# CHAPTER 1

# SETTING THE PROBLEM

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## 1.1. Great Barrier Reef health status

Coral reefs are sometimes referred to as "tropical rainforests of the deep" since they are one of the most diverse, productive, and beautiful marine ecosystems in the world (Spalding et al 2001). They protect coastlines from offshore waves and currents, sustain habitats of some of the world's most endangered species (e.g. turtles), support fisheries of economic and cultural value, provide diving-related tourism, and serve as habitats for organisms that produce natural products of biomedical interest. Considering that healthy coral reefs are such a valuable asset, marine protected areas are becoming a critical tool for maintaining them worldwide.

The Great Barrier Reef Marine Park (GBRMP) is the largest protected reef in the world, and has been well managed since 1975 with a detailed zoning plan, providing areas of strict protection alongside areas of multiple use. Indeed, a new zoning plan has just come into force on 1 July 2004, which increases highly protected areas (so called "no take" zones) from 5 % to 33 % (GBRMPA 2004). As a result of such efforts, GBRMP is usually cited as an example of the most "pristine" and healthy coral reef systems in the world.

However, an increasing weight of evidence shows system-wide decline of coral reefs in the Great Barrier Reef (GBR) over the past decades (Bellwood et al 2004). This can be attributed to a number of causes, among which are over-harvesting, pollution, disease and climate change. Of those, the first two are the direct consequence of human activities. Over-harvesting is not a pressure for the GBR, as the people who live there do not depend on the reef's ecosystems for subsistence and also as strict regulations are provided by GBRMPA. On the other hand, pollution prevention, or equally, protecting water quality in the Great Barrier Reef World Heritage Area (GBRWHA), is recognised as one of the major challenges facing management of the area (Haynes 2001).

## 1.2. Effects of nutrient and sediment on corals

Dissolved nutrients and nutrient-rich sediments, which support the productivity of ecosystems of the GBR, come from a variety of sources with terrestrial runoff being the largest source. This mainly occurs via river discharge, especially during periods of intense rainfall typically associated with tropical cyclones. As a result, river discharge regimes in the GBR catchments are highly seasonal and usually episodic in nature.

Floods and associated plumes are recurrent natural phenomena in the GBR lagoon, and reefs have adapted to inputs of terrestrially derived nutrients and sediments over the course of evolution. Current coral reef communities have evolved under certain levels of nutrients and sediments, and adequate levels of those are crucial for maintaining the biological stability and diversity of coral reefs. However, increased (possibly through human activity) levels of terrestrial freshwater, nutrients, sediment and toxic substances entering the GBR system are potentially a significant threat to the GBR. The effects on corals are considered below.

There is increasing evidence that certain levels of sediments are detrimental to corals. Suspended sediments contribute to water turbidity and attenuate light penetrating the water column, thus decreasing the availability of the primary source of energy for corals, their symbiont zooxanthellae (a microscopic single celled plant), seagrass and benthic algae. In nearshore habitats of the GBR it has been found that distributions and diversity of hard and soft corals and coralline algae are inversely correlated with water turbidity (Furnas 2003). A significant decrease in fertilisation, larval survival and settlement of a scleractinian coral was observed at 50 $g/m^3$ of suspended sediment concentration (equivalent to circa 20 cm visibility) (Gilmour 1999), while increased respiration was recorded after introducing lower suspended sediment levels of about 15 $g/m^3$ (equivalent to 60 cm visibility) to similar species (Telesnicki et al 1995). Under extremely low light conditions (circa 10 % of the surface irradiance level), a coral may lose its most important symbiont zooxanthellae by degradation (Titlyanov et al 2001). However, some corals exhibit higher resistance to sediments with survival rates not being affected even after a 10-day exposure to suspended sediment concentrations up to 200 $g/m^3$ (Rice et al 1992). This is an exception, as other studies suggest that even though energy stores can carry corals through extended periods (weeks to months) of high turbidity and low light, repeated events may reduce energy stores to critically low levels because the rate of energy store (lipid) synthesis is slower than the rate of energy loss (Anthony 2004).

At high suspended sediment levels and sufficient exposure time, direct deposition of sediments on underlying substrate might occur. At low to medium sediment thickness levels (0.5-5 $mg/cm^2$) coral polyps are able to physically clean themselves by secreting mucus and then expelling it off into the water – an energetically expensive process (Fabricius et al 2000). Therefore, prolonged exposure would deplete corals' energy stocks and weaken the system. A number of studies have simulated the various scenarios of sediment deposition that would normally follow severe storms and cyclones. Possible outcomes of high sediment deposition rates include decreased survival of coral juveniles (Fabricius et al 2003), suppressed regrowth of surviving adult colonies due to inability of corals to grow on fine muds or shifting sediments (Nugues et al 2003), and even death of corals and some coral-inhabiting organisms (Sorokin 1993; Philipp et al 2003; Ortiz et al 2004). Coral mortality critically affects reef communities, as corals provide an important trophic link as well as the main habitat structure for their inhabitants. Although organic matter associated with sediments provides an extra nutrient resource for corals and other reef organisms, flocculation, or aggregation of particles, known to occur in organic matter-rich waters, can increase the negative effects mentioned above (Fabricius et al 2000; Weber et al 2004).

Similarly, more nutrients do not necessarily translate into enhanced productivity. The most comprehensive study to date was conducted on One Tree Island (GBR) where a multi-disciplinary team of scientists monitored and recorded nutrient dynamics and biotic responses to variable nutrient enrichment scenarios introduced to a number of small patch reefs (Koop et al 2001). Results from a two-year experiment showed that reef organisms were impacted by elevated nutrients at the level of the organism (e.g. increased coral mortality, reduced reproduction of corals), depending on dose levels, type of nutrient added, and were often species-specific. Overall, the impacts were generally sublethal and subtle, and most of the treated reefs at the end of the experiment were visually similar to control reefs (Koop et al 2001). The investigators also concluded that inorganic nutrient concentrations alone are not adequate to assess biogeochemical conditions on reef. This is because these systems are very efficient in utilizing and recycling all available sources of energy: the main pools of mobile nutrients exist mainly in the living biomass of organisms, and much less in organic matter of detritus and sediments, while the ambient inorganic nutrient pools are usually negligible (Sorokin 1993).

In contrast, a number of studies have shown more deleterious effects of increased nutrients on reef ecosystems, such as oscillations in species composition and even massive die-offs of many of the native organisms if left unchecked (Pastorok et al 1985; Tomascik et al 1987; Dubinsky et al 1996; Edinger et al 1998). Bucher and Fisher (2004) predicted that under conditions of chronically elevated ammonium, urea concentration in a coral would reach a maximum tolerable level followed by a decline in growth and health of the coral. These examples indicate that eutrophication primarily affects coral reefs through ecosystem responses to organic enrichment. Changing the biological balance might alter the local geochemistry and trigger community shifts from the "healthy" coral state to macroalgae colonisation, followed by sea urchin dominance and even degrading to a bare rock environment (Bellwood et al 2004).

Watershed streams and ground water carry a variety of chemicals from agricultural, industrial and domestic activities, among which heavy metals and synthetic organic matter such as herbicides and pesticides associated with sugar farming are the most relevant to the non-urban areas of the GBR (NLWRA 2001). Heavy metals have been detected in tropical marine ecosystems, causing physiological stress, reduced reproductive success, and outright mortality in some invertebrates and fishes (Peters et al 1997). Herbicides adversely affect the animal–algal symbioses in corals, while pesticides interfere with chemical cues responsible for key biological processes, including reproduction and recruitment of a variety of reef organisms (Brodie 1992). However, detailed information with regard to the long-term effects and recovery of coral communities in response to toxic pollutants is lacking (Spalding et al 2001).

Corals are wholly marine organisms unable to grow in freshwater environments. Increased freshwater supply delivered by river floods can lower local salinity to levels that are lethal to corals and reef organisms (Jokiel et al 1993; Furnas 2003; Jokiel 2004). Recovery after a major disturbance can take several decades, with some reefs never fully recoverable (Wolanski et al 2004).

While coral reefs are sensitive to environmental changes, they appear to be able to recover effectively from physical disturbance or temporary pollution events with the course of time. Kaneohe Bay, Hawaii, is a classic example of a polluted reef system that underwent revitalisation once the primary land-based source of pollution was removed (Hunter et al 1995). From the 1950s, localised eutrophication caused by sewage discharge profoundly altered a nearshore reef ecosystem. Significant reduction of salinity resulted in massive mortality of coral reef organisms. Loads of nutrients accompanying the sewage supported a dense and persistent plankton bloom and triggered the overgrowth of corals by algae. After 30 years of pollution with sewage, this stress was removed in 1978 when wastewater treatment programs were installed. Improvements in the health of the bay, including an increase in water clarity, a reduction in plankton, and a decline in inorganic nutrient concentrations, were documented within weeks of the stress removal (Hunter et al 1995). Coral coverage doubled between 1971 and 1983, although after that the recovery process has been interrupted several times by new disturbances resulting in inability of some reefs in the bay to recover fully. Nevertheless, this example clearly indicates the resilient capabilities of natural ecosystems to environmental offences.

### 1.3. Human alterations to river discharge

River flood plumes entering the GBR carry catchment signatures and reflect land uses and associated activities in concentrations of their constituents. Since European settlement, land-use practices such as clearing, agriculture and cattle grazing have led to substantially increased freshwater, sediment and nutrient loads entering the inner GBR. Using Ba/Ca ratios analyses in nearshore corals (Ba is advected with the flood waters and partitioned into the coral carbonate skeleton in proportion to the ambient seawater concentration), McCulloch and co-authors found a five- to tenfold increase in the delivery of sediments from the Burdekin River catchment, the largest catchment in the area (McCulloch et al 2003). One of the most prominent causes for that are clearing of riparian and wetland vegetation and thus elimination of the natural barrier for water and sediments entering the river channel. Typically, a mangrove swamp covering just 3 % of a river catchment is able to trap 30-40 % of the fine sediment load arriving with the river discharge (Wolanski et al 2004). Nutrients associated with suspended particles resulting from soil erosion contribute to an increased terrestrial chemical load entering the marine system. Fertilisation of sugar-cane fields, the main agricultural activity of the region, has been the major source of elevated dissolved nutrients and pollutants (e.g. pesticides) in river discharge since agricultural development of the region (Haynes 2001). Models of runoff, land use and nutrient delivery suggest that riverine sediment and concurrent nutrient fluxes to the GBRWHA from adjoining catchments have increased several fold since the advent of European agricultural practices (NLWRA 2001).

At the moment, there is no evidence of changes in the frequency or severity of cyclones over the past century in the GBR area (Lough 2001). However, according to a number of computer models, a scenario of increased precipitation intensity of tropical cyclones leading to elevated risks of floods, triggered by climate change, is a possibility, as outlined in the latest Intergovernmental Panel on Climate Change (IPCC) report (Watson et al 2001). Nevertheless, the climate change term is the most unknown in the equation because of the complexity of climate feedback loops and interactions.

Thus it is a combination of natural disturbances (floods) and human-enhanced nutrient and sediment inputs that produces the greatest threat to the GBR ecosystems.

### 1.4. Need to monitor

There is no debate that levels of nutrients and sediments discharged by rivers have increased since European settlement. However, there is no direct evidence at the moment that these increased levels affect the coral reefs of the GBR, with some studies even suggesting that human impacts will be largely undetectable in the regional turbidity and sediment accumulation records (Larcombe et al 1999). Overall, neither the magnitude of terrestrial inputs of sediments and nutrients to the GBR nor the effects of terrestrially derived nutrients on ecosystems within the GBR are well constrained at this time (Furnas 2003). However, as stated in the Rio Declaration from the 1992 United Nations Conference on Environment and Development, *"in order to protect the environment, the precautionary approach shall be widely applied by States* [LA: meaning nations] *according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."* (UN 1992).

The possible detrimental effects to corals from increased and more concentrated river runoff are twofold. On the one hand, there is the direct impact of decreased light availability and possible eutrophication, most relevant for fringing (i.e. growing along the coastline or margin of an island or continent) and nearshore reefs. On the other hand, direct evidence of damage might not be obvious for mid-shelf and outer reefs, as plumes rarely reach these rich and mature systems. Nevertheless, subtle effects, through increased background concentrations and gradual build-up of damage in reefs not accustomed to elevated concentrations, can lead to a loss of resilience and irreversible community changes (Bellwood et al 2004). Due to the sensitivity of coral reef ecosystems to natural and anthropogenic stress and because of the rapidity with which some changes occur, methods that provide immediate baseline and subsequent monitoring data over large areas are necessary to focus restoration and conservation efforts, and to produce results on time scales that permit adaptive management.

The unpredictable nature of rainfall and runoff events, as well as the unsteadiness and patchiness of the resulting plumes in a complex region such as the GBR, have traditionally made data logistically difficult to collect. Given the natural temporal and spatial variability observed in plume behaviour, real-time observations of plumes are highly desirable. Such opportunity is readily available with remote sensing technologies. Remote sensing is an appealing alternative approach to direct measurements because it provides non-invasive, synoptic, repetitive data for environmental parameters across broad spatial and temporal domains. These technologies are also cost-effective for regional studies because they eliminate the need to conduct expensive in situ monitoring programs. This is particularly relevant in areas where in situ monitoring has not been properly developed or where there are significant gaps in monitoring capabilities (e.g. insufficient resources to monitor routinely).

1.5. Satellite remote sensing

Remotely sensed ocean colour data acquired with satellite sensors provide temporally resolved synoptic views of ocean regions over long periods of time. These data can be applied to study the spatial and temporal dynamics of ecologically and biogeochemically important properties of the upper ocean, such as phytoplankton pigments, primary production patterns, suspended sediments, dissolved nutrients, and light attenuation properties. These applications indicate the versatility of satellite remotely sensed data for addressing environmental issues in coastal regions. Such issues include: How far do plumes travel? and What is the fate of geophysical properties in the plume? Therefore, remote sensing is potentially suitable for studying river plumes entering coastal oceans.

First generation sensors, the Landsat type visible radiometers with high spatial resolution (~30 m) were found to provide information of unforeseen value on sediments and surface bottom classification (i.e. geomorphological zonation) in coral reef environments (Smith et al 1975; Andrefouet et al 2001), coral reef extent (Mumby et al 1998), patterns of bathymetry to a depth of ~25 m (Stumpf et al 2003), reef communities up to 5 habitat types (Mumby et al 1997), coral loss dynamics (Palandro et al 2003), turbidity patterns in coastal waters (Amos et al 1979; Ritchie et al 1988; Harrington et al 1992), water quality (Baban 1993; Braga et al 1993; Phinn et al 2005). Nevertheless, simultaneous retrieval of a number of water properties in coastal environments is questionable with the three Landsat bands in the visible spectrum (Mumby et al 2004), while a revisit time of the satellite (about 16 days) cannot capture the temporal dynamics of coastal waters (Miller et al 2004).

Among the second generation satellite sensors, the Sea-viewing Wide-Field-of View Sensor (SeaWiFS) holds the longest and the most consistent record of receiving and processing ocean colour data (http://oceancolor.gsfc.nasa.gov/). Launched on August 1, 1997, SeaWiFS began collecting global data operationally in mid-September that year and has continued to perform flawlessly for the past seven years (http://seawifs.gsfc.nasa.gov/SEAWIFS.html). It is unarguably a success story in revealing open ocean primary production patterns.

Nevertheless, when it comes to remote sensing of optically complex waters, which are frequently encountered, for example, in coastal regions, the situation is not as positive. In coastal waters, both inherent and apparent optical properties are influenced by a wide array of physical, biological and chemical processes. In addition to phytoplankton pigments, which is the main ocean product in SeaWiFS, constituents such as coloured dissolved organic matter of both marine and terrigenous origin, biological detritus, and inorganic particulate material (resuspended from the bottom or advected with river waters from the land) can affect both the magnitude and spectral shape of reflected light. As the GBR has relatively clear waters, bottom reflection can also be a factor. Such waters are often referred to as “case II waters” as opposed to “case I waters”, where phytoplankton (or its proxy chlorophyll) is essentially the only unknown in the equation (Sathyendranath 2000). Since neither suspended sediment and nutrient levels nor reliable chlorophyll estimates can be obtained from SeaWiFS-derived data using the existing algorithms, an optical model of the water-leaving radiance in terms of these water properties is required.

Researchers have only recently started using remote ocean colour data for coastal applications, and methods to accurately retrieve optical properties remotely are still evolving. This is due to the complexity of terrestrially affected coastal waters and the technological limitations of satellite sensors to cope with it. Although originally not intended for applications in case II waters, SeaWiFS has inspired several attempts to apply its data in coastal studies (Hu et al 2000; Ruddick et al 2000). When trying to apply the sensor data to coastal environments, the standard SeaWiFS atmospheric correction scheme fails in shallow turbid waters as it was developed for deep clear waters. As the signal received by the satellite is strongly influenced by the atmospheric path and current operational atmospheric correction schemes are inadequate for application in turbid waters typical of flood plumes, an alternative atmospheric correction has to be developed.

## 1.6. Study area

The chosen field site is the Herbert River and adjacent coastal waters of central Queensland, Australia (Figure 1.1). The area is located in the semi-humid tropics of the central GBR zone, with pronounced dry and wet seasons. The summer (December to May) is hot and humid, with most of the 2110 mm annual precipitation falling between January and March (annual average for 1951-1992 (DNRM 2002)). Summer winds are variable, with extended calm periods as well as strong winds and heavy rains produced by cyclones developing in the Coral Sea. Southeast trade winds dominate the cool, sunny, dry season from June to November. With mean sea surface temperatures ranging from 21 to 30˚C and the maximum tidal range of 3.5 m, the coastal ocean in the vicinity of Herbert River enjoys a range of habitats including fringing and mid-shelf coral reefs, sand and mud bottoms, sand and rubble intertidal flats, mangrove forests, and sandy beaches as well as cobble and boulder beaches (Lee Long et al 1998). Fringing reefs on the nearby Palm Islands group typically do not extend deeper than 15 m and are relatively sheltered on the western leeward side of islands.

The port of Lucinda, located on the northeastern part of the Herbert River delta between Hinchinbrook Channel and Gentle Annie Creek (Figure 1.1), exports raw sugar grown in the Ingham district. There is a long jetty, stretching out into the sea for about 6 kilometres east of Lucinda, making it a convenient sampling site. Hinchinbrook Channel is a narrow, 44 km long tidal channel between Hinchinbrook Island and the mainland. Due to simultaneous entry of the flood tide at both entrances to the channel, large amounts of sediment from the Herbert River appear to be trapped, at least for some time, in the mangrove muds which line the channel (Wolanski et al 1990).

The Herbert River catchment covers an area of 9843 km$^2$ and contains a variety of vegetation communities and land uses. Cropping, principally of sugarcane, is cultivated on the floodplain in the lower river, and comprises circa 6.5 % of the total catchment area. Much of the upper catchment is covered by dry savannah woodland where the principal and dominant use for this catchment agricultural land is cattle grazing (74 % of the total catchment area). Approximately 1417 km$^2$ or 14 % of the catchment is in the Wet Tropics World Heritage Area.

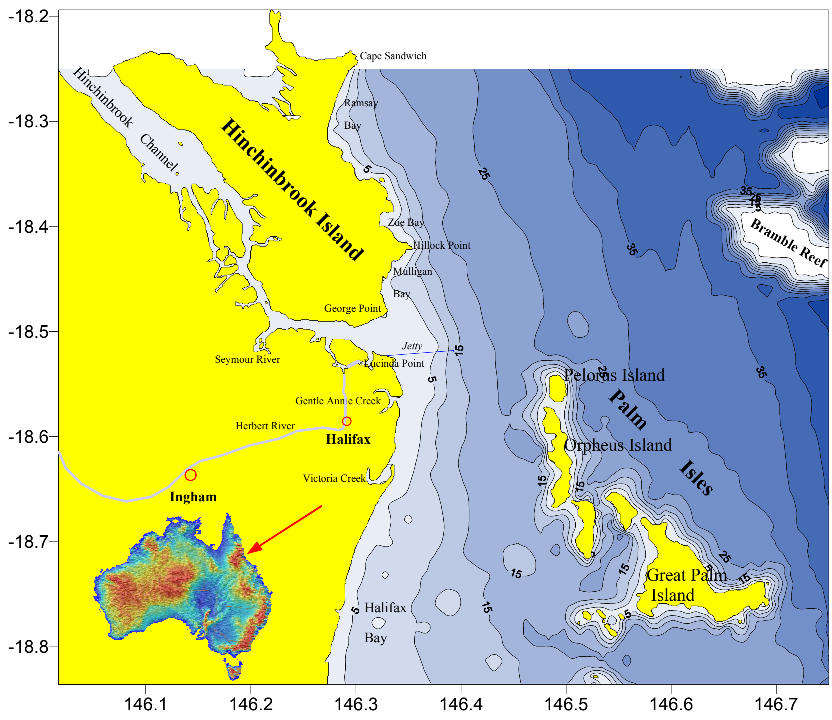


Figure 1.1. Study area – Herbert River and adjacent coastal ocean, Australia. Bramble Reef is the closest mid-shelf reef to the river mouth.

Since European settlement, a significant proportion of the lower catchment has been cleared and common nitrogen and phosphorus fertilizers and pesticides (e.g. Atrazine, Diuron, 2-4D, Chlorpyrifos, MEMC) are routinely applied there. By the 1940s, 70 % losses in the area of riparian forest and 80 % in freshwater wetlands had occurred relative to their estimated pre-European extents (Johnson et al 1999). Therefore, high levels of nutrients and sediments are expected to be transported to the river and subsequently to the coastal ocean. Indeed, according to the GBR assessment, the Herbert River exports of sediments, total nitrogen and total phosphorus have increased 8-fold, 3-fold and 6.5-fold since the 1850s, respectively. As a result, sediment and total phosphorus exports in the Herbert River catchment are estimated as medium risk and total nitrogen export as high risk by the GBRMPA (GBRMPA 2001). Overall, the Herbert River was recently classified as the ninth most polluted river in the GBR catchment on the basis of the River Pollution Index, which incorporates information on mean annual discharge, frequency of flood events, total suspended solids, dissolved inorganic nutrient and fertilizer (Diuron) fluxes, and level of urban development (Devlin et al 2001).

The Herbert River is the largest of the river systems (mean annual flow 5 x $10^6$ ML) in the humid tropics region of northeast Australia and the fourth largest fluvial system draining into the GBR. While middle and upper catchments can be considered wet catchments, the floodplain is located in a much drier area (Furnas 2003). As a result, the Herbert River catchment has characteristics of both wet and dry catchments, distinguishing it from other GBR rivers by unique hydrological properties. The bulk of freshwater and fine sediment exports from the Herbert River most frequently comes as a single large event during the wet season (December to March) (Figure 1.2). Therefore, flood events are the major vectors of sediment and nutrient export, particularly from grazing lands laid bare after long periods of drought.

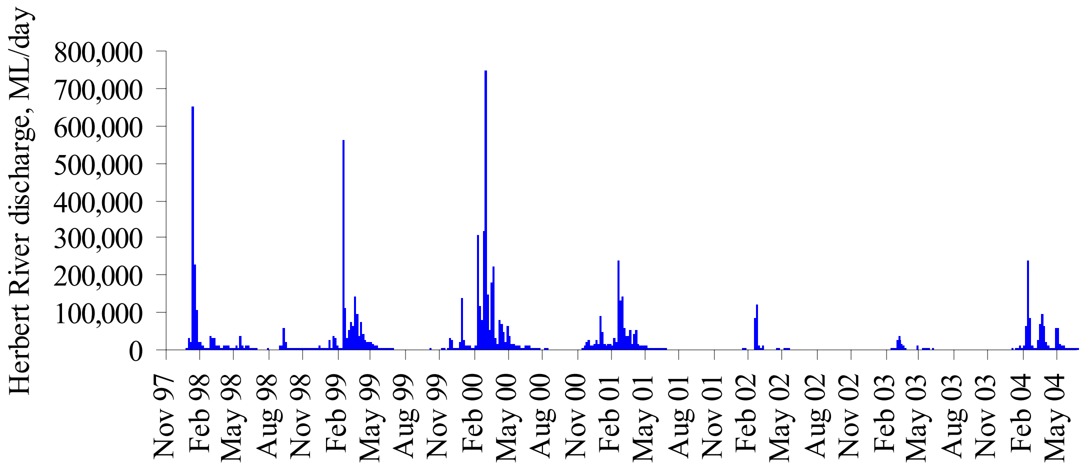


Figure 1.2. Daily flow data in megalitres from Gauging Station GS116001E Herbert River at Ingham covering the period November 1997 to June 2004. Data courtesy of Department of Natural Resources, Mines and Energy.

Significant plume intrusions into the area from the Herbert River as well as from the much larger Burdekin River have been observed and monitored (King et al 2001). According to a recent study, the area experiences one of the highest flood plume occurrences among the GBR catchments (Devlin et al 2001). Coupled with increased freshwater, sediment and nutrient loads due to clearing and fertilisation, flood plumes from the Herbert River are potentially detrimental to the adjacent mid-shelf coral reefs (e.g. Bramble Reef, Figure 1.1). Herbert River plumes do not usually reach these ecosystems, as they tend to follow the alongshore current generated by the South-East Trade Winds. However, under favourable conditions (e.g. NW winds) across-shelf dispersion of a flood plume is a possible scenario. Also powerful Burdekin River plumes were recorded to travel over 200 to 400 km northward along the coast, thus reaching and possibly affecting the Palm Isles (King et al 2001).

All of the above suggest that the extent of plume intrusion into the GBR lagoon in the vicinity of the Herbert River mouth, as well as its composition and the fate of individual components, needs monitoring.

A number of other studies have been undertaken in the area. These studies have looked at sediment and nutrient dynamics in the river during a flood (Mitchell et al 1997), particle size distribution of bottom sediments adjacent to the Herbert River delta (Woolfe et al 2000), geochemical analyses for evolutionary implications of the area (Holmes 1993), classification of Herbert River geomorphology based on relative rates of sedimentation and erosion in its catchment (Woolfe et al 2000), spatial and temporal changes in freshwater wetlands and riparian forests on the Herbert River floodplain (Johnson et al 1999), water quality in the lower part of the catchment of the Herbert River under various land uses (Bramley et al 2002), pesticide contamination in the area (Cavanagh et al 1999; Johnson et al 2000), carbon burial rates and sedimentation processes for the adjacent shelf (Brunskill et al 2002), organic matter decomposition in mud flats of the Hinchinbrook Channel (Alongi et al 1999), dynamics within the Hinchinbrook Channel and flushing of the fringing mangrove swamps (Wolanski et al 1990), and evolution and dynamics of the Herbert River plume in the central GBR using airborne salinity mapper (Burrage et al 2002). Good on-line sources of information about the area include the Herbert River Resource Centre (http://www.hric.org.au/hric_site/hric.asp), Herbert River Flood Study (http://www.herbertriver.com/index.htm) and Herbert Consortium (http://www.aims.gov.au/pages/research/herbert/herbert-index.html).

## 1.7. Research questions and objectives of the study

The overall objective of the present work is **to develop a technique to monitor the dynamics of sediments and nutrients entering the GBR with river plumes associated with high intensity low frequency events (e.g. floods) using ocean colour remote sensing**. This objective falls under one of the strategies of the Reef Water Quality Protection Plan (RWQPP), a multidisciplinary initiative, which aims "*to assist in halting and reversing the decline in the quality of water entering the Reef*" (GBRMPA 2003). The Monitoring and Evaluation Strategy (Strategy I) of the RWQPP includes the following statement: *"Implement a coordinated water quality monitoring program in high-risk catchments to track long-term trends in water quality entering the Great Barrier Reef lagoon"* (GBRMPA 2003).

From the background provided in previous sections, the following research questions emerge:

1. *Is satellite remote sensing suitable for studying flood plumes?*
2. *Can SeaWiFS be used in coastal waters?*
3. *What is the fate of biogeochemical substances of Herbert River plumes in the coastal ocean?*
4. *Do riverine sediments and nutrients reach inshore and mid-shelf coral reefs?*

In order to answer the above research questions, the following targets are set for the present study:

- To study sediment and nutrient dynamics in the Herbert River estuary and adjacent coastal ocean during a flood
- To construct and validate a bio-optical model for the region
- To retrieve chlorophyll (CHL), suspended sediments (TSS) and coloured dissolved organic matter (CDOM) concentrations using the bio-optical model and SeaWiFS data
- To apply the retrieval algorithm to a flood event in Herbert River estuary.

## 1.8. Thesis structure

**Chapter 2** is devoted to a bio-optical model of the region. The history of ocean remote sensing algorithms, regional bio-optical model settings and specifications, and sensitivity analysis of the model are elucidated in the chapter. **Chapter 3** describes the study's fieldwork as well as bio-optical model validation efforts. Results of the application of the developed ocean colour remote sensing technique to a 1999 flood event in the Herbert River are reviewed. Some insights into the geophysical processes of the region are presented in **Chapter 4**, where suspended sediment and nutrient dynamics in the Herbert River estuary during the flood of 2004 are observed and analysed. Finally, the major outcomes of the present work as well as future outlook and a summary are provided in **Chapter 5**.

For ease of reading the thesis and keeping the structure simple and straightforward, a number of **Appendices** have been added. These include lists of abbreviations (Appendix 1) and symbols (Appendix 2) used throughout the text; plan of the February 2004 field expedition (Appendix 3); graphical representation of all data from the field trips (Appendix 4); and SeaWiFS atmospheric correction modification procedure (Appendix 5). Finally, a list of references used in the work contains 179 publications, including 22 books, 118 journal articles, 10 conference proceeding publications and 5 electronic sources. The CD with the thesis is attached.