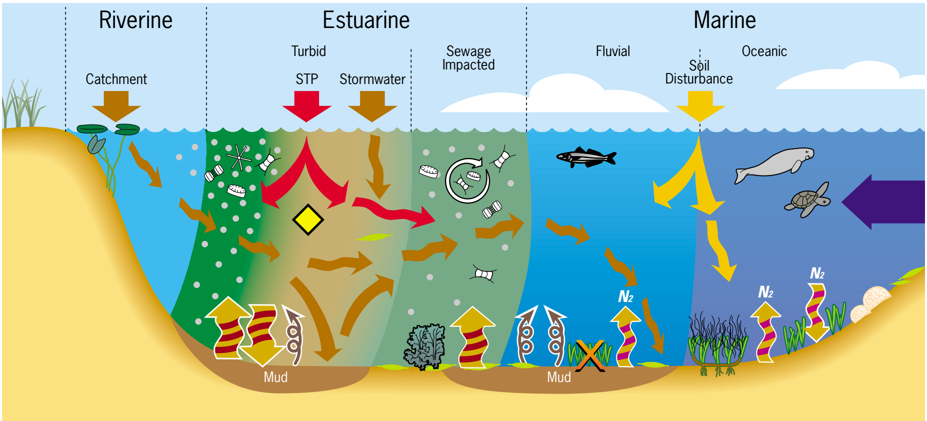
Overall conceptual model

Strong gradients in processes, functional zones and habitat occur in the Moreton region as a result of the inputs of sediments, nutrients and toxicants. The major impacted areas are the river estuaries, especially the Brisbane and Bremer Rivers and the western embayments, especially Bramble Bay. Strong tidal flushing maintains healthy ecosystems near the ocean inlets. The overall conceptual model for Moreton Bay and its river estuaries developed at the beginning of the Study has been updated (refer to Chapter 2). The various processes and impacts depicted on the conceptual model are based on results of the Stage 2 scientific studies. Generation of additional data has provided the information required to improve our understanding of the waterways. The revised conceptual model illustrates:

- the different sources and fates of nutrients and sediments
- the significance of nitrogen as a major limiting nutrient
- the predominance of benthic and pelagic processes in different regions of the bay and river estuaries.

Nutrient and Sediment Origins

Nutrients and sediments enter the waterways from various sources, including sewage, stormwater and catchment runoff. Nutrients from sewage treatment plant effluent affects the tidal estuaries and confined zones in Moreton Bay. The fluvial nutrient region of the marine zone consists of the mud patch of the Bay which corresponds to the area with the highest nutrients (nitrogen, phosphorus, carbon). Peak flood events (1 in 20+ year events) carry sediments either directly from the upper catchments or from scouring of the sediments deposited in the upper estuary during low flow events. The resuspension of fluvial muds through wave or tidal action reduces light penetration, and nutrient fluxes from the sediment contribute significant amounts of nutrients to the overlying water



Conceptual model for Moreton region depicting the major processes and impacts on the riverine estuarine and marine sections. Refer to symbol glossary for definition of process, input, and biota samples

column. The oceanic region of the marine zone is not affected by nutrients from sewage plumes.

Nitrogen as the Major Limiting Nutrient

Phytoplankton bioassays, macroalgal deployment and seagrass fertilisation experiments revealed that nitrogen (N) additions stimulated growth and/or changes in tissue N concentration. These results indicate that N is the limiting nutrient in the study area. However, limitation of plant growth by other factors, for example light in the turbid tidal estuaries, may suggest the reduced biomass and growth in regions where nutrient concentrations (particularly N) are high, for example low phytoplankton biomass in the tidal estuaries.

Pelagic versus Benthic Dominated Processes

The distributions of seagrass and phytoplankton communities are largely determined by suspended sediment and nutrient concentrations in the water column. In regions where light penetration is reduced, and sewage nutrient discharge predominates, pelagic processes dominate (e.g. estuarine regions). Here, through strong tidal currents and subsequent sediment resuspension, light penetration to the benthos is limited, while point source discharges provide biologically available nutrients for water column phytoplankton and bacteria.

In waters with high light penetration and low water column nutrient concentrations, benthic processes dominate (e.g. oceanic marine zone). In this clear water zone, nitrogen produced through nitrogen fixation supports seagrasses and their grazers: sea turtles and dugongs.

The Moreton Bay catchment is a diverse and complex system. Processes, impacts and habitats are not uniform throughout the entire system. Conceptual models recognise the existence of functional zones. Functional zones partition the catchment into regions that are homogenous in key processes, anthropogenic impacts and critical habitats. Physical/chemical water quality parameters are key factors that drive biological system responses.

What is a Conceptual Model?

Conceptual models depict the major environmental features and the community-based environmental values. Conceptual models attempt to encapsulate the most current understanding of a particular ecosystem or location. As more information is obtained and interpreted, and community-derived environmental values are refined and changed, the conceptual model evolves to encapsulate this new understanding and perspective. Conceptual models can be used to

a) communicate the key inputs and processes, impacts and biotic features;

b) prioritise future strategy, research and monitoring efforts; and

c) synthesise divergent results into a single depiction.

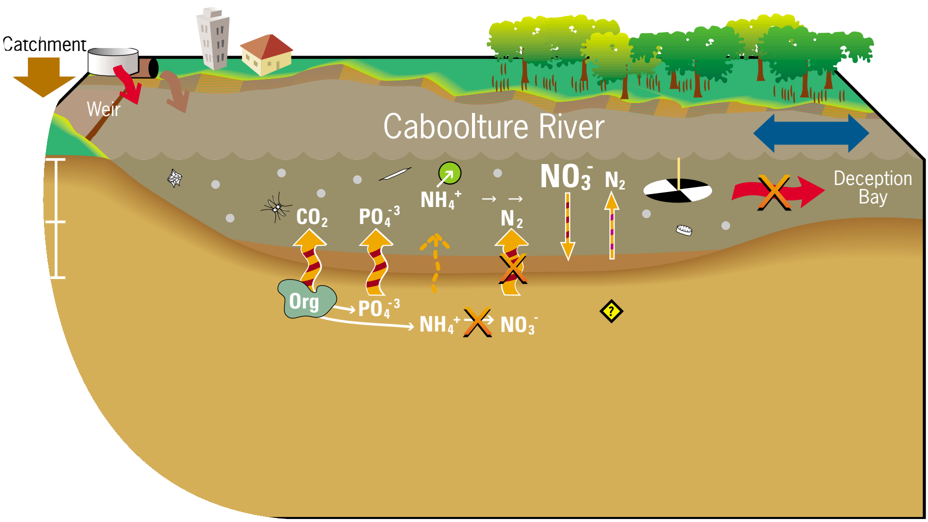
River estuaries: moderately to highly impacted

Caboolture River estuary

- **Nutrient and sediment loads from forestry, agricultural and urban areas**
- **Algal blooms, high nutrients; poor riparian vegetation in lower catchments**
- **Some extent of nutrient processing in the river, no sewage nitrogen impact on Deception Bay**
- **Low and surficial denitrification; possible nutrient fluxes from sediments**

The catchment of the Caboolture River estuary was historically dominated by rural activities and has more recently experienced rapid growth of the urban population. These activities generate stormwater, sewage and catchment runoff predominantly to the upstream reaches of the river. Riparian vegetation has been largely cleared along the river length except near the mouth where mangrove forests remain, reducing the potential for incorporation of these byproducts prior to discharge at the mouth.

Mixing plot results indicated that there is some nutrient processing occurring within the Caboolture River estuary. This may be attributed to the occurrence of denitrification on the sediment surface. The upgrading of the Caboolture Sewage Treatment Plant to Biological Nutrient Removal technology has reduced impacts as well. However, elevated total nitrogen and dissolved inorganic nitrogen concentrations were measured within the estuary and western Deception Bay, indicating nitrogen inputs from other sources, probably non-point sources. The river estuary maintains a diverse phytoplankton community, sometimes exhibiting blooms. This



Refer to Symbol Glossary for definition of process, input, and biota symbols.

Agriculture in the Caboolture River catchment

ENVIRONMENTAL PROTECTION AGENCY

phytoplankton population may also contribute significantly to instream processing of nutrients. Reduction of sewage nutrients from the STP and its placement upstream enables sufficient instream processing that sewage nitrogen becomes of reduced consequence in the lower reaches. Further monitoring is required to gauge the relative contribution of increased loads of nutrients from urbanisation and stormwater and management actions to reduce their impacts.

A sand bar at the mouth of Caboolture River reduces the impacts of tidal energy, however, the estuary remains somewhat turbid. Turbidity is maintained by resuspension of sediments from the river bed leading to an average secchi depth of 0.75 m throughout the river.

Caboolture River

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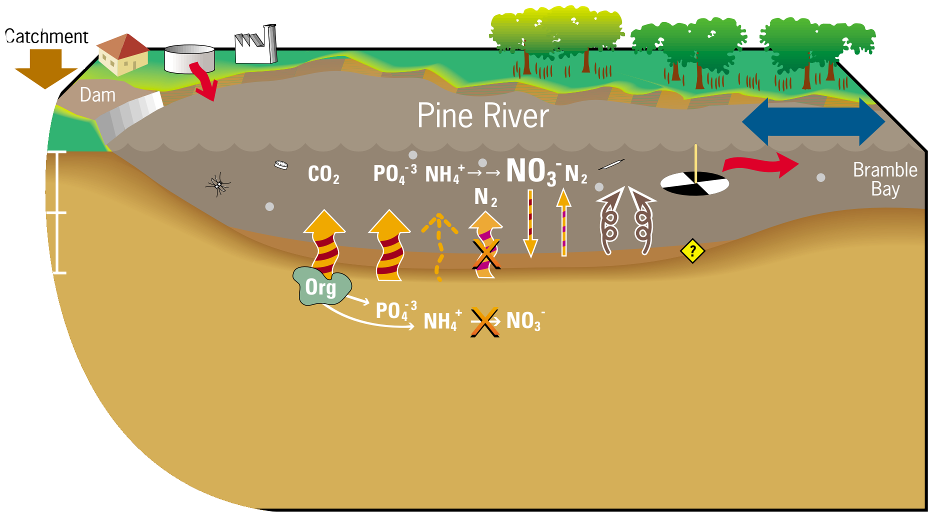
River estuaries: moderately to highly impacted

Pine River estuary

- **Urbanised and industrial catchment; highly degraded**
- **Water column nutrient concentrations high; highly turbid system**
- **Denitrification in sediments blocked; some surficial denitrification**
- **Ammonium possibly leaching to water column**
- **Low phytoplankton diversity; high productivity**

Pine River (comprised of North and South Pine Rivers) flows into Bramble Bay and is characterised by having a small urbanised and industrial catchment with two water supply storages (North Pine Dam and Lake Kurwongbah). The upper catchment receives high levels of nutrients from agriculture, forestry and sewage effluent, sediments from new residential developments and agriculture. Runoff from upper subcatchment areas are captured by the dams, which occasionally experience blue green algal blooms.

Inputs to waterways and water quality in the lower subcatchment are mostly dominated by treated effluent discharges and urban stormwater disposal. Some parts of the river, particularly those close to the mouth, are highly degraded, contributing significant sewage and stormwater inputs into Bramble Bay. Water column nutrient concentrations in the estuary are high. These high water column nutrients result in high phytoplankton productivity (indicated by high chlorophyll levels), and low phytoplankton diversity (phytoplankton community may be dominated by species which can adapt to the poor water quality). The estuary experiences resuspension of sediments and is highly turbid, with an average secchi depth of 0.5 m.



Refer to Symbol Glossary for definition of process, input, and biota symbols.

Mixing plot results indicate that there is no net nitrogen loss or nutrient processing in the Pine River estuary. Nutrients (point sources and non-point sources) are discharged directly and essentially unchanged into Bramble Bay. Some surficial denitrification (on the sediment surface) may be occurring, but there may be significant ammonium flux from the sediments to the water column. No toxicant sampling has been conducted in Pine River, and hence, the presence of toxicants either in the sediments, water column or biota is not confirmed.

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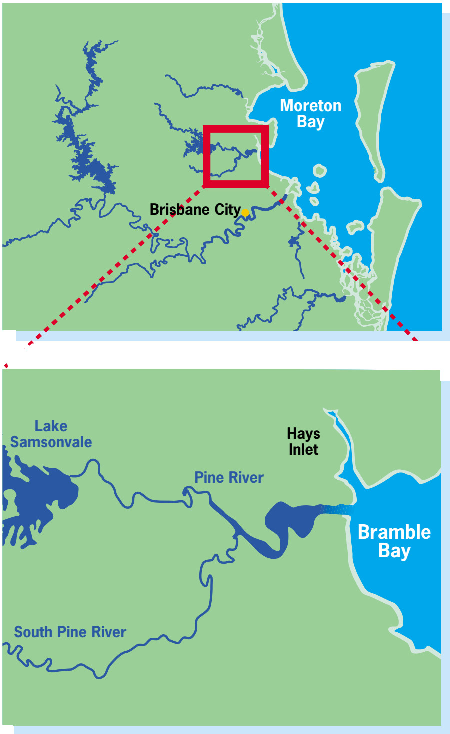
Pine River



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Pine River

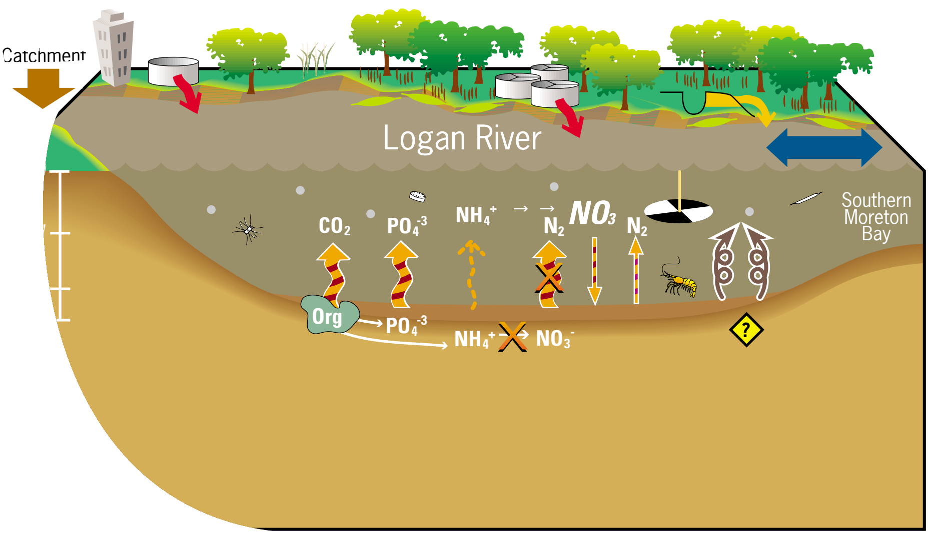
River estuaries: moderately to highly impacted

Logan River estuary

- **Urban and agriculture dominate catchment inputs**
- **Prawn farm effluent and acid-sulfate soil run-off at mouth**
- **Denitrification in the sediment blocked; surficial denitrification**
- **Medium diversity and productivity of phytoplankton**
- **Mangroves intact in regions of the river; seagrass recovery near the river mouth**

Although point and non point source inputs into the Logan River are lower compared to the Brisbane and Pine Rivers, there is nonetheless a diversity of sources. Urban (stormwater and sewage) and agricultural inputs dominate the upper and middle reaches of the river, while effluent from aquaculture farms and runoff from exposed acid-sulfate soils predominate near the mouth. Only a very small plume was detected from the Logan River into southern Moreton Bay.

Water column nutrient concentrations are generally high upstream, however, all nutrients show a trend of decreasing concentrations to the river mouth. Non-conservative mixing plots suggest that some in-stream processing occurs in the river. Surficial (on the sediment surface) denitrification may be occurring, although, as in the other river estuaries, over-all denitrification efficiency is likely to be low. This contributes to the high nitrate concentrations in the water column. Turbidity is high throughout the river, with average secchi depths of 0.75 m, resulting in moderate diversity and productivity of phytoplankton. Mangrove forests are still



Refer to Symbol Glossary for definition of process, input, and biota symbols.

largely intact along the river banks and there are extensive forests at the river mouth. Seagrass beds which disappeared at the mouth of the Logan River approximately 5 years ago have shown recovery near the river mouth in the past year.

Aquaculture along the Logan River

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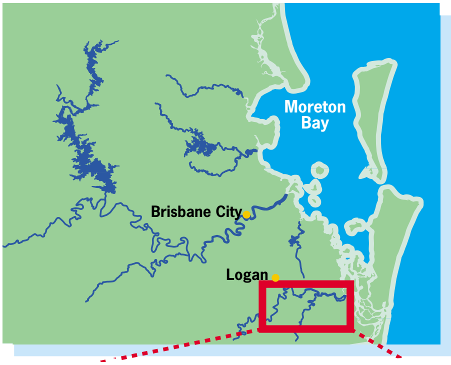

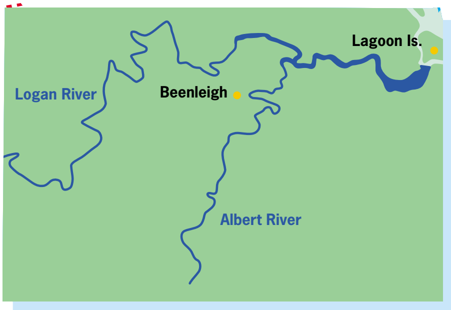

Logan River

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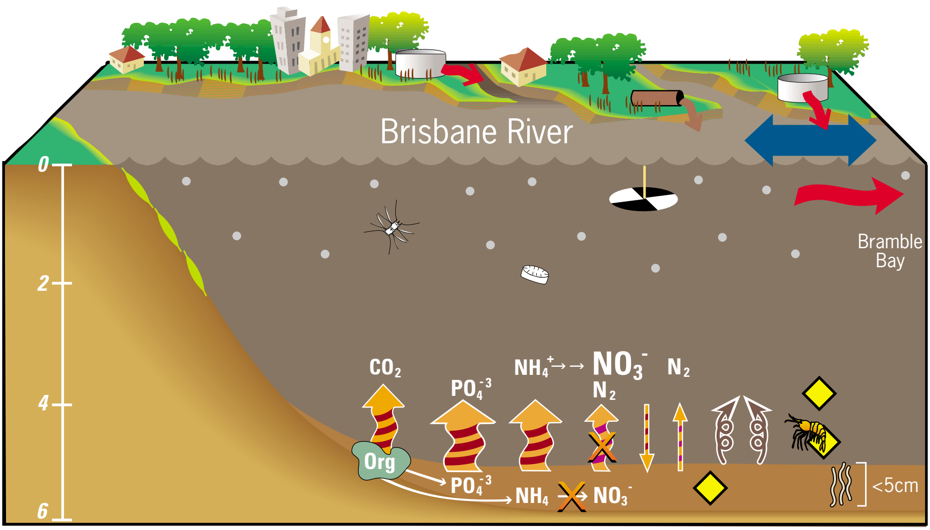
River estuaries: moderately to highly impacted

Brisbane River estuary

- **High sediment and nutrient loads from sewage and non-point sources**
- **Extensive riparian vegetation clearance especially in the lower reaches**
- **Benthic microalgae growing on riverbanks; low phytoplankton abundance and species diversity**
- **Surficial denitrification fuelled by high nitrate fluxes from the water column into the sediments; over-all denitrification rates low**
- **Large phosphorus fluxes from sediments to overlying water**

The Brisbane River catchment is by far the most developed in the Moreton region. Agriculture predominates in the upper reaches, high-density urban regions are found in the middle reaches and industrial and port developments dominate the lower reaches and the river mouth. Such catchment land use affects the over-all water quality in the Brisbane River estuary.

The two largest sewage treatment plants (STPs) in the entire study region are located at Oxley Creek (32 km upstream from the mouth) and Luggage Point at the mouth of the river. Together these STPs service over 1 million people. Consequently, significant volumes of sewage are discharged into the Brisbane River estuary which, in combination with stormwater inputs and agriculture run-off, lead to extremely high nutrient concentrations. Only surficial (on the sediment surface) denitrification occurs in the estuary, hence the over-all denitrification is not very significant. The sediments for the Brisbane River are a sink of oxidised nitrogen. Very high nitrate concentrations in the water



Refer to Symbol Glossary for definition of process, input, and biota symbols.

The Brisbane River winds through the city in its lower reaches

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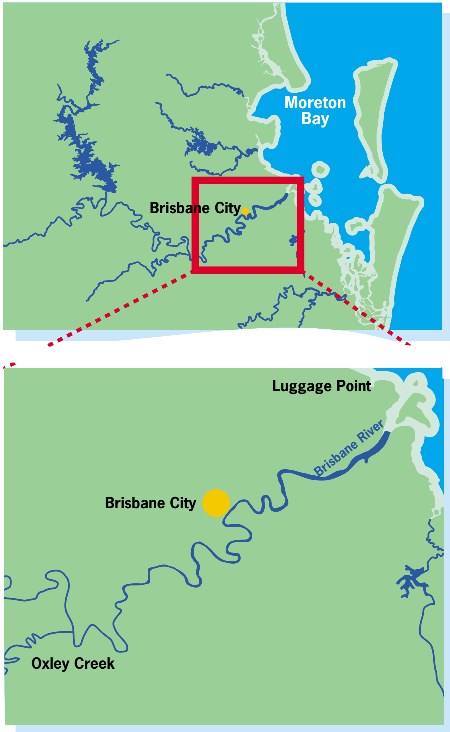


column stimulates sedimentary denitrification only in the sediment layers, so over-all, there is very little coupling of sedimentary nitrification with denitrification in the deeper sediment layers. The sediments are a source of ammonium (NH_4^+) to the water column. There are also large fluxes of phosphorus from the sediments to the overlying waters.

Removal of the sand bar in the mouth of the Brisbane River for navigational purposes and navigational dredging in its lower reaches have increased the extent of tidal energy which has pushed the tidal limit to 90 km upstream. A turbidity maximum is tidally induced and occurs approximately 50 km upstream. The cause of the high turbidity in the river is a complex interplay of an increased sediment supply to the estuary and changed hydrodynamic and morphological processes (tidal velocities, flushing times, sediment trapping capacity) such that a large volume of sediment now remains in suspension. Due to the very high turbidity (0.25 m secchi depth), particularly in the middle reaches of the estuary, there is very low phytoplankton abundance, productivity and diversity in the river. The phytoplankton community is severely light-limited. Mangrove forests are found in the muddy banks of the lower and middle reaches of the river, and these muddy banks are also coated with benthic microalgae.

Toxicants in the sediments, water column and biota were relatively high in Brisbane River compared to Moreton Bay. Dieldrin, exceeded the ANZECC maximum levels in Breakfast Creek. Toxicant levels in the biota however, did not exceed guidelines for human consumption.

The Brisbane River mouth.

HEALTHY WATERWAYS LIBRARY

River estuaries: moderately to highly impacted

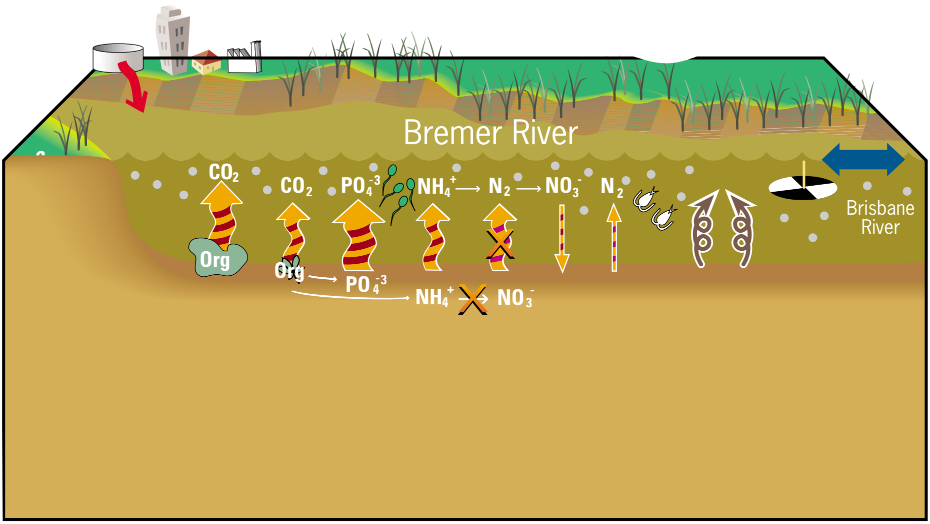
Bremer River estuary

- **Extremely degraded system**
- **High inorganic and organic nutrient loadings**
- **High heterotrophic bacteria**
- **Low phytoplankton production dominated by flagellates**
- **Long water residence times**

The Bremer River estuary is extremely degraded and the overall ecological health is very poor. The riparian vegetation has been mostly cleared, and the river banks are predominantly weed- infested. Stormwater and sewage inputs predominate in the urban areas around Ipswich. In the lower reaches, there is a diversity of nutrient and sediment sources, including runoff from farming activities, sewage discharge and abattoir effluent. These point sources and diffuse inputs to the system result in very high water column nutrient concentrations, particularly nitrate (NO_3^-). High nutrient loading is enhanced by long water residence times resulting from the low flow energy in these upper reaches. High turbidity results in secchi depths of less than 0.5 m.

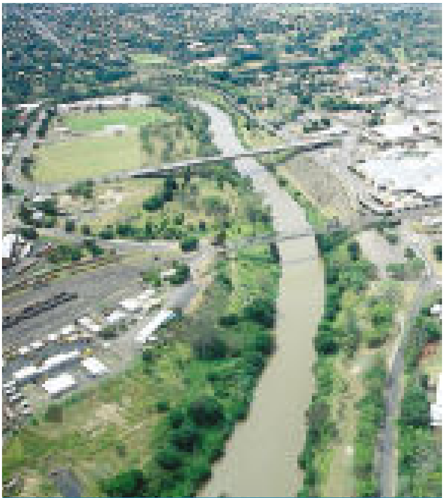
High organic and inorganic nutrient loads have several impacts on the estuary. Bacterioplankton activity is extremely high in the Bremer River. While phytoplankton productivity was low, biomass was comparatively high. Zooplankton diversity at this site was extremely low, dominated by an flagellate species. Herbivorous zooplankton grazing rates were very low.

High organic loads are associated with anaerobic conditions in the sediments. Thus, nitrification and subsequent denitrification in the sediments are blocked. Surficial denitrification may account for some nitrogen loss. A very high phosphorus flux occurs from the sediment, contributing to very high



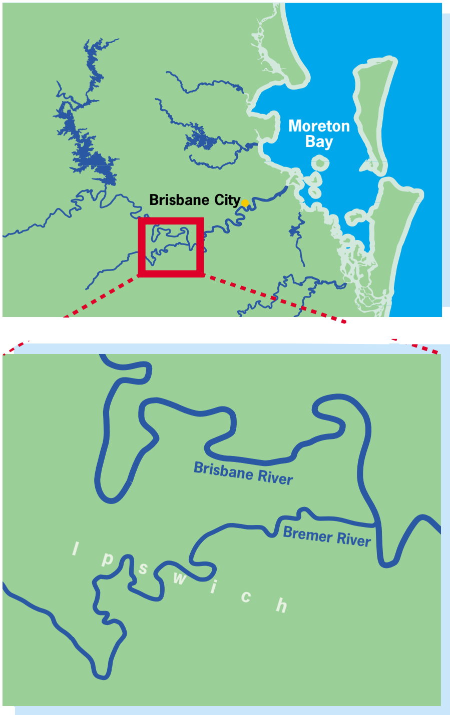
Refer to Symbol Glossary for definition of process, input, and biota symbols.

phosphorus concentrations in the water column. Toxicant levels in the sediments and biota (e.g. copper) were relatively high in the Bremer, although most of them are below the guidelines for human consumption.



Bremer River

HEALTHY WATERWAYS LIBRARY



Bremer River

HEALTHY WATERWAYS LIBRARY

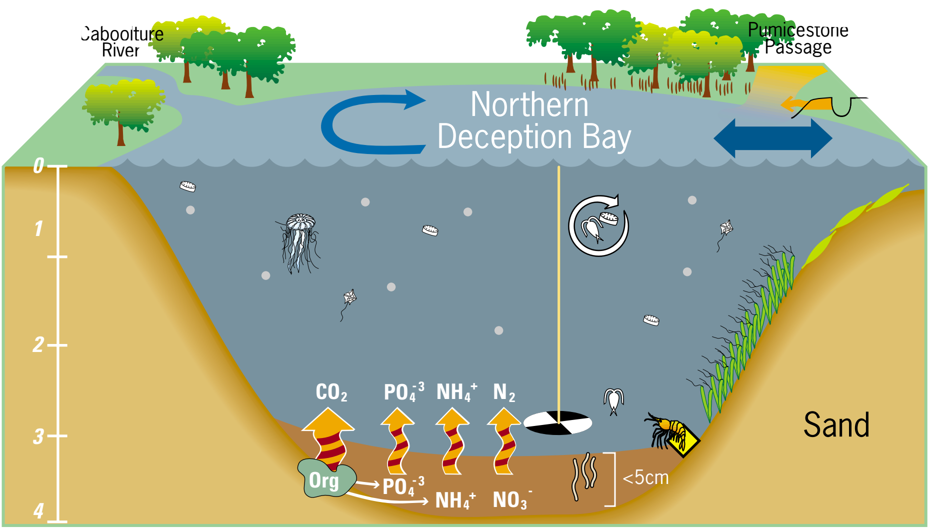
Moreton Bay: highly impacted to relatively pristine

Northern Deception Bay

- **Low nutrient concentrations; absence of sewage nitrogen**
- **Good light penetration resulting in healthy seagrass beds**
- **Human health and ecological impacts from cyanobacteria blooms**
- **Intact sediment processes (high denitrification, low nutrient fluxes)**
- **Large numbers of *Catostylus* affecting zooplankton abundance and diversity**

Nutrient concentrations (Nitrogen and Phosphorus) in northern Deception Bay were relatively low. These low concentrations result from a combination of low residence time (good flushing from North Passage and Pumicestone Passage) and low sewage N inputs from Caboolture River. Sediment nutrient processes are largely intact, with denitrification occurring in the sediments to release N as N_2 gas. Hence, only low rates of ammonium NH_4^+ flux into the water column were observed. Seagrass beds in the area are fairly healthy, although occurrence of *Lyngbya* blooms may lead to localised seagrass loss.

Although turbidity was generally low in northern Deception Bay (secchi depths of up to 4 m), episodes of light reduction from resuspension of muds are increasing in duration and frequency resulting in a declining light environment. This is threatening seagrass beds in areas with reduced depth penetration or potential loss as has occurred in southern Deception Bay.



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Mangrove forests are largely intact, but are coming under increasing threat from urban developments such as canal estates along Pumicestone Passage.

Because of low nutrient concentrations and turbidity, intact sediment nutrient processing and presence of seagrass, northern Deception Bay was considered one of the healthiest regions in the western areas of Moreton Bay. However, there is anecdotal evidence to suggest that over the last ten years blooms of the toxic cyanobacteria *Lyngbya majuscula* have been increasing in frequency and severity. The absence of sewage nitrogen and low phosphorus concentrations, as well as initial research suggests that *Lyngbya* blooms may be linked to high bioavailable iron availability. *Lyngbya* blooms have significant ecological (seagrass loss, large nitrogen inputs, reduced fisheries) and human health implications (dermatitis, asthma and eye irritation) and requires further research and monitoring.

***Lyngbya*, settling on sesagrass**

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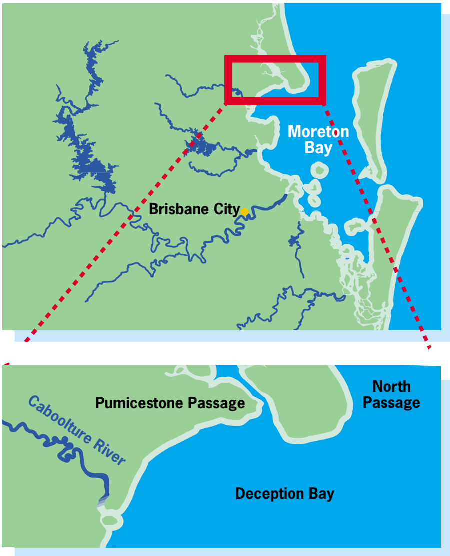


Apart from high levels of some metals (copper) in some biota samples from the Pumicestone Passage, overall concentrations of toxicants were low. Toxicants in both sediments and biota samples were below ANZECC guidelines for human consumption.

Mangrove fringe and seagrass bed in northern Deception Bay

ENVIRONMENTAL PROTECTION AGENCY

Moreton Bay: highly impacted to relatively pristine

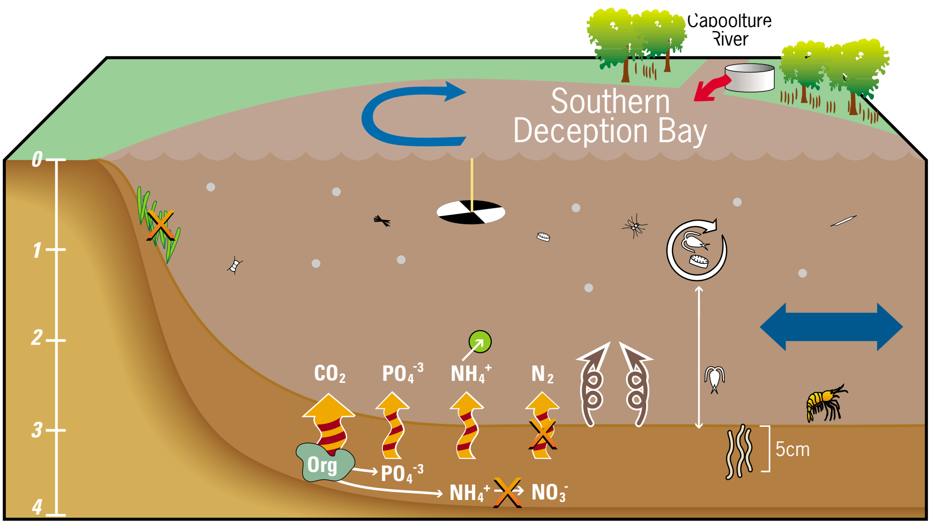
Southern Deception Bay

- **Inputs from stormwater and agriculture**
- **Low water column nutrient concentrations, but fairly turbid system**
- **Sediment nutrient processes relatively intact**
- **Low phytoplankton biomass, but high phytoplankton diversity**
- **Seagrass beds (1500 ha) lost after May 1996 flood**

Southern Deception Bay predominantly receives inputs from stormwater and agricultural run-off and supports both a rural and urbanised catchment. This part of the Bay was fairly turbid, 0.75 m secchi depth, although water column nutrient concentrations were fairly low. Phytoplankton biomass and diversity were intermediate between Bramble Bay and eastern Bay sites. Zooplankton grazing played a key role in determining phytoplankton community structure. High zooplankton grazing rates at night are indicative of demersal populations of phytoplankton (e.g. demersal copepods). Low grazing rates during the day are attributed to the large number of *Catostylus* (blue jellyfish).

Sediment denitrification efficiency maybe moderate, and fluxes of nutrients from the sediments to the water column occur. Southern Deception Bay receives inputs from Caboolture River and the nearby catchments. Bottom sediments may be resuspended due to significant trawling activities in the area.

After the May 1996 flood, seagrass beds in this area (approximately 1500 ha) disappeared and have not yet recolonised. These seagrasses may



Refer to Symbol Glossary for definition of process, input, and biota symbols.


Mangroves in southern Deception Bay

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have been living on the edge of their habitat requirements and the highly turbid waters after the floods led to severe reduction of light. Mangrove forests, which provide important habitats to invertebrates and fish, are still largely intact. As in other Bay sites, the dominant mangrove species is the grey mangrove *Avicennia marina*.


Southern Deception Bay

HEALTHY WATERWAYS LIBRARY

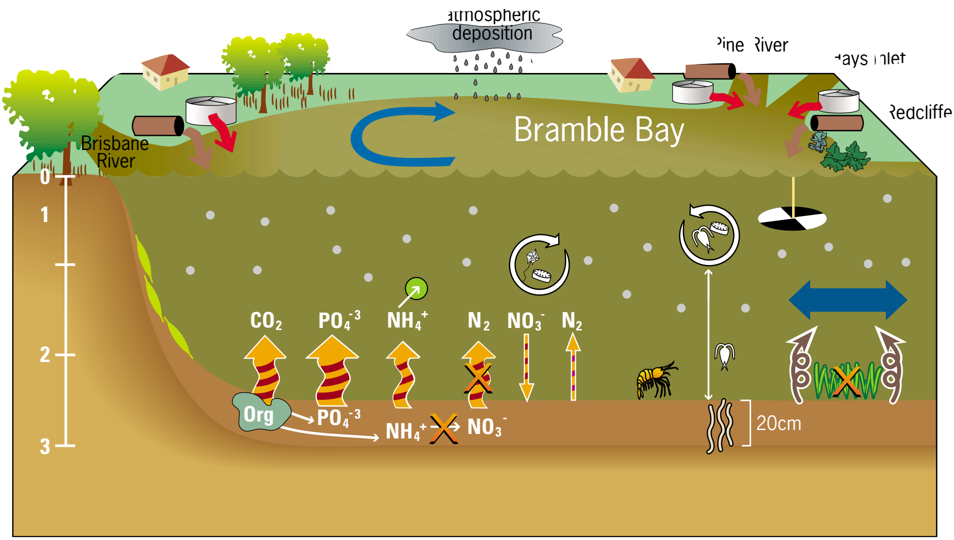
Bramble Bay

- **Most degraded embayment within Moreton Bay; high water column nutrients and turbidity**
- **Anecdotal loss of seagrass beds**
- **Denitrification blocked, nutrients leaching out of sediments**
- **Phytoplankton blooms, exhibiting bloom-crash cycles**

Bramble Bay, characterised by high water column nutrients and turbidity, is the most degraded embayment within Moreton Bay. Loads from the most highly populated and developed regions of the catchment eventually end up in Bramble Bay. Both the Brisbane and Pine Rivers discharge into Bramble Bay, carrying high loads of nutrients and suspended sediments. Sewage plume mapping detected two distinct plumes in Bramble Bay arising from each of these river systems.

Water column nutrient concentrations were the highest in Bramble Bay compared to other western embayments. These nutrients contributed to high chlorophyll *a* concentrations, particularly in the March sampling. Sediment denitrification processes may be blocked as a result of anoxia in the sediments and subsequently there is a high flux of ammonium to the water column from the sediments. High water column nitrate (NO_3^-) concentrations possibly result in some surficial denitrification.

Historical accounts suggest that Bramble Bay supported large seagrass beds and that dugongs used to feed on these seagrass beds. At present, there are no seagrass beds in Bramble Bay. The disappearance of seagrass beds may be related



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to the historical change in water quality, especially reductions in light availability due to decreased turbidity. Continual resuspension of the fine muddy sediments in Bramble Bay sustain high suspended sediment concentrations in the water column and result in the chronic decline of light availability.

In Hays Inlet and on the Redcliffe peninsula, high nutrient concentrations have contributed to a bloom of the green algae *Ulva*. Mangrove forests remain in Hays Inlet and at the mouth of the Pine River. Phytoplankton productivity and biomass were high, with the population controlled largely by zooplankton. Diversity of phytoplankton was low and the community exhibited a bloom-crash cycle.

***Ulva* bloom in Bramble Bay**

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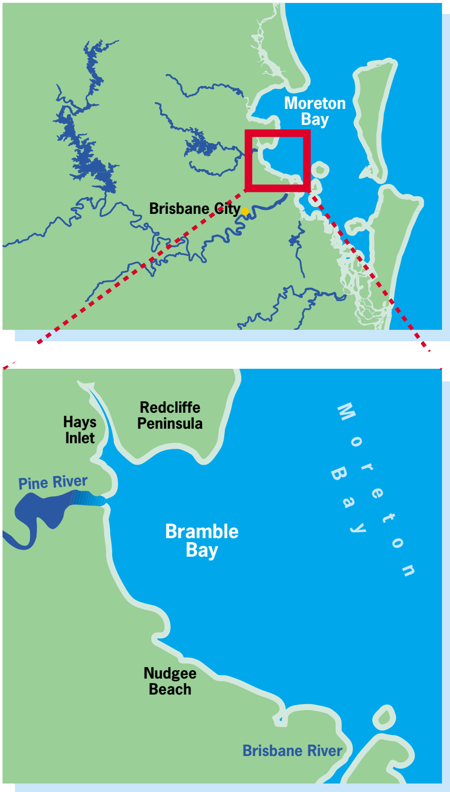

***Ulva* inhabiting the rocky shores of Bramble Bay**

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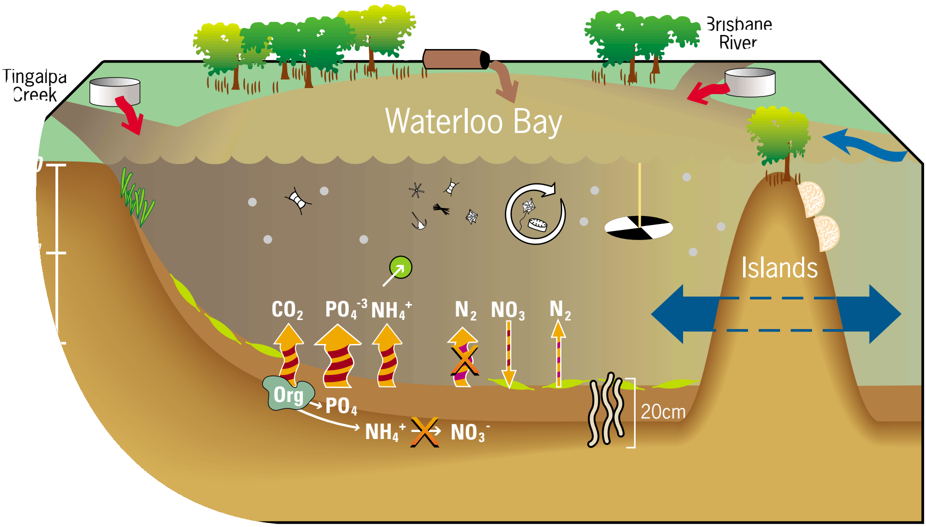
Waterloo Bay

- **Sewage and stormwater inputs**
- **Oceanic water quality, in some areas due to oceanic exchange**
- **Muddy sediments are 'poised'; increase in loading or decrease in oxygen could lead to nutrient fluxes**
- **Fairly healthy seagrass beds in the southern end under threat due to increasing turbidity**

Waterloo Bay has inputs from both sewage and stormwater. Stormwater drains into Waterloo Bay from the predominantly urban catchment. Sewage plume mapping detected the influence of sewage nutrients from Tingalpa Creek and from the Brisbane River extending into northern Waterloo Bay. Nonetheless, nutrient concentrations remained relatively low. Occasional oceanic water quality in the northern end of Waterloo Bay may be attributed to the influence of ocean exchange via both North and South Passages.

Some sediment processing of nutrients occurs enabling the loss of nitrogen as N_2 gas (denitrification) and this is enhanced by surficial denitrification. High flushing and low residence times in the bay help to maintain sufficiently aerobic sediments. However, the muddy sediments are considered 'poised' with respect to denitrification efficiency. Small changes in the nitrification/denitrification coupling within the sediments determine the balance between the proportions of fixed biologically available N (as ammonia and oxides) and gaseous 'unavailable' N released to overlying waters. The denitrification efficiency of muddy sediments was dramatically reduced



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when oxygen concentrations were reduced by 50%. This may reflect a critical instability in the microbiological capacity of muddy sediments to tolerate increasing eutrophication. A little less oxygen in the water column, or a bit more organic matter added to the sediments could tip the scales towards a much greater release rate of biologically available N.

Turbidity was fairly high with average secchi depths of 0.75 m. In the southern part of the bay increasing turbidity and reduced light penetration is threatening seagrasses, particularly those living on the edge of their habitat requirements (e.g. bottom edge of their depth range). Further increases in turbidity are likely to result in significant seagrass loss in the region. Some of the most significant coral communities are found within Waterloo Bay and bordering islands. These too are under threat from turbidity in Bay particularly during flood events. Much of the shoreline of Waterloo Bay has mangrove forests. However, the landward extent of these communities has been significantly reduced in the past from urbanisation.

Corals off Green Island

UNIVERSITY OF QUEENSLAND

Waterloo Bay and Tingalpa Creek

ENVIRONMENT PROTECTION AGENCY

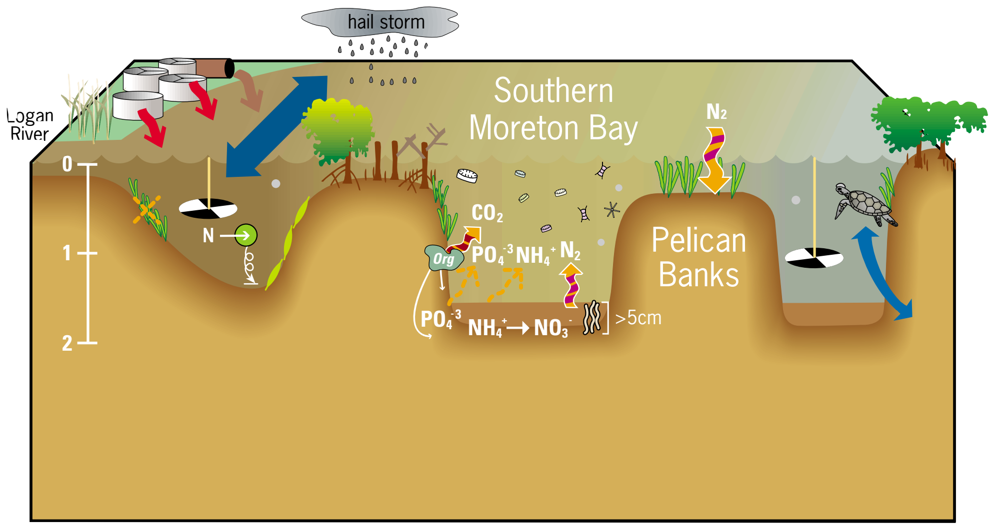
Moreton Bay: highly impacted to relatively pristine

Southern Moreton Bay

- **Broad diversity of ecosystems indicating east-west gradients in water quality**
- **Seagrass loss and recovery documented in the vicinity of Logan River mouth**
- **Healthy seagrass beds, phytoplankton communities and mangroves in Pelican Banks**
- **Relatively low water column nutrients and intact sediment processes**

Southern Moreton Bay is a complex formation of channels and islands supporting a extensive mangroves and some seagrasses. The region encompasses a broad diversity of ecosystems expanding from the mainland to the bordering islands and including Logan River to Pelican Banks. Nutrient and sediment inputs to Southern Moreton Bay are relatively low, predominantly arising from the Logan River. Although a small sewage plume was identified extending from the Logan River into southern Moreton Bay, inputs from aquaculture and stormwater may contribute significantly to sediment and nutrient loads. Water circulation is affected by the complexity of channels through the islands and sand bars and ultimately the ocean inlet at Jumpinpin.

Water column nutrient concentrations are generally low and sediment nutrient processes are largely intact. Nitrification and denitrification occured within the sediments reducing the flux of ammonium from the sediments within the channels and eastern embayments. However, at the Logan River mouth, denitrification was likely restricted to the sediment surface.



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Mangrove forest at the Logan River mouth

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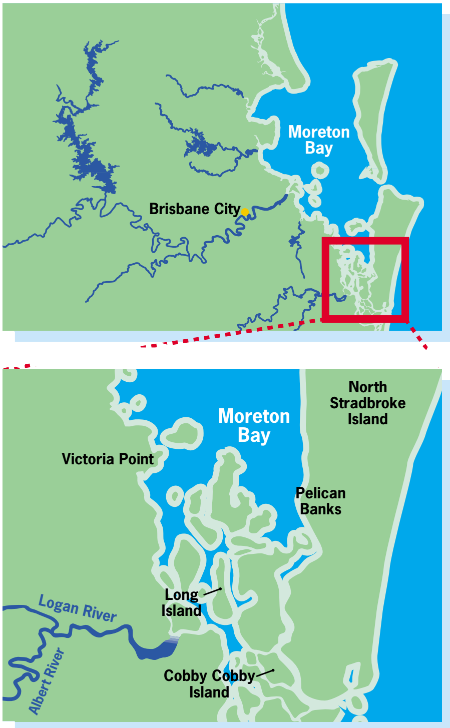

Turbidity was high particularly in the western regions. Secchi depths less than 0.75 m were typical, but reached 1.5 m in the eastern portion of southern Moreton Bay at Pelican Banks. As a result phytoplankton productivity is frequently light-limited. The phytoplankton community was diatom-dominated, with typical oceanic populations.

Seagrass loss in the vicinity of the Logan River mouth was documented over a period of five years (1987-92) and linked to decreased light availability. However, regrowth of these seagrass beds was observed after the May 1996 flood, possibly relating to a change in the hydrodynamic/circulation patterns in the area. Healthy seagrass beds in Pelican Banks experienced a temporary decline after the May 1996 flood, but recovered within a few months.

Mangrove forest losses resulting from coastal developments and natural losses (e.g. 1997 hail storm) were compensated for by mangrove incursion into salt marshes at the upper tidal limits.

Southern Moreton Bay's network of channels and islands

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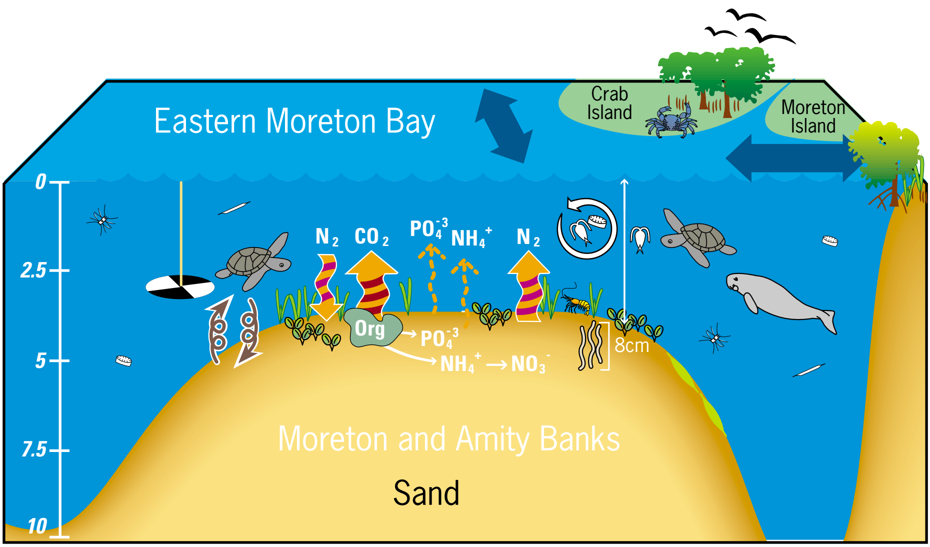
Moreton Bay: highly impacted to relatively pristine

Eastern Moreton Bay

- **Relatively pristine region supporting healthy seagrass beds and dugong populations**
- **High nitrogen fixation and denitrification efficiencies**
- **Low nitrogen fluxes**
- **Lower column nutrients resulting in low phytoplankton productivity**
- **Zooplankton grazing controls phytoplankton populations**

Eastern Moreton Bay is a relatively pristine region representing good ecological health and water quality. Flushing through South Passage ensures that minor contributions from stormwater and sewage do not reside and impact the system. Water column nutrient concentrations are low and sediment nutrient processes are intact. Nitrogen (N) input predominantly arises from nitrogen fixation associated with seagrasses. Nitrogen fluxes from the sediments to the overlying waters were low. Coupled sedimentary nitrification and denitrification is active and efficient (>90%) and these sediments appear to be recycling sedimentary N. Sedimentary nitrification and denitrification are enhanced by oxygen fluxes through the root systems of seagrasses. Phosphorus fluxes were low in seagrass sediments and bioirrigation to shallow depths was evident.

Because of the low water column nutrient concentrations and relatively strong currents, phytoplankton productivity was low and nutrient limited. Zooplankton grazing appeared to control phytoplankton populations. Benthic microalgal biomass was high, particularly in the shallower regions (<5 m depth). Plankton species diversity was high



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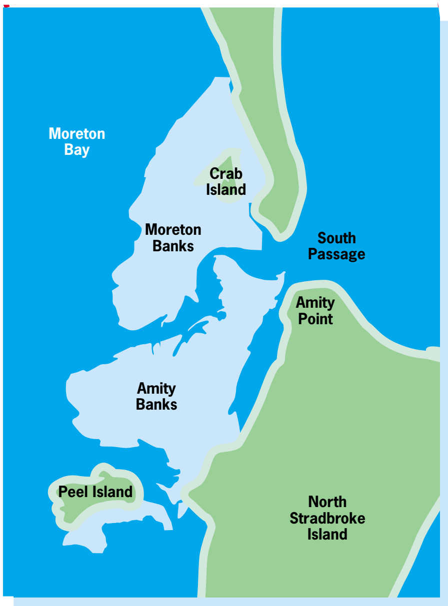
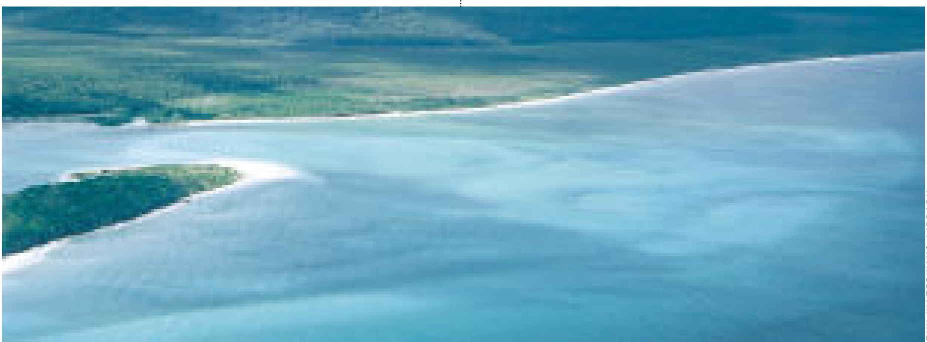
with the phytoplankton being diatom-dominated indicating a strong oceanic influence and zooplankton constituting many fish, shellfish and crustacean juveniles.

The eastern banks support healthy seagrasses grazed by up to 900 dugongs. All seven Moreton Bay seagrass species can be found in the eastern Bay. Dugong food species predominate, particularly on Moreton and Amity Banks where dugongs graze during high tides. Moreton and Stradbroke Islands have large stands of fringing mangroves. Crab Island, a mangrove island off south Moreton Island, maintains a large bird population.

CHRIS ROELFSEMA

Eastern Moreton Bay sand banks supporting seagrasses





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Seagrass beds in Eastern Moreton Bay

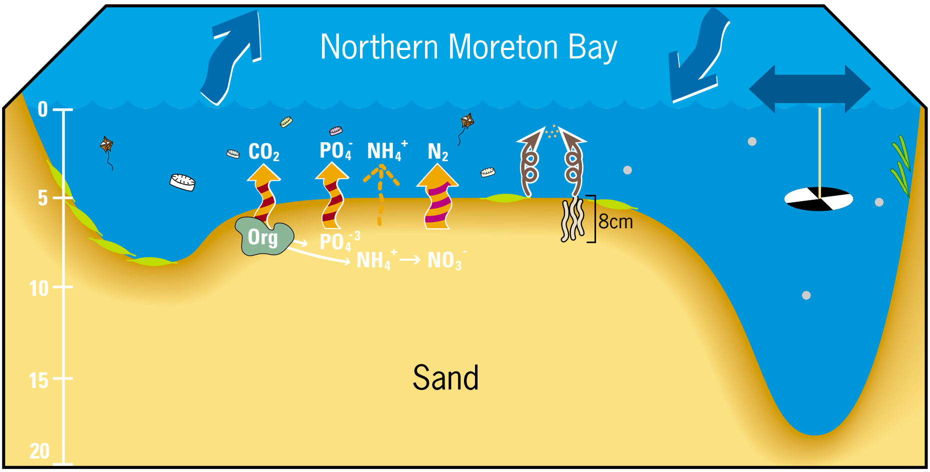
Moreton Bay: highly impacted to relatively pristine

Northern Moreton Bay

- **Well-flushed due to high oceanic exchange through North Passage**
- **Sand resuspension but low turbidity and low water column nutrient concentrations**
- **Sediment nutrient processes intact**
- **High benthic microalgal production, diverse phytoplankton community; but low productivity**
- **Supports dugong, turtle and occasional whale populations**

Northern Moreton Bay is a very healthy and relatively pristine ecosystem, supporting dugongs, turtles and occasional Humpback whales which may enter the bay during the course of their North - South migration. This portion of the Bay does not receive any point or non-point loads. Due to the low nutrient concentrations and strong water movement in the area, there is low phytoplankton productivity, in spite of very good light penetration. However, benthic microalgae grow on the shallow sand banks, contributing to the benthic production in the area.

This portion of the Bay is very well-flushed due to high oceanic exchange via the North Passage. Due to the strong currents, the sandy bottom sediments are constantly resuspended and moved, resulting in aerobic sediments. Biomarker data indicate diatomaceous inputs of labile organic matter into the top few (< 2 cm) sediments. This labile organic matter is probably degraded, resulting in the formation of nitrate (NO_3^-), which is in turn denitrified. Denitrification is efficient in the sediments and there was little or no nutrient flux from the sediments.



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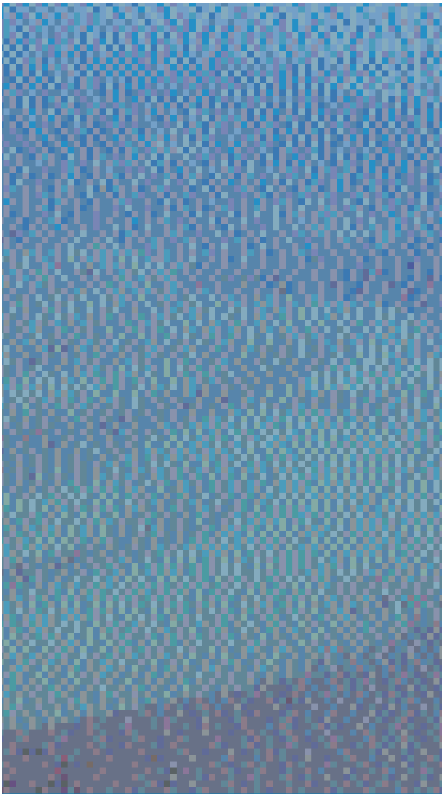

Sand banks in norhtern Moreton Bay

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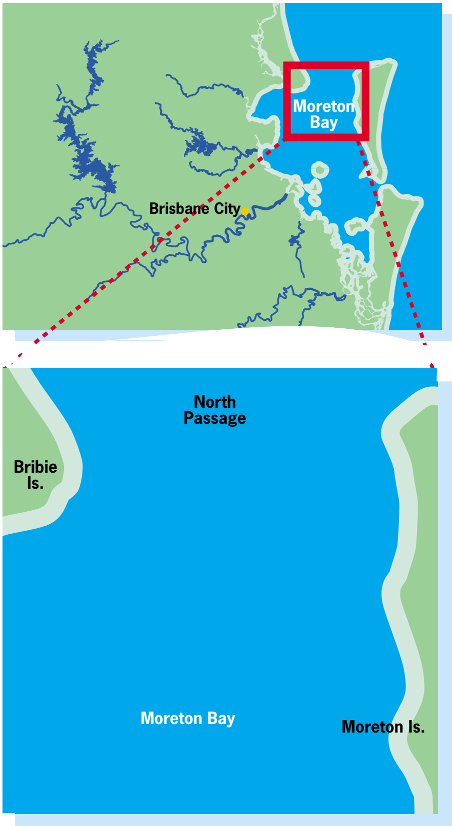

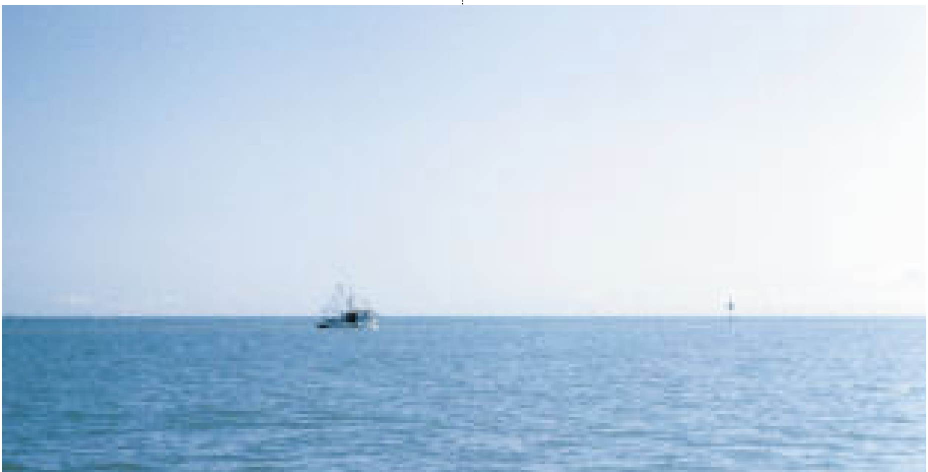

Northern Moreton Bay

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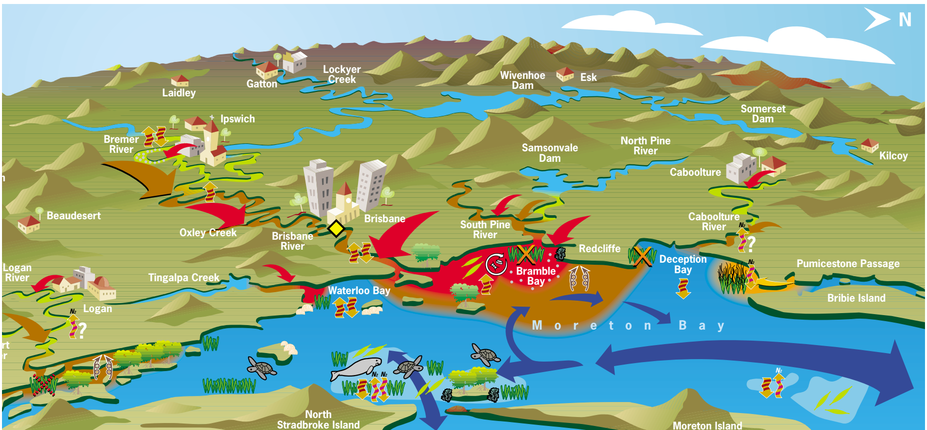
Functional zones defined

The functional zone diagram illustrates the geographical location of the different zones in the conceptual models. The zones can be defined as:

- Riverine: upper reaches of the rivers, Bay and the tidal influences. These are the regions to be examined in Stage 3 of the Study
- Estuarine (Turbid): Bremer River estuary to the mouth of the Brisbane River, Pine River (downstream of North Pine Dam and Lake Samsonvale), Caboolture River, and Logan River.
- Estuarine (sewage impacted): western Moreton Bay, particularly the regions of the Bay affected by sewage plumes. Sewage plume mapping has defined the region of sewage influence to include the Brisbane and Pine Rivers, Tingalpa Creek, Hays Inlet, Bramble Bay and Waterloo Bay. There is no evidence of sewage influence in Deception Bay. The largest sewage impacted area is the Bramble Bay region which receives sewage nitrogen from the Brisbane River, Pine River and Redcliffe sewage treatment plants. Occasional phytoplankton blooms occur in the sewage impacted zone
- Marine (Fluvial): extends most of the way across Moreton Bay from the mouth of the Brisbane River, north to Deception Bay and south into Waterloo Bay. These areas have muddy sediments which are resuspended by waves and tides, resulting in high turbidity. Fluvial regions are found in Bramble Bay, southern Deception Bay, northern Waterloo Bay and southern Moreton Bay. Also as a result of high light attenuation, anecdotal and recorded seagrass loss and decline has occurred in these regions.
- Marine (oceanic): eastern Moreton Bay, including Moreton and Amity Banks and northern Deception Bay. High tidal flushing, particularly through the North Passage maintains clear waters, low nutrient concentrations and intact sediment nutrient processing. Extensive seagrass beds in eastern Moreton Bay support dugong and turtle grazing while in Deception Bay the seagrass beds are under threat from *Lyngbya* blooms.



Three dimensional conceptual model for the river estuaries and moreton Bay. The major processes within and impacts on, are depicted and functional zones are mapped for the region

CHAPTER 15

Ecological Health Monitoring

HEALTHY WATERWAYS LIBRARY

HEALTHY WATERWAYS LIBRARY

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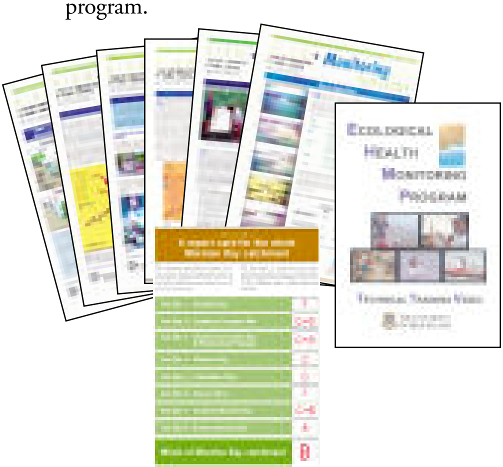
- Ecological health monitoring: important resource management tool
- Ecological health defined with measurable ecosystem features
- Functional zones mapped
- Ecological health indicators developed
- Sampling strategy: annual survey and monthly widespread
- Sampling strategy: monthly intensive and contingency
- Use of spatial statistics to determine and evaluate sampling strategy
- Incorporation of review and reporting into monitoring program
- Independent audit of investments in environmental protection

Ecological health monitoring: important resource management tool

An Ecological Health Monitoring Program (EHMP) is one of the most important tools available for resource management. It provides an independent audit of the effectiveness of environmental protection initiated by the Brisbane City Council, Ipswich City Council, Caboolture Shire Council, Pine Rivers Shire Council, Redcliffe City Council and Redland Shire Council. The program was developed by the Design and Implementation of Baseline Monitoring (DIBM) task within the Brisbane River and Moreton Bay Wastewater Management Study. The project team combined the expertise of groups within Queensland Environmental Protection Agency, CSIRO and The University of Queensland.

The EHMP is based on a conceptual model that integrates our current scientific understanding of the waterways with community-derived environmental values. Ecological health indicators based on key processes, relevant anthropogenic impacts and critical habitats have been developed. Indicators measure water quality, sediment features and biological responses in a rigorous spatial and statistical program.



EHMP: Outcomes and Deliverables

- Assess ecological outcomes of environmental management program
- Evaluate effectiveness of investment in:
  - sewage plant upgrades
  - stormwater controls
  - wastewater treatment
- Fulfil ecological health component of licensing requirements

This EHMP uses an outcome-based approach to monitoring. It focuses on assessing the ecosystem response to natural and anthropogenic inputs. In the past, monitoring programs have focused on the inputs themselves (e.g. nutrient and sediment loads), rather than the impacts of these inputs on the ecosystem. An outcome-based approach to monitoring allows management bodies to readily evaluate and communicate the ecosystem and community benefits derived from their investment in environmental protection.

The EHMP includes a communication strategy that will deliver clear and informative accounts of monitoring activities, results and community benefits. The major elements in this strategy are an annual report card for the study area and regular monitoring newsletters. There will also be an annual technical report, describing all techniques used and data obtained for the year. All monitoring data will be integrated into a single data base. A simple web interface will be used to allow ready access to data by all stakeholders.

Ecological health defined with measurable ecosystem features

Examples of poor ecological health

Lyngbya **washed up on beaches**

Flood carries sediments to Bay

Nutrients and sediments in stormwater runoff

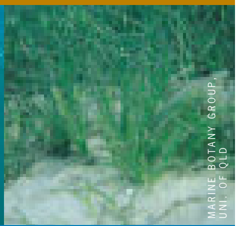
Algal bloom in Bramble Bay

Examples of good ecological health

Healthy seagrass banks in eastern Bay

Large turtle population

Large dugong population in eastern Bay



Diverse and resilient seagrass beds in eastern Bay

What is ecological health?

Ecological health has been variously defined including:

- The maintenance of biodiversity and ecosystem integrity (Draft ANZECC Guidelines), and
- Represented by
  a) a lack of a 'distress syndrome'
  b) stability over time, and
  c) resilience to change
  (Rapport et al., 1995, Evaluating and monitoring the health of large scale ecosystems).

These definitions are appropriate for describing the ecological health concept, but do not define ecological health in terms of measurable quantities.

Our definition of ecological health is that:

- Key processes operate to maintain stable and sustainable ecosystems
- Zones of anthropogenic impacts do not deteriorate
- Critical habitats remain intact

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Healthy seagrass habitat

Functional zones mapped

Indicators used for monitoring are derived from the processes, impacts and habitat types operating within each functional zone. The following indicators were selected to test for impacts of and responses to nutrient and sediment loadings in the region:

- phytoplankton bioassays, characterising the responses of phytoplankton to nutrients and light and identifying limiting nutrients
- sewage plume maps, mapping the influence and geographical extent of sewage nitrogen in the ecosystem
- seagrass distribution and depth range, using responses of a critical habitat to evaluate impacts of turbidity

Marine oceanic functional zone

HEALTHY WATERWAYS LIBRARY

Estuarine sewage nutrients functional zone

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Map depicting functional zones in the Bay and Rivers. Biological indicators will test for impacts of and responses to nutrient and sediment loadings in the region.

Monitoring ecological health

Change in ecological health is measured as a change in the boundaries of functional zones identified by ecological health indicators

- Change is defined in comparison with either historical scenarios or appropriate contemporary reference sites
- A functional zone is defined as a geographic entity which has common structural and functional characteristics; in particular it is homogenous in:
  a) Key Processes,
  b) Relevant anthropogenic impacts, and
  c) Critical habitats

which can be defined in a Conceptual Model, and quantified by measurement.

- Ecological health indicators are defined as measurable ecosystem features that provide information on Processes, Anthropogenic inputs or Habitats, as depicted in Conceptual Models.

Ecological health indicators developed

Water quality measurements have been collected by the relevant state agencies (currently Queensland Environmental Protection Agency QEPA); over the past three decades. These records provide an historical context for current understanding of the Moreton Bay system, and allow long term changes to be identified. These measurements are retained in the proposed monitoring strategy. Sampling throughout the Bay will be aimed at maintaining and extending the coverage of historical measurements of water quality.

Continued coverage of traditional water quality measurements

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Phytoplankton incubated under controlled light and nutrient conditions can be used as a biological assay to infer the environmental factors that control phytoplankton growth in their natural environment. Phytoplankton bioassays (refer to Chapter 10) will be carried out for 12 to 24 sites within each zone. The bioassay responses will be mapped to locate areas at risk of phytoplankton blooms.

Phytoplankton bioassays used to infer factors controlling phytoplankton growth

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To map the source and fate of sewage-derived nitrogen, a method has been developed which utilises changes in the $\delta^{15}N$ values of a macroalgae incubated *in situ* (refer to Chapter 11 for more details of methods). Maps of the $\delta^{15}N$ distribution can then be used to determine the extent and impact of sewage nitrogen in the environment.

Sewage source and fate mapped with deployed macroalgae

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The distribution of seagrass, a critical habitat in Moreton Bay, is directly dependent on light availability. Seagrasses are therefore sensitive indicators of changes in turbidity and therefore, light availability. There are two monitoring strategies for seagrass. The first strategy is broad scale mapping throughout the Bay. The second strategy is based on the well defined relationship between the water depth at which seagrass can survive and light availability. Seagrass depth range (refer to Chapter 6) which identifies localised changes, is measured at selected sites. The number of depth transects per site and the number of different sites have been chosen from a statistical analysis of existing data.

QEPA rangers carry out seagrass depth range monitoring to detect increases in turbidity

ENVIRONMENTAL PROTECTION AGENCY

Sampling strategy: annual survey and monthly

The proposed monitoring program is structured into a number of tasks. Each task has a defined spatial and temporal scale, and calls for a particular spectrum of expertise. This structure facilitates effective program management.

Tasks are summarised as:

Sampling and Data Acquisition

- an annual intensive survey of the study region, to characterise long term change and to provide a regional scientific context for other data
- monthly widespread sampling to characterise changes which occur throughout the year, and to focus on degraded and sensitive areas
- monthly intensive sampling to evaluate small scale variability in a particularly sensitive area (Waterloo Bay)
- contingency sampling will be used to investigate the consequences of specific events (e.g. flood, oil spill, algal bloom). The precise form of sampling will depend on the nature of the event

Review and Reporting

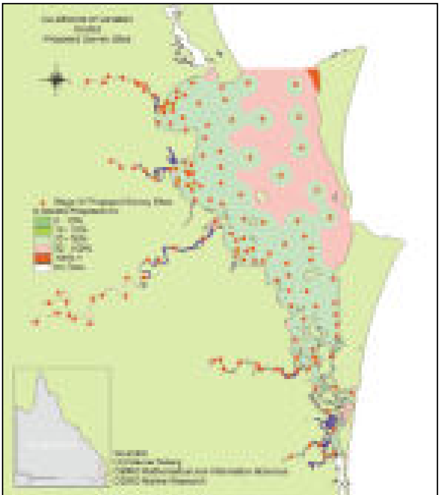
Review is an integral part of a monitoring program. Quarterly reviews based on spatial and statistical analyses of results will provide regular quality control on data generated. An annual review will, in addition to technical reports, be used to synthesise and interpret results providing updated report cards. In addition to more formal reports, monitoring newsletters will present concise and informative summaries of continuing effort and findings.

Annual Survey

- Traditional water quality
- Bioassays
- Plume maps
- Seagrass depth range
- Vegetative isotopes

The annual survey will provide a spatially intensive sampling of water quality and ecological health indices. It will provide the data for precise maps of ecological health indices. These maps aid in characterising long term change arising from remediation programs. Sampling at this spatial intensity (scope and resolution) would not be economically feasible at shorter intervals.

The sampling schedule includes phytoplankton bioassays, sewage plume maps, seagrass depth range and vegetative isotope assays.



Sampling sites proposed for 1999 annual survey. Site selected to maintain continuity with existing data and to obtain appropriate precision over the study area.

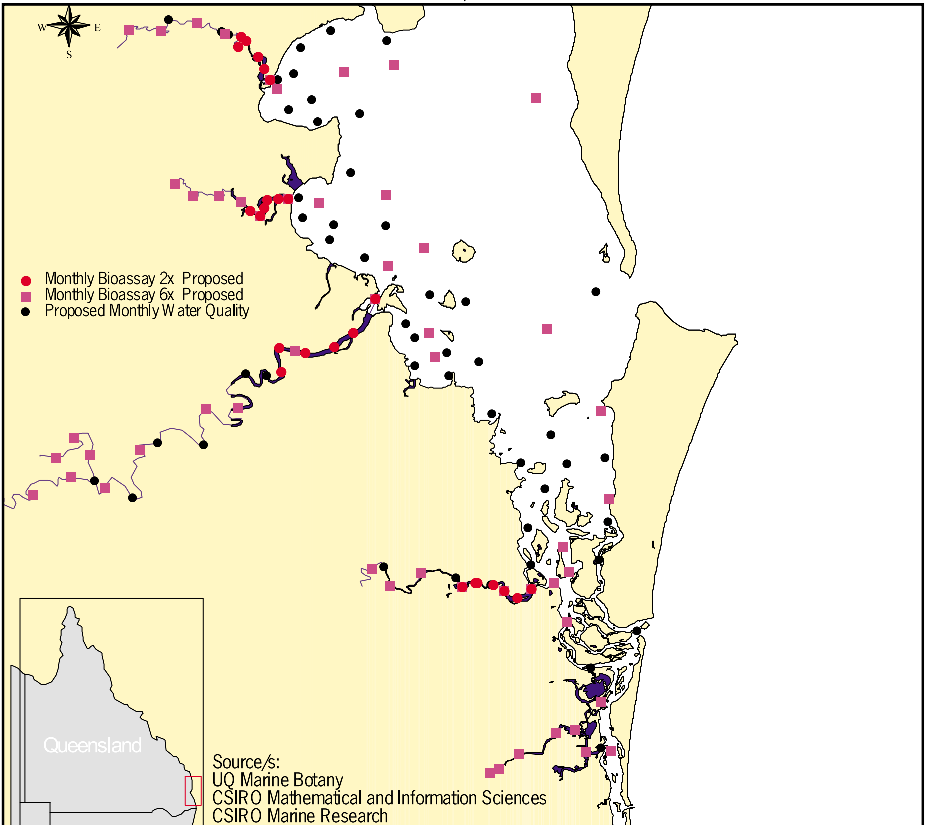
widespread

Monthly Widespread Sampling

- Traditional water quality (mixing plots in rivers)
- Bioassays (6 x yr^{-1})

Preliminary sampling has demonstrated marked seasonal changes in the ecological health indicators to be monitored. Continuing monthly sampling will provide a seasonal context within which long term changes in the annual intensive sampling results can be interpreted. The monthly sampling involves fewer sites than the annual intensive sampling program. The sample scheme is more intense in the western and southern bays and rivers, and will give results that are more precise in these sensitive regions.

Water physico/chemical properties will be measured at 12 sites in each of the 4 major rivers. Nutrient mixing plots will be produced to identify net gains to or losses of nutrients fromthe system. In addition, there are 45 sites in Moreton Bay, concentrated in the western and southern Bays, to provide more precise information in sensitive and degraded areas.

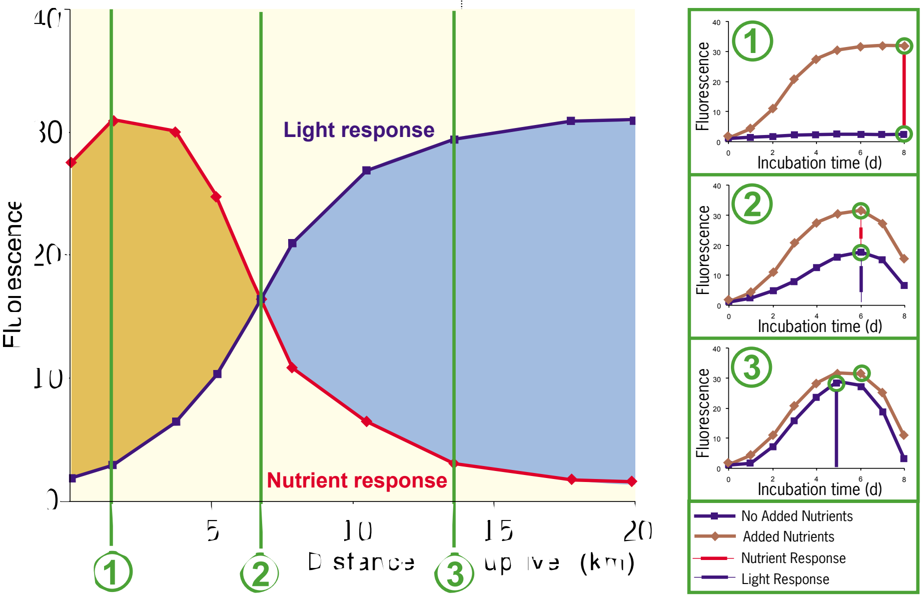


Proposed monitoring sites for the monthly widespread survey. Continual monthly sampling will provide a seasonal context for long term changes not detected in annual intensive sampling.

Sampling strategy: monthly intensive and

Three main types of phytoplankton bioassays will be employed. To provide information about light limitation and overall nutrient limitation to monitor the boundary between the light limited zone and the nutrient limited zone in each of the rivers, a simplified version of the assay used in the annual surveys (a control with no nutrients augmented, and a treated sample with all major nutrients augmented) will be used. To monitor the response of phytoplankton in the upper reaches of the rivers to specific nutrients, six nutrient treatments will be applied to samples from these sites (control, ammonium, nitrate, phosphate, silica and all). To detect change in the spectrum of nutrient limitation in the Bay, five sites are planned and each will be tested with the full set of nutrient treatments.

Bioassay sampling for fluorescence analysis



Phytoplankton bioassay responses - light or nutrient- interpretation represented diagrammatically. In the bioassay, phytoplankton respond to nutrients toward the mouth of the river and to light availability upstream.

contingency

Monthly Intensive Sampling

- Traditional water quality
- Plume maps
- Seagrass depth range
- Sediment nutrient flux
- Sediment oxygen flux

This task is designed to assess the temporal and spatial variability in a particularly sensitive area of the study: Waterloo Bay. It will elicit the linkages between nutrient and sediment loadings (key physico/chemical properties) and ecosystem responses, and provide data for quantitative assessment of model relationships.

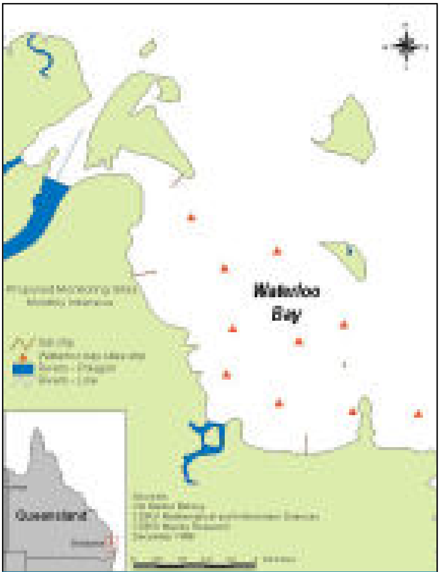
The task will involve measurement of:

- Sewage plume extent based on deployment and retrieval of macroalgae at twelve sites within Waterloo Bay. Results from two intensive surveys indicate that the impact of sewage derived nitrogen is strongly seasonal. Waterloo Bay contained only a small plume during October, but a large plume during February.

- Seagrass Depth Range: at three sites currently sampled by QEPA. Waterloo Bay is the last area in Western Moreton Bay to have extensive healthy seagrass beds. This is probably the most vulnerable of the remaining seagrass habitats, and is likely to respond most rapidly to changes in water quality.

- Water Quality: at the twelve sewage plume sites. Water quality in Waterloo Bay is variable from month to month. This variability may indicate that the bay is stressed – processes are no longer able to maintain stable nutrient concentrations.

- Sediment nutrient flux: sampled every two months at the sewage plume sites.



Sites within Waterloo Bay, the focus of the monthly intensive sampling strategy.

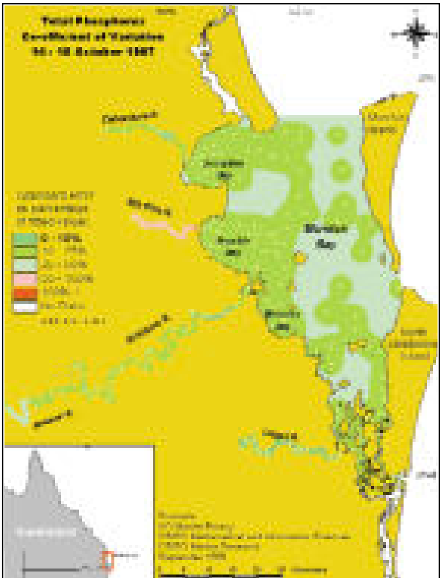
Contigency Sampling

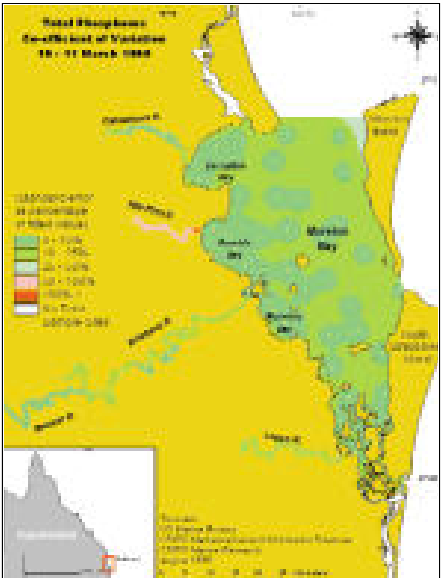
- Traditional water quality
- Bioassays
- Plume maps
- Seagrass depth range
- Vegetative isotopic ratios

During the lifetime of any monitoring program there will be events that cannot be anticipated. These include floods, oil spills and algal blooms. Contingency sampling will chart the recovery of the ecosystem following any one of these unexpected events. In addition to assisting with management responses to ecosystem threats, it will allow the resilience of the system to be defined. Contingency sampling will be instigated on the advice of the executive monitoring team. If no trigger occurs in a given year, funding will be carried forward to the following year.

Use of spatial statistics to determine and evaluate sampling strategy

A critical component in developing the sampling strategy was the spatial statistical analyses based on the data generated from the Design and Implementation of Baseline Monitoring (DIBM) task. Characterising the spatial variability of parameters allows optimisation of sampling schemes in terms of spatial intensity. Sample sites for the annual survey have been chosen to provide continuity with existing data series (i.e. to maintain the sample sites used by Queensland Environmental Protection Agency), and to obtain appropriate precision over the study area. The precision was determined by computing predictive Coefficients of Variation (CV) for each parameter, based on the proposed set of sampling points. These predictive CVs incorporate data from the DIBM task, analysed with spatial statistical techniques. This process allows the consequence of varying the sampling intensity to be evaluated. The sampling design was chosen to maximise precision in the western Bay where the greatest threats to ecological health have been identified and possibly greater variability of environmental parameters. As such, a larger number of sampling stations are being proposed for the western parts of the Bay.





Coefficient of Variation maps for two intensive samplings of total phosphorus, in September 1997 and March 1998. These maps were created for each parameter, giving estimates of the degree of certainty that the differences between points is real.

Incorporation of review and reporting into monitoring program

Review and Reporting

- Statistical analysis
- GIS presentations
- External independent review
- Annual technical report
- Annual report card
- Monitoring newsletters

Monitoring Steering Committee

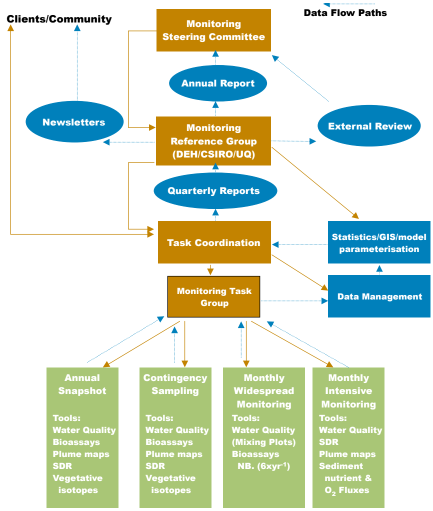
This committee comprises: Queensland Environmental Protection Agency representative, Councils, Chairman of the Monitoring Reference Group. It represents stakeholder interests, signs off on annual reports, and approves modification to the monitoring strategy. Its role is in top level direction rather than day-to-day management.

Monitoring Reference Group

This body comprises individuals with the following relevant scientific and management expertise: regulatory and licensing affairs, physico-chemical water quality, sediment dynamics, biological indicators, spatial statistics and Geographical Information System (GIS) techniques and data management. This body is responsible for coordination of monitoring tasks, scientific evaluation and integration of monitoring results, and reporting. It will formulate monitoring strategy subject to approval by the Monitoring Steering Committee. This group will meet quarterly, or more frequently as needed.

Monitoring Task Group

The Monitoring Task Group is a subset of the Monitoring Reference Group, and comprises those members of the reference group with primary responsibility for discrete monitoring tasks and activities. This group will interact regularly, as required, to produce deliverables for the Monitoring Reference Group.

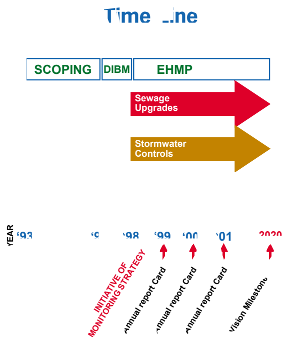


Time Line

The monitoring program duration of three years is compatible with the funding cycle of the continuing South East Queensland Regional Water Quality Management Strategy. The three year period is also an appropriate interval for review and evaluation of the monitoring program.

Independent External Review

Independent external review by acknowledged experts will be used to maintain scientific credibility, and to ensure that the monitoring program meets international best practice.



Independent audit of investments in environmental protection

Management of the Moreton Bay ecosystem is at a critical juncture with considerable resources now being devoted to sewage treatment upgrades and stormwater controls. It is important that the effectiveness of these measures is evaluated. This monitoring program addresses the ecological health of the waterways affected by this investment. It will evaluate the outcomes of this substantial investment in environmental protection, and communicate these outcomes to the broader community. In addition, it will provide a long-term basis for environmental planning.

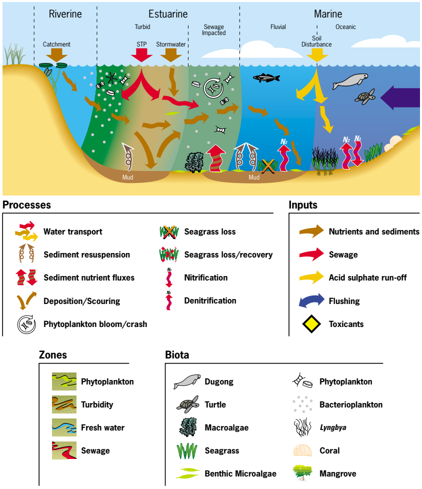
Stakeholder Management Actions

Sewage Treatment
- Improved sewage treatment facilities
- Reduction in sewage overflows and unnecessary flows to sewers
- Investigate and implement wastewater reuse schemes

Stormwater Management
- Installation of urban stormwater quality improvement devices
- Subdivision approvals linked to stormwater management

Catchment Management
- Appointment of Catchment Management Officers
- Development of catchment management plans
- Involvement in Integrated Catchment Management
- Revegetation and protection of riparian zones

Current Conceptual Model



Ecological Health Moniting

Ecological Health Indicator Sampling
- Water quality (physical/chemical)
- Sewage plume mapping
- Seagrass depth range
- Phytoplankton bioassays
- Sediment nutrient flux

Data Analysis, Management and Delivery
- Analytical techniques and procedures (NATA registered)
- Database design and maintenance
- Data reporting

Spatial Design and Analysis
- Statistical design of cost effective sampling strategy
- Statistical and spatial analysis of data
- GIS - data presentation for review

Actions

Reduction in Nutrients and Sediments

Monitoring

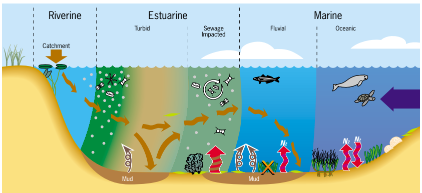
Ecological Health Indicators

Sewage Treatment
- Develop licensing conditions for current and future wastewater discharges
- Investigate and review wastewater reuse schemes

Stormwater Management
- Responsible for urban stormwater management review
- Develop model plan for urban stormwater management

Catchment Management
- Development of Moreton Bay Zoning Plan
- Involvement in Waterwatch and Waterwise
- Support for Catchment Coordinating Committees

Future Conceptual Model



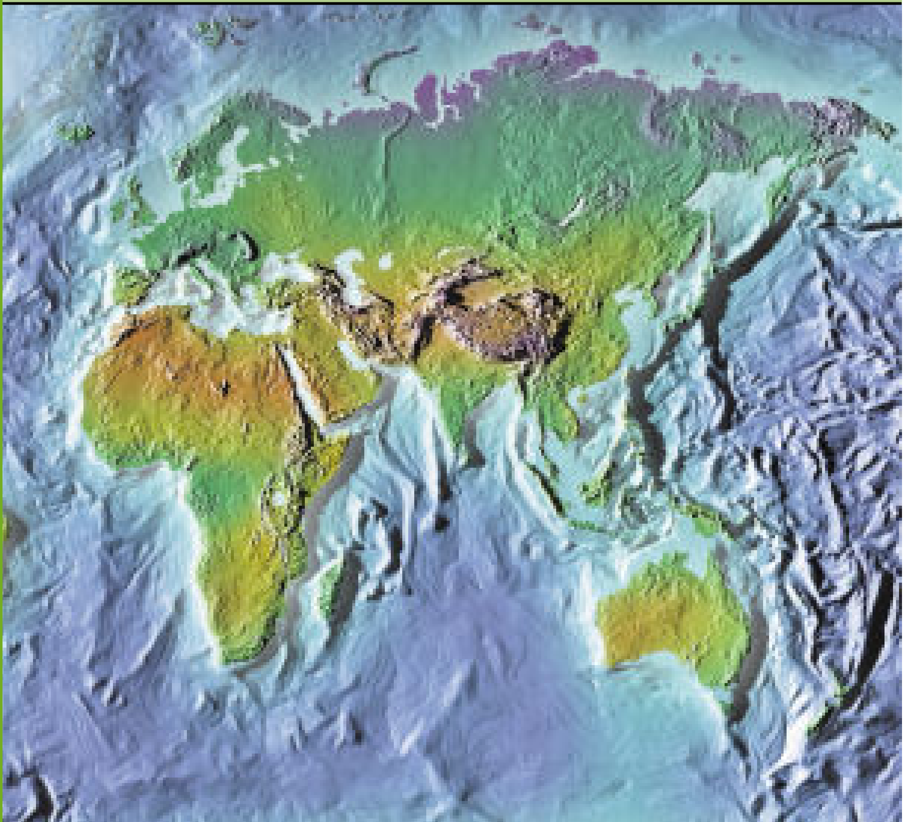
Review and Reporting
- Regular workshops for data interpretation
- Communication of synthesized results to stakeholders
- Regular monitoring newsletters
- Annual technical report
- Annual report card
- External independent review

Project Management and Coordination
- Multi-disciplinaryteam for program vision and direction
- Collaborative structure linking science and management
- Coordination of catchment monitoring activities

Next section ▶

CHAPTER 16

Moreton Bay Study in Perspective



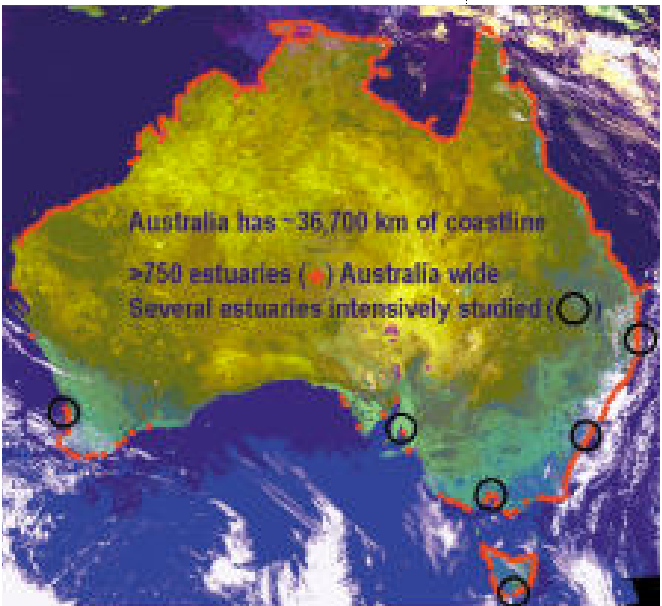
- Abundance of Australian estuaries
- Australian estuaries differ from Northern Hemisphere estuaries
- Australian estuaries dominated by rainfall patterns
- Series of previous Australian coastal studies
- Port Phillip Bay Study most similar to Moreton Bay Study
- Hervey Bay: ecological issues without large population
- Moreton Bay Study results may be applicable to inshore Great Barrier Reef
- Chesapeake Bay: benchmark estuary
- Chesapeake Bay: well studied but degraded
- Moreton Bay Study: catchment focus in Stage 3
- Moreton Bay Study Stage 3: wider scope and membership
- The coastal management challenge

Abundance of Australian estuaries

An important aspect of a major scientific study is providing the contextual basis for the results obtained. In this way, results from previous studies in other parts of the world can be compared and contrasted. The Moreton Bay Study benefited from many previous studies, especially the large and intensive Port Phillip Bay Study which was completed at the same time as the Moreton Bay Study was gearing up. In addition, Chesapeake Bay in North America, the most intensively studied estuary in the world, provides a scientific benchmark for comparison.

Estuaries at virtually all stages of evolution can be recognised along the Australian coastline (Roy, P., 1984, Coastal Geomorphology in Australia). Based of the classification of Digby et al. (A physical Classification of Australian estuaries, 1998), there are 758 estuaries, Australia-wide, most of which are concentrated in the tropical and sub-tropical regions. The considerable diversity in physical, chemical and biological aspects result in a diversity of estuaries, which are difficult to classify based solely on broad generalisations.

Because of the differences between Australian estuaries and the Northern Hemisphere counterparts, it is difficult to classify Australian estuaries based on criteria developed for Northern Hemisphere estuaries. Low rainfall patterns over much of the country combined with relatively small coastal catchments and high evaporation rates mean that Australian annual river discharges are the lowest and most variable in the world (Saenger, P., in press, A Physical Classification of Australian Estuaries).



There are 758 estuaries along the Australian coastline (indicated by red dots). Only very few of these have been extensively studied, particularly near to major centres of population (indicated by black circle).

SATELLITE IMAGE PROVIDED BY THE AUSTRALIAN CENTRE FOR REMOTE SENSING

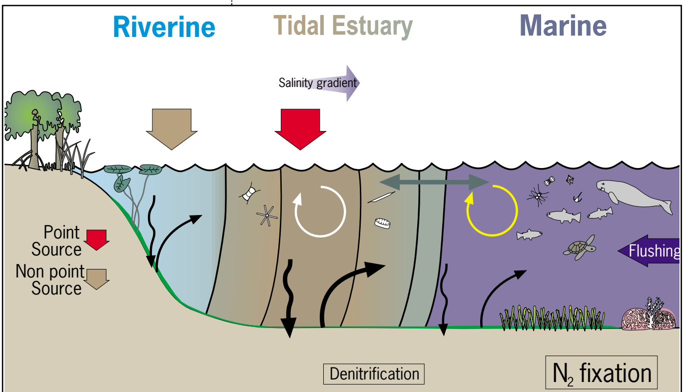
Extensive studies of individual estuaries have, to date, been limited to a small number near to large population centres or research institutes. With increasing pressures on estuaries (e.g. increased catchment development, population growth, increased nutrient and sediment loads), there is a need for an integrated approach to estuarine classification, taking into account the various interactions between the geological, hydrological and ecological processes occurring in these systems.

Australian estuaries differ from Northern Hemisphere estuaries

There are several key features which differentiate Australian estuaries from those in the rest of the world, in particular Northern Hemisphere estuaries, which dominate the scientific literature. Australian estuaries are subject to great climatic variability resulting in low freshwater input throughout most of the year, with short-lived, high-energy flood events during wet seasons. Australian estuaries are impacted by the concentration of the human population along rivers and estuaries, despite a low population for the land area overall.

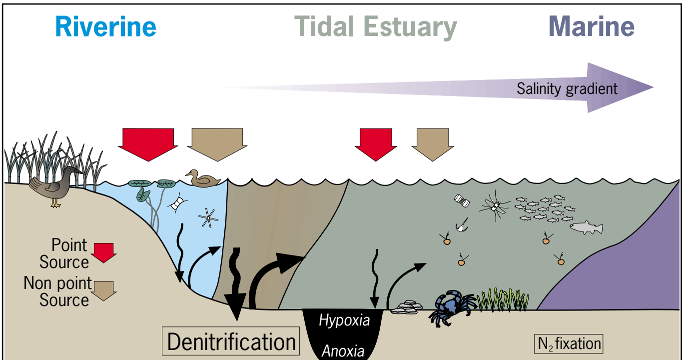
Northern Hemisphere estuaries are highly-stratified with long salinity gradients, high ambient nutrient concentrations with substantial residual nutrients available in the water column. Australian estuaries are, one the other hand, characterised by a lack of vertical stratification with pulsed run-off events. While broad scale generalisations have been made for purposes of comparison, there are a variety of features that affect individual estuaries which confound attempts to generalise. This again highlights the need for an integrated approach in the classification and management of Australian estuaries.

- Generally low nutrients (nutrient-poor soils, no major upwellings)
- Variability of rainfall
- Overall lack of precipitation
- Low relief; an ancient landscape
- Both temperate and tropical components



Generic conceptual model for Australian estuaries, based on the Moreton Bay model.

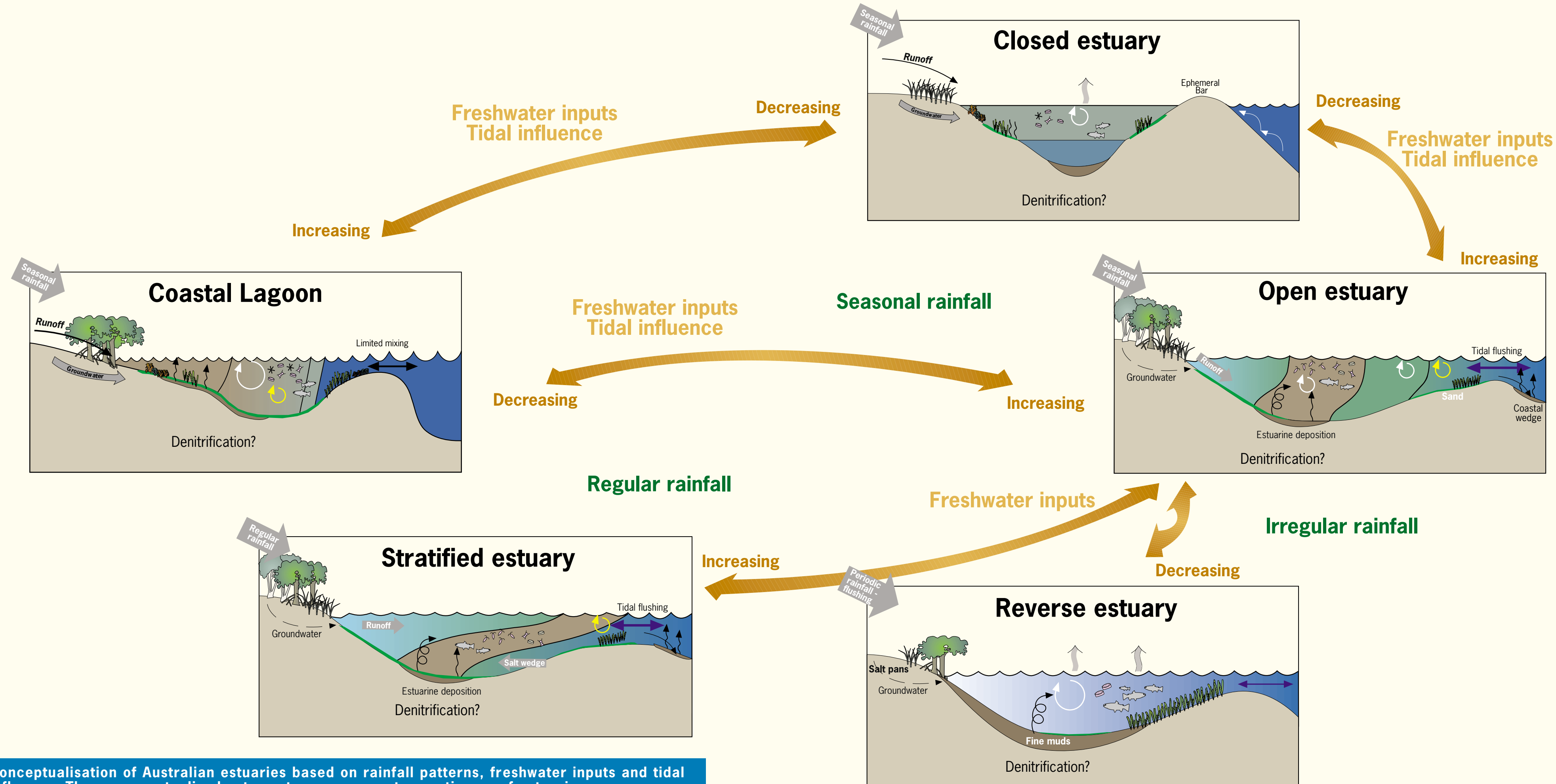
- Vertically stratified
- Long salinity gradients
- High ambient nutrient loads
- Substantial residual nutrients in water column
- Hypoxia/anoxia common



Generic conceptual model for Northern Hemisphere estuaries, based on the Chesapeake Bay model.

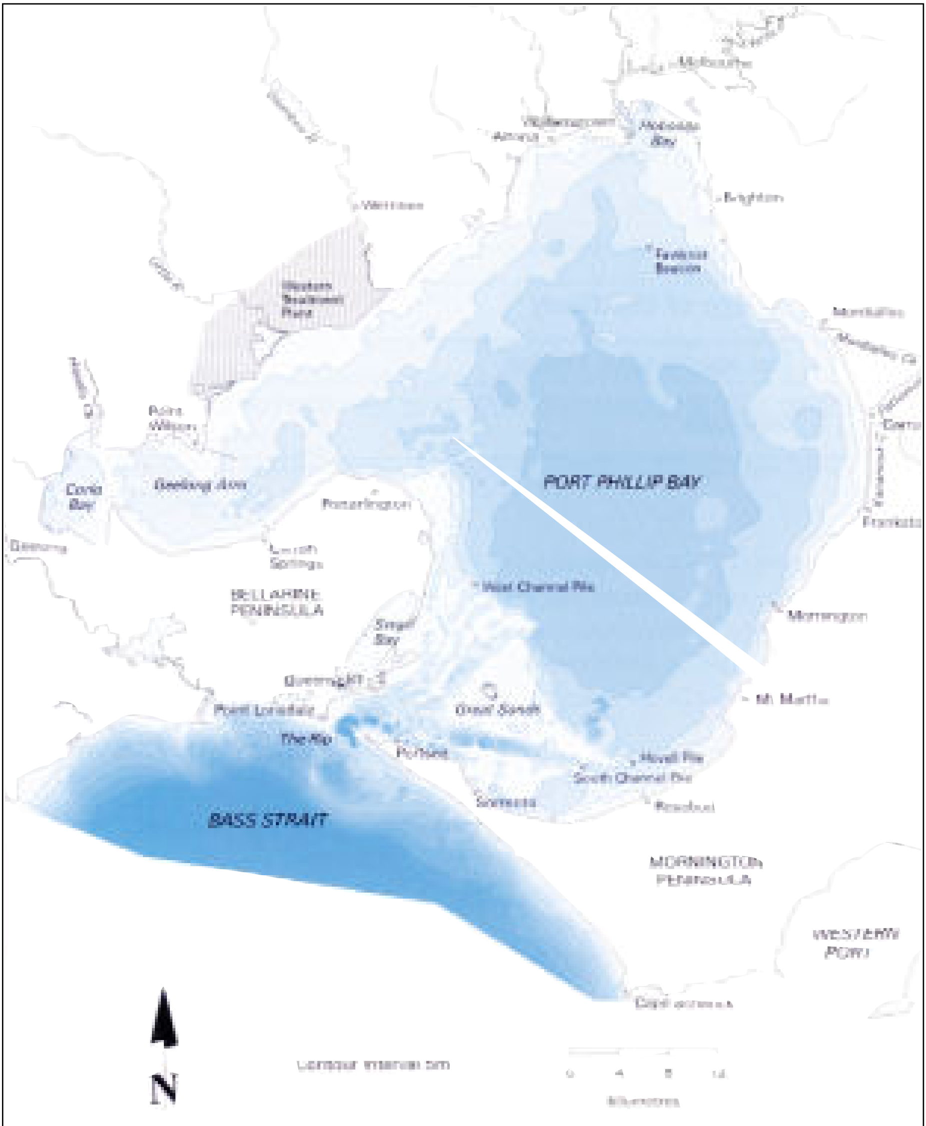
Australian estuaries dominated by rainfall patterns

Australian estuaries are dominated by rainfall patterns, in particular, the seasonality of rainfall. Most Australian estuaries do not experience regular rainfall throughout the year, hence, they rarely develop the vertically stratified estuary typical of North America and Europe. Seasonal rainfall patterns, along with tidal influence interact to change the conductivity of the estuary with the ocean. High rainfall and tidal energy maintain open estuaries, as opposed to coastal lagoons or closed estuaries with lower rainfall and tidal energy, resulting in restricted oceanic exchange. Arid climates with irregular rainfall can lead to 'reverse' estuaries, in which salinity actually exceeds oceanic seawater due to excess evaporation. Using this classification scheme, Moreton Bay and its river estuaries are open estuaries, with seasonal rainfall and appreciable tidal energy resulting in little vertical stratification, but significant horizontal gradients in water quality.



Conceptualisation of Australian estuaries based on rainfall patterns, freshwater inputs and tidal influence. These conceptualised estuary types represent a continuum of estuarine processes, with discrete conceptual models for five estuary types: closed estuary, coastal lagoon, open estuary, stratified estuary and reverse estuaries.

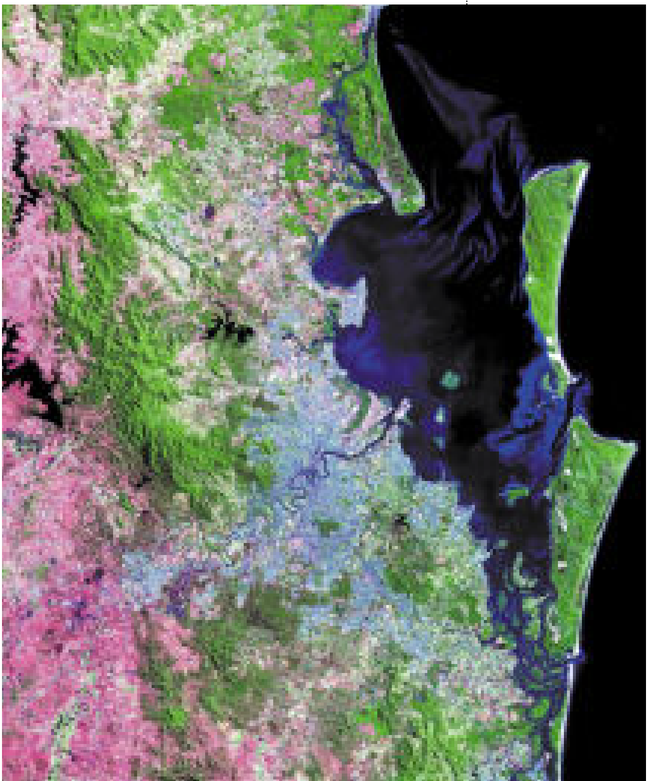
Port Phillip Bay Study most similar to Moreton



Port Phillip Bay Study region, with major population centres, the sewage treatment facility on the Bay perimeters and depth contours (at 5/m intervals) within the Bay marked (Harris, et al., 1996, Port Phillip Bay Environmental Study Final Report).

Bay Study

The Port Phillip Bay Environmental Study conveniently finished as the Moreton Bay Study was being initiated, allowing some of the key findings to be incorporated and for some of the scientific groups to overlap. The Moreton Bay Study did not have the benefit of previous integrated studies in the region, hence the importance of the Port Phillip Bay Study. The identification that sediment denitrification was a key transformation in nitrogen cycling, the ubiquitous nature of benthic microalgae, the localised nature of toxicant impacts, the relative inputs of point and non-point source nutrients were all aspects from the Port Phillip Bay Study that provided an initial focus for the Moreton Bay Study. The use of sediment flux chambers, geographical information systems (GIS), spatial statistical analyses, a numerical hydrodynamical model and the scientific integration of simultaneous component tasks were all capitalised on in the Moreton Bay Study based on the experience gained in the Port Phillip Bay Study.



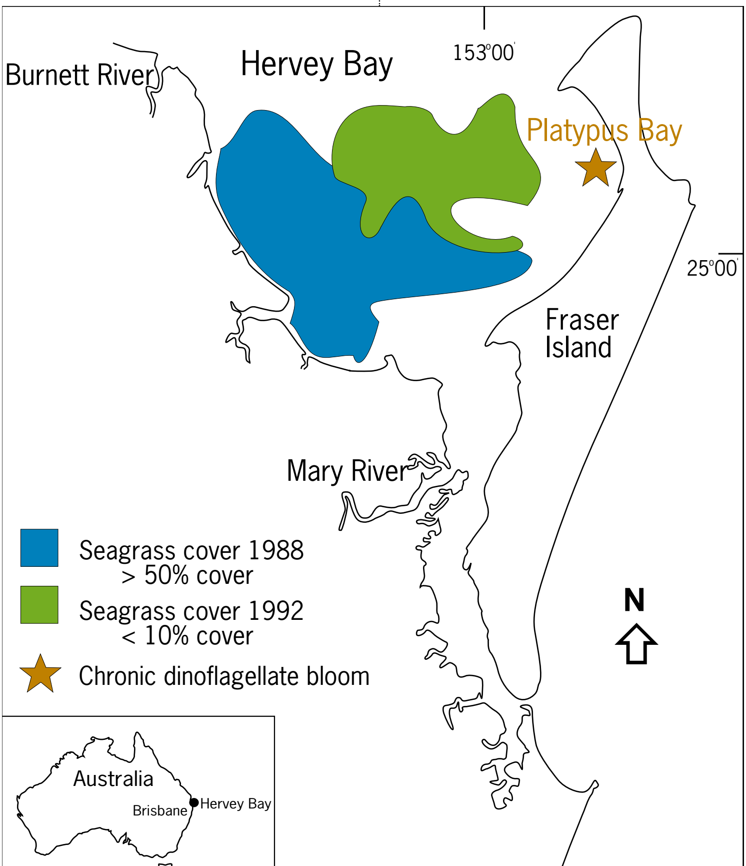
Moreton Bay Study region, with major population centres on the western shores (white-pink areas) and the shallow nature, particularly in the eastern and northern regions of the Bay visible (pale blue).

Comparison table of Moreton Bay and Port Phillip Bay characteristics

	Port Phillip Bay	Moreton Bay
Surface area (km^2)	1930	1523
Major capital city adjacent	Melbourne	Brisbane
Large population in catchment	3 million	1.5 million
Residence time (d)	~ 365	~ 45
Catchment area (km^2)	9790	21220
Latitude (˚N)	38˚	27˚

Hervey Bay: ecological issues without large population

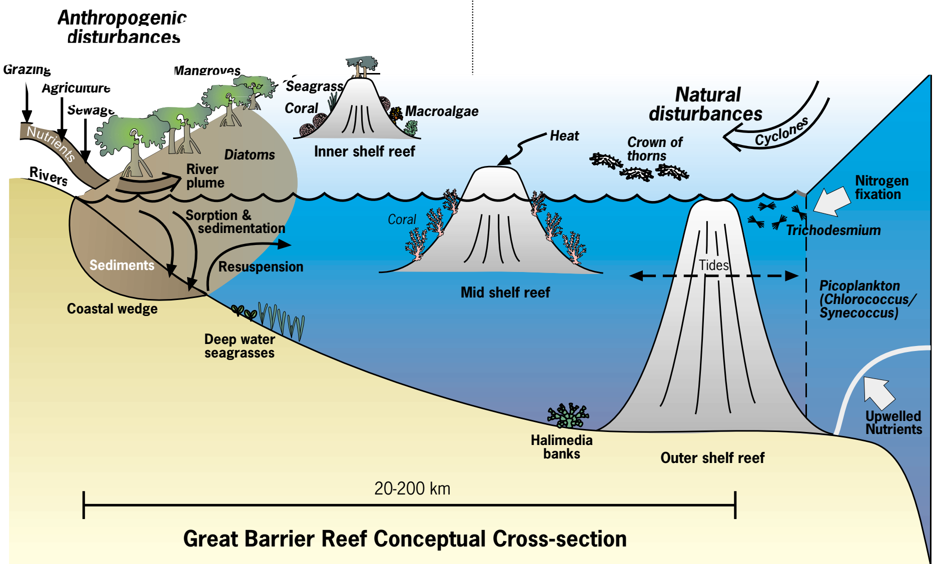
Hervey Bay, about 200 km north of Moreton Bay, is a similar ecosystem to Moreton Bay, hence a brief comparison is in order. Both Bays have large rivers and catchments that discharge into a shallow embayment. Both Bays have large sand barrier islands restricting oceanic exchange. Hervey Bay is much larger, has more effective oceanic flushing (no sand banks in the northern passage) and has little urban development. Yet, Hervey Bay has some serious environmental issues: chronic dinoflagellate populations in the Platypus Bay region of Fraser Island that cause ciguatera poisoning in resident fish populations, and sporadic floods that have led to seagrass declines and subsequent dugong starvation/migration (1000 km^2 in 1992). Some of the environmental issues associated with Moreton Bay may be a result of its unique location and configuration, with the large population pressure accentuating the problems.



Map of the Hervey Bay region with regions affects by environmental issues marked. Chronic dinoflagellate blooms in Platypus Bay have caused ciguatera poisoning in resident fish populations and sporadic floods have caused significant declines in seagrass area and cover, resulting in starvation and migration of dugongs (compiled from Preen, A.R., et al., 1995, Aquatic Botany).

Moreton Bay Study results may be applicable to inshore Great Barrier Reef

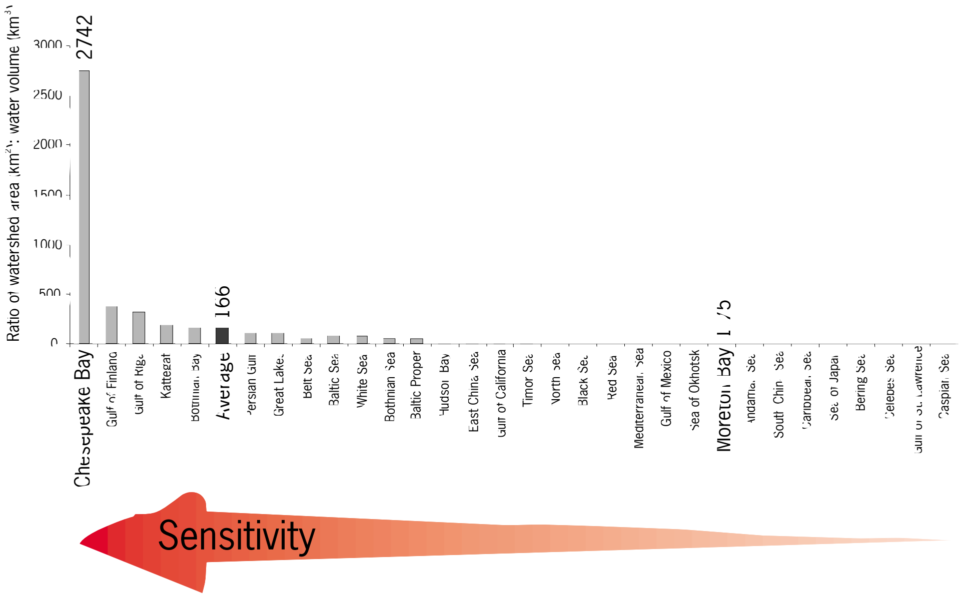
The fluvial nutrient zone of central and western Moreton Bay is similar to the coastal wedge of inshore regions of the Great Barrier Reef. In both cases, the deposition of sediments and associated nutrients from the river catchments are concentrated into discrete areas near the river mouths. Resuspension of sediments can increase turbidity and release nutrients through desorptive processes in the areas of deposited catchment sediments. The principal source(s) of these sediments and associated nutrients is an ongoing research topic in both regions, particularly since the combined effects of sediments and nutrients are of considerable concern in both Moreton Bay and inshore Great Barrier Reef. The other environmental issues identified on the Great Barrier Reef conceptual model; coral bleaching, crown-of-thorns, and cyclones are classified as 'natural' disturbances, however, they may well be indirect anthropogenic disturbances. For example, global warming from greenhouse gas emissions could be related to coral bleaching and cyclone frequency and intensity. Crown-of-thorns outbreaks have been linked to a variety of anthropogenic activities (e.g. fishing and eutrophication). These types of indirect or 'natural' disturbances have not been explicitly incorporated into the Moreton Bay conceptual model. Sea level rise and global warming could indeed have dramatic impacts on Moreton Bay, and research into these type of disturbances should be undertaken in the future.



Conceptual model for a cross-section of the Great Barrier Reef. Anthropogenic disturbances predominate in the inshore sections, with agricultural and sewage inputs, while natural disturbances predominate in the outer shelf reef regions.

Chesapeake Bay: benchmark estuary

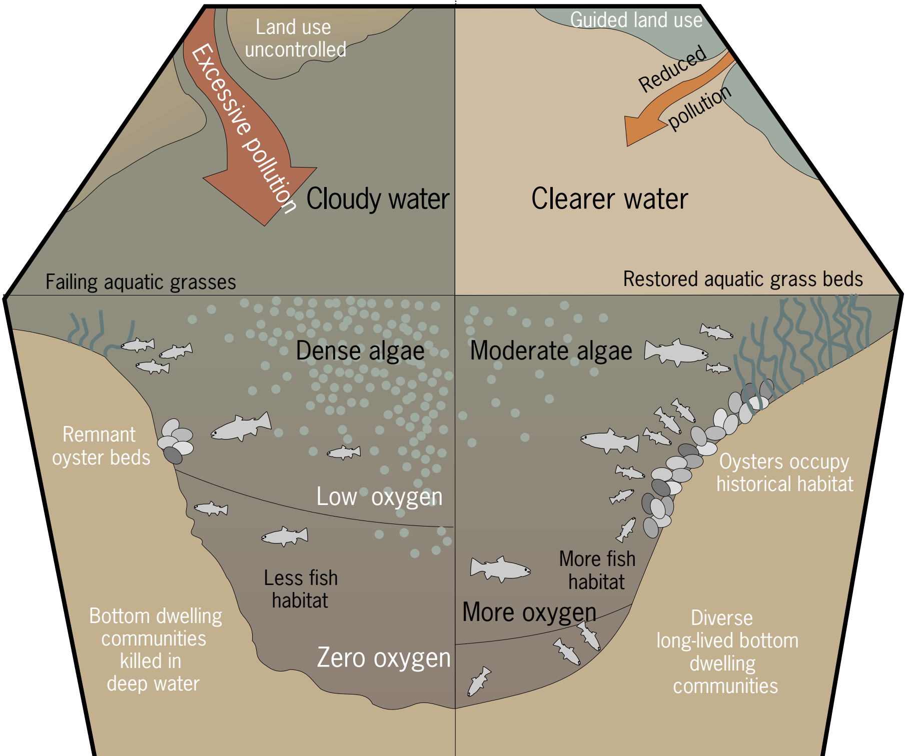
Chesapeake Bay, on the east coast of the U.S.A., has the largest catchment area per Bay volume of any estuary in the world. While this relationship contributes to the overall productive nature of Chesapeake Bay, it also accounts for a high degree of sensitivity to development pressures. In addition, Chesapeake Bay has a large population in its catchment (approximately 15 million people), with a plethora of scientists and resource managers in the region. It is very well studied, but significantly degraded. Historical accounts of Chesapeake Bay emphasize the large migratory bird populations, oyster bars, fish populations, and extensive salt marshes and seagrass meadows. In contrast, the current situation in Chesapeake Bay includes seasonal low oxygen events (hypoxia/anoxia) in the deep channels, toxic dinoflagellate blooms (*Pfiesteria*) causing fish kills, eroding salt marshes and island subsidence due to rapid sea level rise (groundwater extraction), with only remnant seagrass meadows and oyster bars remaining (Horton, T. and Eichbaum, WM., 1991, Turning the Tide - Saving the Chesapeake Bay).



Ratio of catchment area to bay water volume for some of the world's estuaries, with an indication of the sensitivity to degradation of these estuaries based on this ratio (Horton, T. and Eichbaum, W.M., 1991, Turning the Tide-Saving the Chesapeake Bay). Chesapeake Bay, with a high catchment area: Bay volume is vulnerable to degradation, while Moreton Bay is at the lower end of the scale and therefore much less vulnerable to degradation resulting from catchment degradation.

Chesapeake Bay: well studied but degraded

Moreton Bay has a much smaller catchment area per Bay volume, hence is much less sensitive to land development pressures when compared to Chesapeake Bay. The Moreton Bay catchment also has 10-fold less people (1.5 million versus 15 million). As a consequence, environmental degradation in the Moreton Bay region is significantly less severe than Chesapeake Bay, with much of Moreton Bay containing essentially intact ecosystem processes. The Moreton Bay region has a small number of researchers and resource managers, however, this is rapidly changing. A new research station at Stradbroke Island, a new research vessel (Sea Wanderer II), and new positions at the universities and state agencies will be building both the infrastructure and personnel to achieve a more consistent and concerted effort at research and resource management. The intent is that the research and management activities in Moreton Bay can begin to emulate the level of commitment in Chesapeake Bay BEFORE significant environmental degradation takes place.

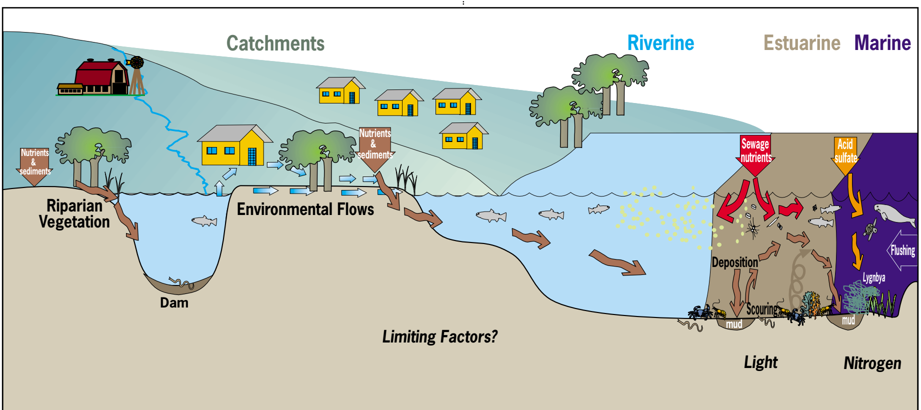


Conceptual diagram for Chesapeake Bay depicting the current degraded condition of the Bay (left) and the future healthy condition for the bay (right) (Horton, T. and Eichbaum, W.M., 1991, Turning the Tide-Saving the Chesapeake Bay). The increasing research and management activities in Moreton Bay is intended to increase understanding and protection before significant degradation takes place.

Moreton Bay Study: catchment focus in Stage 3

Stage 3 of the Study focuses on the freshwater catchment areas of the Moreton Region and incorporates the North (Noosa, Maroochy, Caloundra) and South (Gold Coast) Regions. It is being funded and developed by all of the South East Queensland Regional Organisation of Councils (SEQROC) (plus Crows Nest), with funding primarily from the Commonwealth's Natural Heritage Trust Rivercare and Coast and Clean Seas programs and the Queensland Environmental Protection Agency (QEPA) Healthy Waterways program. Contributions from the Department of Natural Resources (DNR), Queensland Transport (QT), South East Queensland Water Board (SEQWB), Port of Brisbane Corporation (PoBC) and the Commonwealth's Australian Research Council Strategic Partnerships in Research Technology (SPIRT) program, through the University of Queensland and Griffith University, are also supporting the development of the Water Quality Strategy in Stage 3.

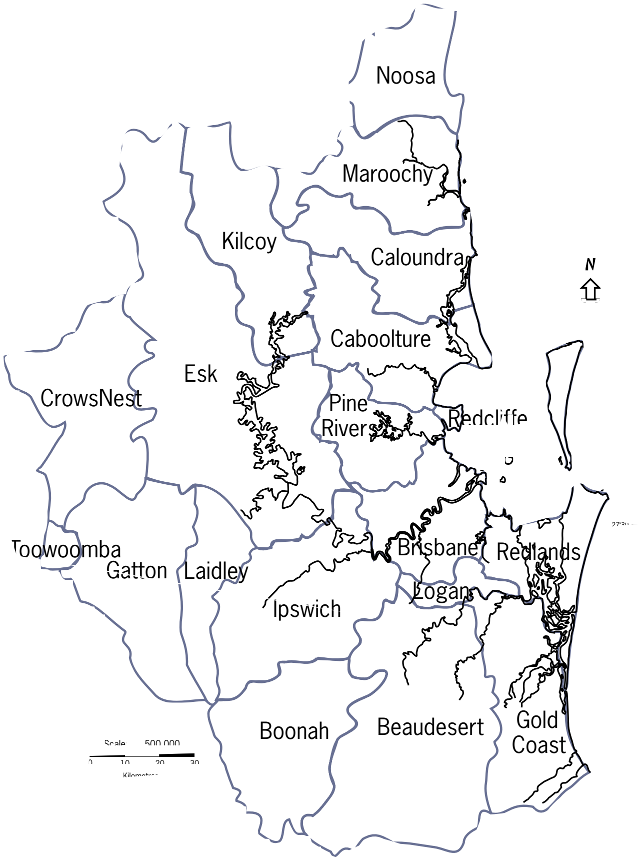
Stage 3 will be undertaken in the same collaborative manner as Stage 2, with particular emphasis on landholders, community catchment/landcare groups and local government in developing appropriate water quality and catchment management actions. Key issues identified by both stakeholder and scientific groups include the sourcing of sediments and nutrients (including their potential impact on in-stream biota and the locations of the ultimate sink(s) and storage(s) for these materials; the role of riparian vegetation in maintaining/improving ecological health in-stream and of the downstream reaches of the rivers; and the development of an integrated and cost-effective monitoring program for the freshwater areas of the catchment. These tasks incorporate existing programs such as Waterwatch and catchment group monitoring. Stage 3 will also build on the outcomes of Stage 2 and address some key issues identified in Stage 2 as requiring further investigation.



Initial conceptual model for Stage 3 depicting major issues and processes to be addressed in Stage 3 as identified by scientists and stakeholders. The geographic focus of Stage 3 is in the freshwater catchment regions, but will also address key issues in the marine and estuarine regions identified in Stage 2 as requiring further investigation.

Moreton Bay Study Stage 3: wider scope and membership

The ultimate aim of Stage 3 is the delivery of the vision of the Study (refer to Chapter 2). The Moreton Bay Catchment Water Quality Management Strategy will be further developed in Stage 3, in a manner consistent with regional priority needs, to become a regional water quality management strategy for south-east Queensland. Integration of stakeholders across the whole catchment of the region is identified as crucial in order to come up with a consistent approach to improving water quality and ecological health throughout the catchments and eventually achieving the vision.



Stage 3 of the Strategy involves membership by a much greater number of local councils. The Strategy has expanded to involve all catchments of the sout-east Queensland region.

Stage 3 key issues

- Riparian rehabilitation
- Sediment and nutrient sourcing
- Integrated monitoring program for freshwaters
- Limiting nutrients
- Non-point source loads
- Catchment land use and water quality
- Environmental flows
- Sediment processes
- *Lyngbya* blooms
- Turbidity sources and processes
- Bremer River processes
- Ship source pollution
- Vessel wash impacts
- Ballast water and introduced pests in the port area
- Water allocation
- Toxicants and pathogens

The coastal management challenge

The coastal management challenge, in regions throughout the world, is to cope with increasing human population pressures without irreversibly damaging the rivers, estuaries and coastal oceans. The expansion of fertiliser-intensive agriculture and the migration of people to the coast has led to increased nutrient enrichment of coastal waters. In addition, fine-grained sediments from urban and catchment runoff and the discharge of various toxicants have also contributed to environmental degradation in coastal regions. In this way, the Moreton Bay Study provides an example of the combined pressures stemming from increasing human population. The overall conclusions and recommendations from the Moreton Bay Study are not likely to be very different from many other regions, namely significant degradation in portions of the coastal ecosystem in which restoration is needed, along with intact portions of the coastal ecosystem in which some protection is warranted. The relative proportion of intact versus degraded ecosystem is variable, and Moreton Bay is fortunate in having a relatively large amount of its ecosystems still essentially intact.

The partnership arrangement with simultaneous scientific investigations and strategy development involving the various stakeholders has proven to be an effective method of conducting environmental research and monitoring in the Moreton Bay Study. It has resulted in many of the recommendations from the Study having already been incorporated by various government and community groups. The acceptance of the recommendations has been facilitated by effective communication of scientific and monitoring results, and this report represents one component of this effort. Bringing SCIENCE (Scientists Communicate Informative Essential News Concisely and Effectively) to the interested parties was an important part of the overall Healthy Waterways Campaign. Another part of the communication process was stakeholder identification of various issues. In particular, the toxic blooms of *Lyngbya* were first identified by commercial fishermen as a human and ecological health issue after the Study was underway. The response by the Moreton Bay Study was to redirect efforts to delineate and investigate the *Lyngbya* bloom.

The Moreton Bay Study with its associated Healthy Waterways Campaign provides an example of how to address the overall challenge of increased coastal pressures. A common vision, a regional approach, a staged set of tasks with close linkages between stakeholders and the science and management appear to be essential elements of a successful program. Two-way communication between scientists and resource managers is also crucial. Another aspect that emerged from the Moreton Bay Study was that continued strategy development, further research and ongoing monitoring are necessary, albeit at a reduced intensity from the efforts captured in this book. One of the enduring successes of the Moreton Bay Study was the success of the key partners in obtaining a new Cooperative Research Centre focusing on Coastal Zone, Estuarine and Waterway Management. These ongoing activities are necessary to ensure that the various management actions are achieving their intended aims and to have the ability to adapt to new and emerging challenges. The future of our coastal waterways is at stake, and we will need all of the insights, lessons and tools (and more!) to meet the coastal management challenge.

HEALTHY WATERWAYS
Because we're all in the same boat

Next section ▶

Glossary

Adsorbed	Bound to sediment grains in an exchangeable form, referring to, for example, nutrients
Aerobic	Metabolism with oxygen
Ambient	The background environmental condition
Ammonium	The reduced form of nitrogen (NH_4^+)
Anaerobic	Metabolism without oxygen
Anthropogenic	Resulting from human activities
ATP	(Adenosine Tri Phosphate) high energy compound used for cellular energy needs
Autotroph	An organism capable of converting carbon dioxide into organic molecules
Bacteria	A primitive group of ubiquitous, microscopic, single celled organisms lacking a nucleus
Benthic	Pertaining to the seafloor or river bottom
Benthic Microalgae	(BMA) Microscopic plants which inhabit the sediment surface or interstitial water, mostly diatoms and dinoflagellates
Biodiversity	The range of different species present in an area
Bioirrigation	The increased exchange of overlying water into sediments due to reworking of the sediments by animal activity
Biomass	The amount of living material
Biota	All living organisms; plants and animals
Bloom	An event in which a biotic population rapidly expands
BRMBWMS	Brisbane River and Moreton Bay Wastewater Management Strategy (Currently SEQRWQMS)
Catchment	The area of land which collects and transfers rainwater into a waterway
Chlorophyll	Major pigment that captures light for photosynthesis, found in cells of plants and bacteria

Chlorophyta	Green algae which contain the chlorophyll pigments
Conceptual model	A diagram depicting the most current understanding of the major ecosystem features and processes (biological, physical and chemical components) of a particular location.
Crustacean	A class of predominantly aquatic organisms which generally have a hard shell (e.g. crabs, prawns, lobsters)
Cyanobacteria	Primitive, photosynthetic bacteria occurring as single cells or in filaments, some of which are often capable of nitrogen fixation (often referred to as blue-green algae)
Denitrification	The conversion, carried out by anaerobic bacteria, of the biologically available, oxidised form of nitrogen (NO_3^-) to nitrogen gas (N_2) which is biologically unavailable
Detritus	Fragments of dead and decomposing plants and animals
Diatom	A group of unicellular, pelagic and benthic microalgae which are characterised by the presence of an intricate silica skeleton
Dinoflagellate	A group of unicellular algae characterised by two flagella. Some are autotrophic while others are heterotrophic. Responsible for 'red tides'
DNA	(Deoxyribulose Nucleic Acid) genetic material in all living organisms
Ecological health	An ecosystem in which key processes are sustained, habitats remain intact and the zones of anthropogenic impacts do not deteriorate
Estuary	Zone of mixing of fresh and salt water in the lower reaches of a river
Fluorescence	Re-emission of long wavelengths of light from the pigments which capture light in photosynthesis
Fluorometer	An instrument which determines chlorophyll concentration by fluorescence
Flushing	Exchange of water from one location to another
Habitat	The environment in which a plant or animal lives
Heterotroph	An organism which cannot photosynthesise and instead acquires carbon by ingestion of organic molecules
Hydrodynamic	The movement of water
Infauna	Animals that live in the sediment
Interstitial	The water between sediment grains
Intertidal	The area along the coast below high tide and above low tide

Invertebrate	Animals without backbones
Lyngbya majuscula	Filamentous, toxic cyanobacteria
Macroalgae	Multicellular plants that are visible to the human eye; green algae, red algae and brown algae
Mangrove	Trees which inhabit the intertidal zone on sheltered coastlines. Their lower trunk and roots are periodically flooded with the tides
Monitoring	Continual measurements in order to determine changes in the environment
Nitrate	The most abundant oxidised form of nitrogen (NO_3^-)
Nitrification	The conversion, carried out by aerobic bacteria, of the reduced form of nitrogen, ammonium (NH_4^+), to the oxidised forms, nitrite (NO_2^-) then nitrate (NO_3^-)
Nitrite	An oxidised from of nitrogen (NO_2^-)
Nitrogen	An essential nutrient for all organisms forming a component of amino acids, protein, and genetic material
Nitrogen fixation	The conversion of nitrogen gas (N_2), which is biologically unavailable to most organisms, to ammonia, a process carried out by a select group of bacteria and cyanobacteria
Non-point source	A source, of, for example nutrients or sediment, not restricted to one discharge location
Nutrient	Essential elements required by an organism for growth
Nutrient flux	The transfer of nutrients within sediments to or from the water column
Pelagic	Pertaining to the water column
Phaeophyta	Brown algae which contain green chlorophyll pigments and orange carotenoid pigments
Phosphorus	An essential nutrient for all organisms forming a component of, for example, ATP and phospholipids
Photosynthesis	The process carried out by plants and some bacteria in which light energy is harvested by pigments (mostly chlorophyll) and utilised to convert carbon dioxide and water into organic molecules and oxygen
Phytoplankton	Microscopic, planktonic plants which are either single celled or form chains
Point source	A single point discharge, of, for example, nutrients or sediment

Productivity	The rate at which biomass is produced
Redfield ratio	Atomic ratio of nutrient content in aquatic plants and seawater (carbon:nitrogen:phosphorus)
Resisdence time	Average length of time that water or compounds dissolved in the water remain in a certain location
Resuspension	Process in which sediment particles are brought back into suspension in the water column by waves, tide or wind
Rhodophyta	Red algae containing green chlorophyll and red phycobilin pigments
Salinity	Salt content of seawater expressed in parts per thousand
Seagrass	Marine flowering plants which are generally rooted in the sediments
Secchi disc	A plate-sized disc which is lowered into the water column to determine how deep it remains visible from the surface
Sediment	Particulate matter at the bottom of the water column of rivers and the Bay, generally derived from soil on land
SEQRWQMS	South East Queensland Regional Water Quality Management Strategy (formerly BRMBWMS)
Sewage effluent	Household and industrial wastewater that has been treated to reduce solids, organic and nutrient content
Sorbed	Bound to sediment particles, either by being absorbed into the particle or adsorbed onto the particle surface
STP	Sewage treatment plant
Stratification (vertical)	Physical layering of the water column resulting from density differences primarily due to temperature or salinity differences
Taxa	General taxonomical term for a sub-group of organisms (e.g. species, genus, family etc.)
Tonnes	(t) unit of weight measure equalling 1000 kg
Toxicant	A substance that can harm living organisms
Turbidity	The condition resulting from the presence of suspended particles in the watercolumn which attenuate light
Vertebrates	Animals with backbones
Zooplankton	Non-photosynthetic plankton which have heterotrophic nutrition (includes protists, animals and larvae of animals)

Symbol Glossary

Processes

- $Org \rightarrow NH_4^+$ Ammonification
- Seagrass loss
- $NH_4^+ \rightarrow NO_3$ Nitrification
- Seagrass loss/recovery
- Sediment resuspension
- Surficial denitrification
- Sediment nutrient fluxes
- Nitrogen fixation
- Deposition/Scouring
- Denitrification
- Phytoplankton bloom/crash
- Blocked process
- Secchi depth
- Phytoplankton uptake
- Organic matter
- Sedimentation
- Zooplankton migration
- Wind induced circulation
- Zooplankton grazing
- Low or undetectable sediment nutrient flux

Inputs

- Nutrients and sediments
- Sewage
- Acid sulfate run-off
- Flushing
- Toxicants
- Acid sulfate run-off
- Stormwater Drain
- Sewage treatment plant
- Aquaculture
- Water transport

Biota

- Dugong
- Phytoplankton
- Turtle
- Bacterioplankton
- Macroalgae
- *Lyngbya*
- Seagrass
- Coral
- Seagrass
- Mangrove
- Benthic Microalgae
- Hail damaged mangroves
- Prawn
- Salt marsh
- Zooplankton
- Birds
- Crab
- Jellyfish
- Worms

Further Reading List

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Relevant Reading from the Study

Brisbane River and Moreton Bay Newsletter: Scientific Task Updates: 1-4

Brisbane River and Moreton Bay Wastewater Management Strategy Information Sheets

DIBM Monitoring Newsletters: 1-6

Ecological Health Monitoring Program Proposal Newsletter

Ecological Health Monitoring Program Video

Healthy Waterways Video

Moreton Bay Catchment Water Quality Management Strategy

The crew member's guide to the health of our waterways.

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Location Index

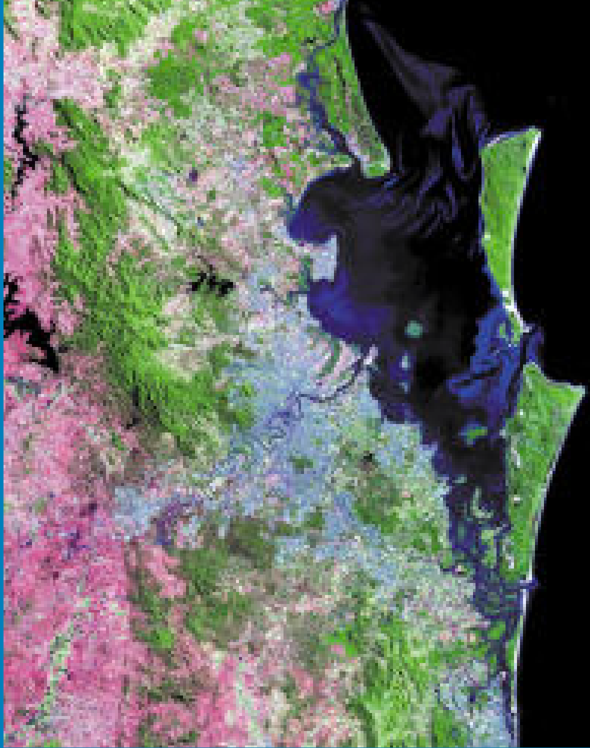
Bold face numbers indicate figure, map, diagram or photograph

Subject Index

Bold face numbers indicate figure, map, diagram or photograph

This book provides the

- **Highlights of the scientific data**
- **Interpretation of results**
- **Rationale for the water quality strategy**



obtained in the Moreton Bay Study. The Moreton Bay Study provided the scientific basis for the Healthy Waterways campaign and was the most concentrated research effort ever conducted in the region. Over 100 scientists from Australia and overseas intensively studied Moreton Bay and its river estuaries and this book provides an overview of the results in an information-rich, jargon-free, communication-based format.

The following questions are addressed in the book:

- **What is the ecological health of Moreton Bay and its river estuaries?**
- **How has water quality changed since pre-European settlement?**
- **What are the circulation patterns in Moreton Bay?**
- **Where does the sewage effluent end up?**
- **Why is the Brisbane River turbid?**
- **What killed the seagrass in Bramble Bay?**
- **Where do the sediments and nutrients entering Moreton Bay come from?**
- **Are toxicants important?**
- **What is causing severe skin rashes in Deception Bay?**
- **How is this study and region any different than other studies in other locations?**

The companion book, Crew Member's Guide to the Health of Our Waterways, provides a cry for help and encourages you to join the Healthy Waterways crew. This book, Moreton Bay Study: A Scientific Basis for the Healthy Waterways Campaign, provides you with the crucial information necessary to answer that cry for help.