Whinney, James Christopher (2007) ***Physical conditions on marginal coral reefs.*** **PhD Thesis, James Cook University.**

https://doi.org/10.25903/7xhh%2Dsf90

Physical Conditions on Marginal Coral Reefs

Thesis submitted by

James Christopher WHINNEY MPhys

In March 2007

for the degree of Doctor of Philosophy
in the School of Mathematics, Physics, and Information Technology
James Cook University

STATEMENT OF ACCESS

I, the undersigned, author of this work, understand that James Cook University will make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and I do not wish to place any further restriction on access to this work.

Signature

Date

STATEMENT OF SOURCES

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Signature

Date

ELECTRONIC COPY

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library is an accurate copy of the print thesis submitted, within the limits of the technology available.

Signature

Date

STATEMENT ON THE CONTRIBUTION OF OTHERS

The contributions of others towards this thesis included knowledgeable discussions, proofreading of manuscripts, and manual help with field work.

Project costs were covered by the supervisor. Fees and stipend support were paid by an International Postgraduate Research Scholarship and by the School of Mathematics, Physics, and Information Technology.

Signature

Date

ACKNOWLEDGEMENTS

I would like to thank my friends and family for there support during my studies, particularly my wife, Zhen. Thank you to all those people who helped me with my field work and with academic advice, especially my supervisor, Peter Ridd, for his expert advice, guidance and support.

Abstract

The Great Barrier Reef Lagoon (GBRL) is an area of great biodiversity containing 350 species of corals, 10 of which are endemic to the region. In recent years many threats to this ecosystem have been revealed, such as crown-of-thorns starfish and coral bleaching as well as excess concentrations of nutrients and sediments. Information on the effects of water quality and also the amounts of nutrients and sediments that reefs are subjected to is limited. This is especially true for inshore reefs where issues of water quality are most important.

This work focuses on the Rockingham Bay and Family Islands region. In this region a reef in Lugger Bay near Mission Beach was selected for a detailed study. It is a highly marginal reef (a reef occurring close to perceived environmental thresholds for coral survival) with high levels of sediments and organic matter and close to the mouths of two rivers: the Tully and the Hull. This makes the reef one of the most at threat from eutrophication and increases in sediment. Part of this work was to document all the physical conditions of the reef including currents, wind speed and direction, light levels, temperature, nutrients, and suspended sediment concentration (SSC). The reef's health and age were also found by means of photographic surveys and core samples respectively.

The main results from the study showed a reef surviving in extreme physical conditions. The SSC on the reef were very high, exceeding 200 mg/l for 28% of the time. Light extinction was common, occurring on 49% of the days that data was recorded. The local rivers did not have much effect on the SSC or nutrient concentrations on the reef. The Tully River only has a wet-season average SSC of 23 mg/l and a maximum of 230 mg/l; resuspension was much more significant. Coral cover on the reef was reasonable, about 57%, and algae only covered 12% of the coral. However, coral species biodiversity was low, with one species of *Porites* making up 85% of the coral cover. These results indicate that some species of coral are able to survive in areas of high sediment and nutrient concentrations, and that clean rivers in the GBRL are not a great threat to coral reefs.

The SSC data was also used to develop an empirical model, which predicts SSC for a specific site using just wind data. The model is accurate enough to be used in environmental monitoring to predict an expected SSC, which can be prepared with observed SSC from a site where marine construction is taking place so it can be determined whether the work has increased the SSC to a dangerous level. This makes it an important tool as many such construction projects occur in the GBRL each year and there is no other accurate method of determining what the natural SSC would be if work was not taking place.

A new instrument was also developed to infer nutrient concentrations in the water column, to try to overcome problems with existing methods. The instrument works by measuring the speed at which algae grow on a glass plate using a fluorometer. Tests were made to determine how well algal growth would relate to nutrient concentrations, if other factors like temperature, light levels and algal type were not controlled. Results showed that growth was too dependent on these other factors to be a good indicator of nutrient concentrations. The sensor could, however, be used to determine the effect nutrients have on algal growth, which in itself is a potential threat to corals.

Table of Contents

List of Figures

List of Tables

1 - Introduction

Influences of Nutrients and Sediments in the GBRL

Sediment and Nutrient Inputs to the GBRL

Sediments and nutrients are both significant factors in influencing the state of coral reefs. Both enter the Great Barrier Reef Lagoon (GBRL) from a number of different sources one of which is from riverine inputs. These riverine inputs are particularly consequential as they can be affected by human activity. Changes in land use in the river catchments neighbouring the GBRL from those prior to human settlement can lead to more sediments and nutrients being washed into the rivers.

Sediments

The catchment area of the rivers flowing into the Great Barrier Reef is 423,070 km^2 which is twice the area of the barrier reef itself. The most significant contribution comes from the Burdekin and Fitzroy river basins which account for 64% of the total area. Approximately 1.1 million people live within the catchment area where the main land use is agriculture. By land area, cattle grazing is the most important industry taking up about 76% of the area, with timber covering about 7% and sugar cane 1% (Furnas 2003).

Sediments have been washed down rivers and into the GBRL over the course of millennia and have been deposited to form a wedge about 5m thick in the inner-shelf region going out to the 20 m isobath (Williams 2001, Belperio 1983). The wedges are especially conspicuous in north-facing bays where they are protected from the prevailing South East winds (Williams 2001, Woolfe et al. 1998). Corals are unable to live on these wedges but they are found just on the seaward side (Williams 2001, Larcombe and Woolfe 1999). The quantity of sediments entering the lagoon via terrestrial run-off has increased since European settlement by about a 3 to 4 fold increase since 1800 (Williams 2001).

Sediment in suspension comes from two sources: firstly from the riverine inputs into the lagoon and secondly from resuspension of deposited sediments. The resuspension is a result of wave action. In the inshore region the wedge of deposited sediment provides an ample supply of sediment for resuspension so it is not a limiting factor for resuspension. Therefore some believe that an increase in supply of sediments from the rivers will not affect suspended sediment concentrations (SSC) and instead it is limited by the hydrodynamics of the system (Larcombe and Woolfe 1999). Only further from the shore at the mid and outer reef where deposited sediment levels are low can the quantity of deposited sediment limit SSC. However as this area is far removed from the prodelta, an increase in sediment levels in terrestrial runoff would have little effect on it (Larcombe and Woolfe 1999).

The primary source of energy for sediment transport is the South East trade wind that blows for most of the dry season. The winds tend to drive the sediment northward along the coast and also produce swell waves that resuspend material (Larcombe and Woolfe 1999). In local areas, tides can be an important factor in generating turbidity too. On short time scales cyclones can lead to turbidity and also movement of sediment on a local scale. However in general this has little impact on the long term position of sediment as the SE waves move the sediments after the storm has passed (Larcombe and Woolfe 1999).

Another means of sediment transport is river plumes. As the water flows into the rivers and out to sea it picks up mud and nutrients from the land so by the time it reaches the ocean it is laden with sediments. For example, in the Great Barrier Reef catchment area the Tully River exports $0.13\text{x}10^6$ tonnes of fine sediment per year while the Herbert exports $0.54\text{x}10^6$ tonnes and the Burdekin $3.8\text{x}10^6$ tonnes. The total sediment input from all the rivers feeding the GBRL is $14\text{x}10^6$ tonnes per year (Furnas 2003). The specifics of the catchment area dictate the quantities of sediments involved; the size of the area is important but also how steep it is and how much vegetation there is to prevent erosion (Wolanski 2003). Plumes also carry with them a large volume of low salinity water, which can be harmful to corals exposed for too long to it. However, as this water is less dense it tends to float above the normal seawater, mixing gradually as it flows along, so preventing a major drop in salinity at one location.

River plumes have a short-term and local influence on turbidity (Wolanski 1994, Taylor 1996). If winds are favourable the plumes can reach the mid and outer reef shelves (Brodie 1996, Brodie and Furnas 1996). The scale of the influence of river plumes is greatly debated. Plumes may only occur for a few days each year but they supply a significant amount of all the sediments added by terrestrial runoff, so some believe that they are of great importance to the annual SSC budget (Wolanski 2003, Devlin et al. 2001, Furnas 2003). Conversely the river plumes tend to be only a few metres thick and carry a small load of sediment compared to sediment loads observed during resuspension events (Taylor 1996). For example a major plume from the Barron River which stretched over an area of 45km by 10km only contained about 9000 tonnes of suspended sediment (Larcombe and Woolfe 1999). In contrast, swell waves in Cleveland Bay acting over an area of 200 km^2 and a depth of 5 m are able to disturb 50,000 tonnes of sediment (Larcombe and Woolfe 1999).

Nutrients

Many of the world's reefs see high levels of nutrients added to the waters surrounding them via land run off (Wilkinson 2002) and it is especially a problem in areas with large densities of people. The Great Barrier Reef is unique in that the population in the land area adjoining it is relatively small, however, there are large areas where land use has changed and agricultural industries such as growing sugar cane and raising cattle have become significant (Furnas 2003). Through the use of fertilisers and through increased erosion brought on by removal of forests the total amount of nutrients flowing into the sea has increased dramatically since European settlement (Moss et al 1992, Williams 2001). It is estimated that phosphorous concentration in rivers have increased by 10-fold and nitrogen 2-fold in the past 200 years (Williams 2001).

Nutrients in the GBRL have a number of sources other than riverine input. Calculations of the relative magnitudes of these various sources by Furnas et al (1996) illustrate the comparative importance of riverine input. For example about 40,000 tonnes of nitrogen enter the GBRL via rivers annually. Upwelling from the ocean, rainfall and reefal production each supply about half of the river input (Figure 1.1). Benthic release supplies a further 5 times the riverine input, and contributions from trichodesium production provide more than half as much as river inputs but this could be much higher. Each year 100 times the riverine nutrient input is circulated through the water column and the sediment by means of resuspension and deposition of sediments. There are also large reservoirs of nitrogen in the lagoon (Figure 1.2). Dissolved and particulate matter in the water column in the lagoon contains 10 times the annual riverine input of nitrogen and the top 20 cm of sediment, 400 times. It is unknown how much nitrogen there is in the biomass of larger organisms and reefs. A similar story is true for phosphorous; i.e. river inflows are a comparatively minor process.

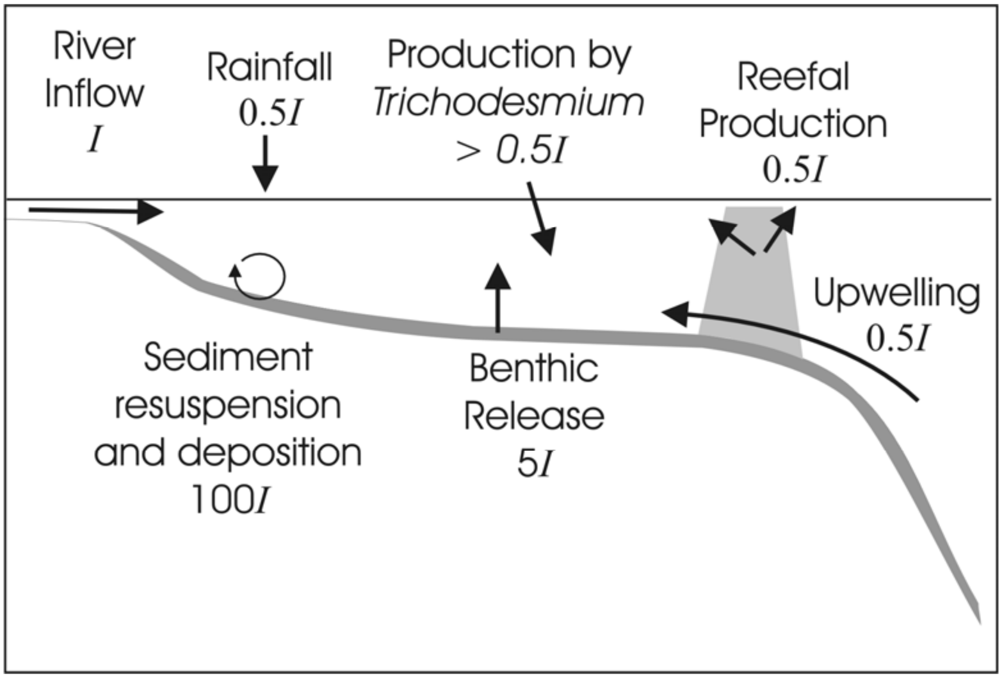

Figure 1.1: Fluxes of nitrogen in the Great Barrier Reef Lagoon. *I* represents the present day annual discharge of nitrogen. Data is from Furnas et al (1996).

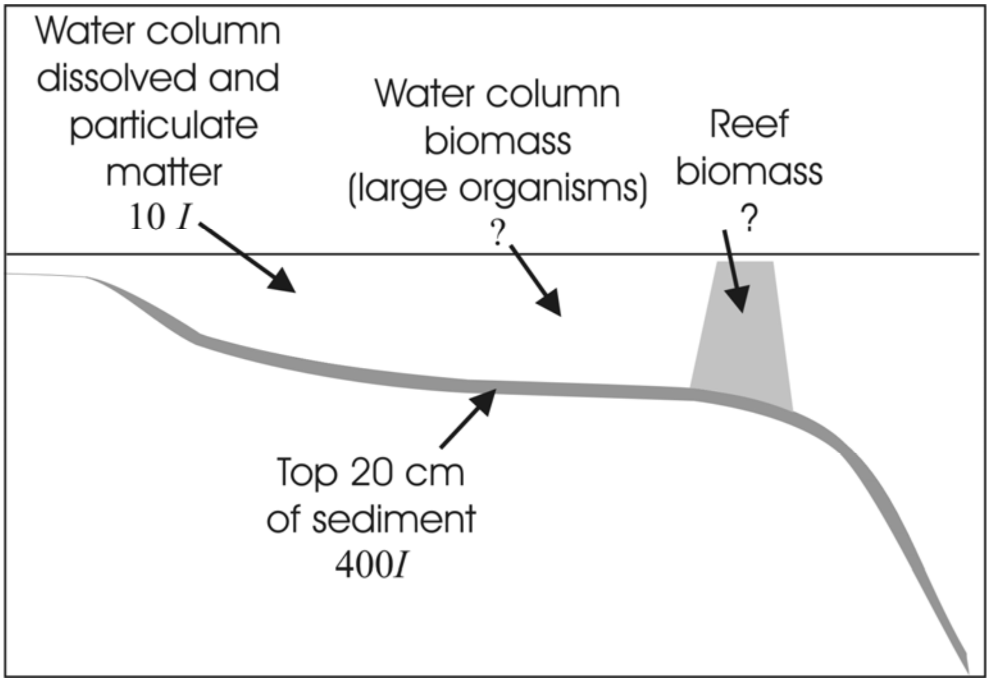

Figure 1.2: Reservoirs of nitrogen in the Great Barrier Reef Lagoon. *I* represents the present day annual discharge of nitrogen. Data is from Furnas et al (1996).

This outline of nitrogen fluxes in the lagoon illustrates that while changes in riverine inputs of nitrogen are important they do not dominate the system and may not have a major effect in many locations. However, in environments close to the mouths of rivers, these river inputs may affect the local nutrient balance and so possibly alter balances in the ecosystem. This effect is most likely to be seen during river plumes, when large quantities of sediments and nutrients are washed down the rivers in a short time period.

Potential Impacts of Sediments and Nutrients

There are a number of ways in which sediments and nutrients can affect the marine environment. Corals can be susceptible to changes in nutrients and sediments. Some effects are fatal whilst others reduce growth and reproduction and some give advantages to other organisms such as algae that compete with the coral for habitat.

Sediments

The deposition of suspended sediments onto corals can cause potentially fatal smothering. Sediments that land on corals can be removed by physical action or by the excretion of mucus. However, if the deposition of sediment is too rapid the corals may not be able to remove it all and if the corals remain covered for too long this can lead to tissue death by smothering or bacterial infection (Fabricius and Wolanski 2000, Marshall and Orr 1931).

Sediments can also affect corals' energy balance and so reduce growth. The removal of deposited sediment requires energy and while the sediment covers the coral, photosynthesis is reduced as light levels are diminished (Anthony and Fabricius 2000, Riegl 1995). Suspended sediment also reduces the amount of light reaching the coral, limiting the energy the coral can get from photosynthesis (Williams 2001, Stafford-Smith 1993). However suspended sediments can also be beneficial to corals as some species use the organic material in the suspended sediments as a source of food (Williams 2001, Anthony and Fabricius 2000). This leads to some species gaining an advantage over others in high sediment conditions.

Sediments can also affect coral reproduction. Gilmour (1999) studied this using laboratory and field experiments on *Acropora digitifera* (a *scleractinian* coral) to compare the effects of high (about 100 mgl^{-1}), low (about 50 mgl^{-1}) and control (about 0 mgl^{-1}) levels of suspended sediment on the fertilisation, larval survival and settlement stages of reproduction. The results showed a significant decrease in fertilisation with both high and low levels of sediments, but the embryonic development did not seem to be inhibited. Larval survival and settlement were also reduced. Interestingly there was little difference between the effects of the high and low levels of sediment.

To adapt to high suspended sediment conditions many corals are able to morph into more resistant forms (Williams 2001, Stafford- Smith 1993). High nutrient levels also reduce the numbers of species as a few nutrient resistant taxa are able to dominate the area (Fabricius and Dommisse 2000). Fabricius and De'ath (2001a) found a strong relation between visibility and soft coral species biodiversity. In regions where the visibility was less than 10m, the number of genera dropped quickly as visibility reduced. High variety was observed when visibility was greater than 10m.

Research on the spatial distribution of crustose coralline algae (CCA) in the Great Barrier Reef (Fabricius and De'ath 2001b) demonstrated a link between sediment and CCA cover. The research indicated that in inshore areas with high sediment levels, the CCA cover was lower than the clear outer shelf areas. This is significant as the CCA produce large amounts of limestone and cement the reef together and also serve as an area for settlement for many reef benthos.

Nutrients

High concentrations of nutrients have been shown to reduce coral growth and calcification rates. This occurs as nutrients increase the amounts of *zooxanthellae* and *chlorophyll a* present inside the corals, which can lead to a disturbance in the relationship between the zooxanthellae and the host (Ferrier-Pages 2000). Ferrier-Pages et al (2000) tested what effect a variety of nutrients would have on different corals. Four tanks were set up containing ten types of coral, one to test ammonium, one for phosphorus, another for ammonium and phosphorus, and one as a control. For four weeks the ammonium (N) concentration was 10µm and the phosphorus (P) concentration was 2µm. Afterwards N was increased to 20 µm and P was kept constant for another five weeks. Then all tanks were given a final five weeks with low nutrient levels (µm close to 0) to see how the corals recovered. The results showed a variety of effects on the growth rates of different species. In most cases the corals appeared to be resilient to quite high levels of ammonium. Almost all showed signs of recovery when the nutrients where removed, but for the tank which had been exposed to P the recovery was slow, however, in the tank which had been exposed to a combination of N and P the recovery was much better. This was believed to be because the phosphorus acts differently when combined with ammonium and can be removed by algal growth preventing it from interfering with calcification.

In areas with both high sediment and nutrient concentrations marine snow can form, increasing the potential of coral smothering. When suspended in the water column, estuarine mud can combine with organic matter produced by biological activity as a result of high nutrient concentrations, to create large sticky particles called marine snow. If these particles fall on corals, the particles large size and cohesiveness make them much more difficult for the corals to remove than single sediment particles and increase the likelihood of smothering. Fabricius and Wolanski (2000) investigated the effects of marine snow on coral and coral-inhabiting barnacles. They placed these organisms in one tank containing offshore water (low in nutrients) and another containing near-shore water (high in nutrients). Next suspended mud was added in amounts up to 170 mg l^{-1}. In the off-shore tank the nutrients and sediments flocculated into particles of a size of approximately 50 μm. However, in the near-shore tank the particles reached sizes of between 200 to 2000 μm. The organisms were able to clear the small particles except when exposed to very high levels of settlement. But when covered by large particles, the corals, calanoid copepods, and the barnacles failed to move the particles, and the barnacles and copepods were dead within an hour.

Increases in nutrient concentrations can lead to the production of phytoplankton. As phytoplankton concentrations rise, water turbidity will increase, which will reduce the amount of light reaching the seabed. This will decrease coral photosynthesis and as a consequence reduce the amount of energy available (Williams 2001, Smith et al 1981).

Another potential threat to corals from nutrients is that of algal over-growth. Since algae require nutrients for growth, an increase in available nutrients can lead to faster growth of algae. This may allow the algae to dominate, covering all potential coral recruitment sites and even covering the coral itself (Bell 1992, Lapointe 1997, Adey 1998).

However, increases in nutrient concentration do not necessarily lead to an increase in algal growth. Other factors are important for the growth of algae such as light and temperature. In many cases these factors will be limiting growth, so an increase in nutrients will not lead to an increase in algal growth. It is the nutrient uptake that is more important than the nutrient concentration (Atkinson 1988, Larned & Atkinson 1997). It has been shown by Schaffelke and Klumpp (1997, 1998a, b) that while the growth of

Sargassum Baccularia does increase as nutrient concentrations are raised, the growth rate saturates at moderately high levels of nutrients.

Even when increases in nutrient concentrations do lead to an increased production of algae it does not always mean that there is an increase in algal biomass (Carpenter 1988; Hatcher 1997). The growth of algae is often controlled by herbivory. Several studies have shown algal cover depends more strongly on herbivory levels than it does on nutrient concentrations (Littler & Littler 1984, McCook 1996, 1997, Russ & McCook 1999, Scott & Russ 1987).

If coral is covered by algae it is not necessarily true that the algae killed the coral. It can also be that the corals die for some other reason such as storm damage or disease and the algae fills the empty space (Kinsley 1988, Done 1992, Hughes 1994). It is also true that algae and corals can live in the same area in a non-destructive relationship (Hatcher 1985). For example, at Goold Is. McCook (1999) found that the corals have survived well for the 7 years it was studied, while surrounded by *Sargassum*.

Crown-of-thorns starfish have caused damage to reefs throughout the Indo-Pacific region, with several major outbreaks of these coral-eating starfish occurring in the past four decades (Birkeland and Lucas, 1990). The severity of these outbreaks might be linked to nutrient levels as high nutrient concentrations may enhance the survival of *Acanthaster planci* larvae (Brodie et al 2005). Increased survival of crown-of-thorns starfish larvae could lead to larger outbreaks as more starfish reach maturity.

Thesis Outline

Inshore reefs close to river estuaries are some of the most at risk in the GBRL. The reefs' proximity to river mouths means that these reefs are exposed to higher levels of nutrients and sediments than other reefs. Also the reefs' locations mean that there are likely to be large quantities of sediment previously deposited in their vicinity that will lead to higher SSC from resuspension.

This work investigates an inshore reef with high nutrient and sediment concentrations. The purpose of this is to determine exactly what physical conditions the reef is subjected to, such as SSC, nutrients, and light levels. From this it can be established what the upper boundaries for these parameters are for a reef in the GBRL. By making comparisons with the outputs from local rivers it can also be determined how much of an effect these rivers have on the reefs. It is important to see whether SSC is raised by high discharges from rivers. The effect of the rivers on nutrient concentrations on reefs is also significant particularly during river plumes.

The study also assesses the condition of the reef, examining factors such as coral cover, coral species biodiversity, algal encroachment and approximate age of the reef, all of which help to develop an understanding of the reef health of inshore reefs and the potential problems they may have.

As well as terrestrial inputs via rivers, marine engineering work such as dredging is another potential anthropogenic impact on inshore reefs. Marine engineering work often leads to the resuspension of large amounts of deposited sediments, particularly in dredging work. Reefs close to such work may be impacted by the increased SSC. Part of this work will investigate a potentially useful tool for environmental monitoring during these engineering activities. The tool is a model that can predict SSC produced by wind generated wave resuspension. If SSC produced by wave resuspension for a particular site can be predicted, the predictions can be compared with values recorded during marine engineering work. This will determine whether the work has increased SSC by a significant amount and thus whether it has the potential to harm the corals.

High nutrient concentrations are a significant threat to corals particularly those in inshore reefs close to riverine sources of nutrients. However all current methods used to measure these concentrations have disadvantages. This work will investigate the potential of a new method for measuring nutrient concentrations, which uses algal growth as a surrogate.

Lugger Bay Reef

Lugger Bay Reef in the GBRL, Australia (Figures 1.3 and 1.4) is a good example of a turbid reef. The reef is about 8 km north of the Tully River and 15 km north of the Murray River, both of which have been labelled as medium/high risk to inshore reefs by the Great Barrier Reef Marine Park Authority (GBRMPA 2001). Of the two rivers, the Tully is the largest with an annual discharge of 0.13×10^6 tonnes of fine sediment, 138 tonnes of phosphorus and 1,303 tonnes of nitrogen (Furnas 2003). The smaller river, the Murray, discharges 0.04×10^6 tonnes of fine sediment, 40 tonnes of phosphorus and, 400 tonnes of nitrogen per year (Furnas 2003). The river catchments are used for a mixture of crops, timber and grazing, the main crops are sugar and bananas. In the Tully river basin 10% of the area is used for sugar cane. Other crops including bananas use 2%, timber uses 61% and grazing 21%. In the Murray basin sugar cane uses 6.3% of the area, 1% is used for other crops such as bananas, 30% is used for grazing and 33% for timber (Furnas 2003). The largest river in the area is the Herbert River, which is 60 km to the south and discharges 0.50×10^6 tonnes of fine sediment, 200 tonnes of phosphorus and 2,000 tonnes of nitrogen (Furnas 2003).

About 5 to 15 km offshore from Lugger Bay is the Family Islands group, with tourist resorts on the largest island, Dunk Island and on Bedarra Island. A number of the islands have fringing reefs. The Family Islands group affords Lugger Bay some protection from waves coming from the east and the bay is sheltered from waves from the south by Tam-O-Shanter Point just a few hundred metres to the south of the reef. The reef is exposed to south-easterly and north-easterly waves.

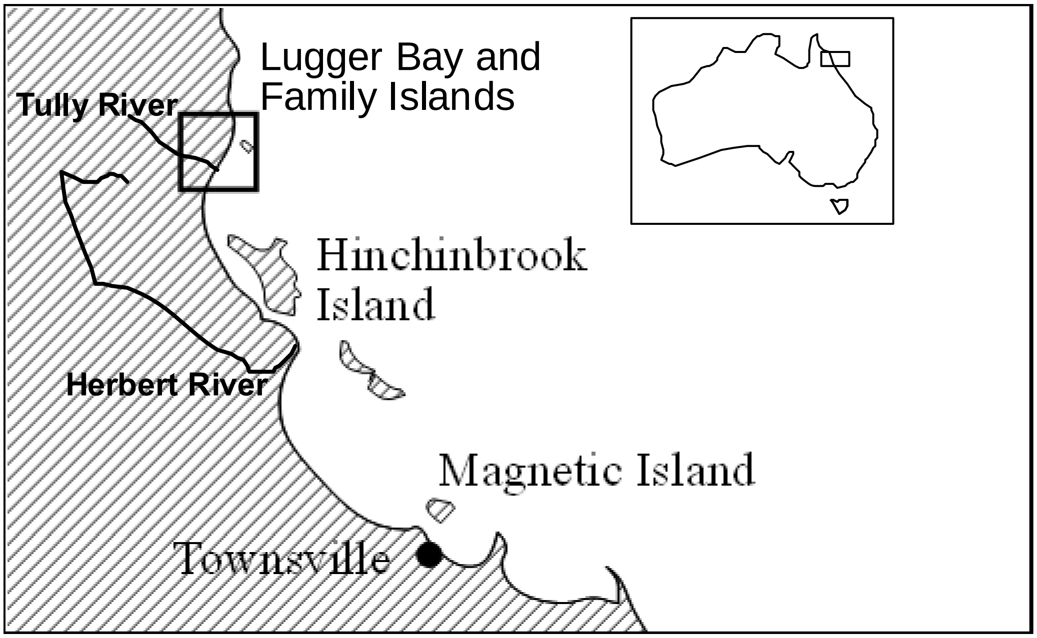

Figure 1.3: Location of Lugger Bay in the North Queensland area.

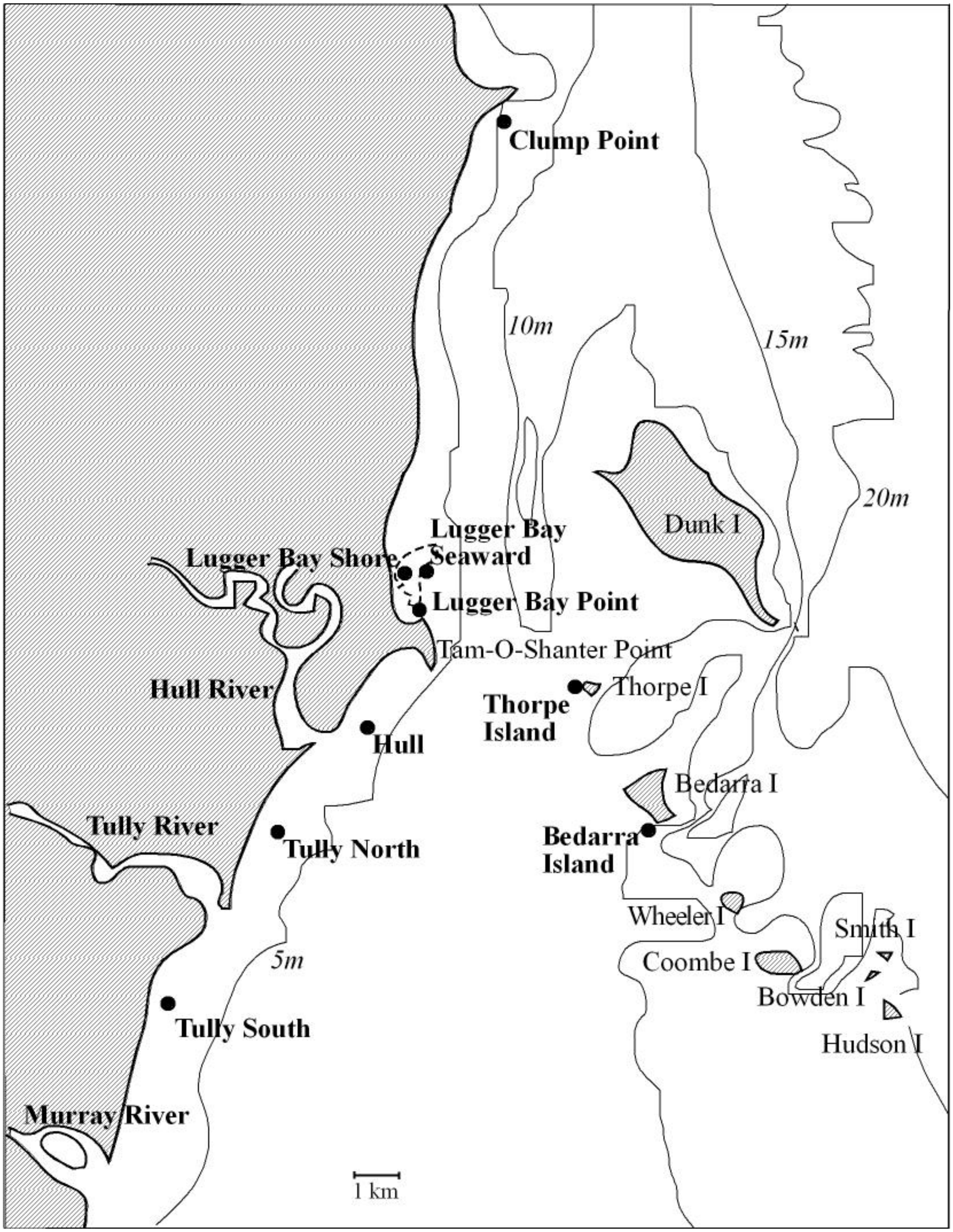

Figure 1.4: Lugger Bay and the surrounding area. The Dots indicate locations where instruments were deployed.

Lugger Bay Reef is an L-shaped reef about 400 m long, 300m wide at the widest part and 150 m wide at the narrowest (Figure 1.5). The reef is dominated by *Porites* corals, which occur in large bombies in the outer portion of the reef and merge towards the centre to form a reef flat. The reef is about 400 m from the high tide line on the shore to the east and about 500 m from Tam-O-Shanter point to the south.

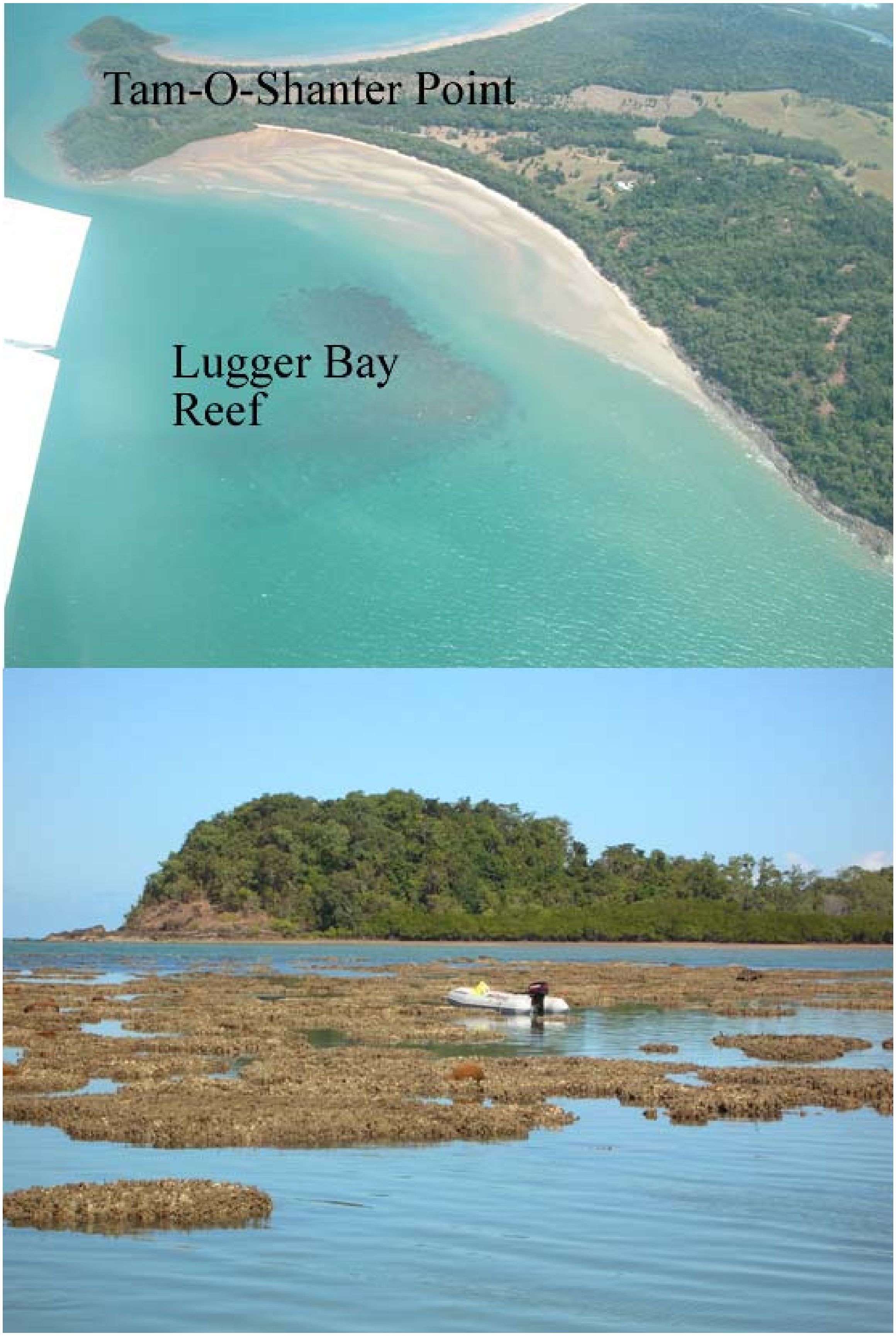

Figure 1.5: Lugger Bay Reef. Top photograph shows the reef from the air with Tam-O-Shanter Point behind the reef. Bottom photograph shows part of the reef during an extreme low tide.

There are many reasons to study a reef such as Lugger Bay Reef. It documents the physical conditions in which these inshore reefs close to river mouths exist. It also examines whether the reef is under threat, and if changes in land use have put the reef at risk. Investigating the rivers and how they interact with local marine habitats gives more insight into the potential problems rivers, and riverine pollution, can cause, and can be useful when determining the most effective ways to minimise anthropogenic impacts on these habitats.

Study Techniques

The methods used in the study included loggers measuring a variety of parameters such as SSC, fluorescence, light and waves. The reef was also examined with phototransects and percussion cores. The loggers were deployed on the reef and throughout the area to get a picture of local variations and transport. The sites used were Tully South, Tully North and Hull (Figure 1.4) to examine the inputs from the rivers; Lugger Bay Shore, Lugger Bay Seaward and Lugger Bay Point to measure conditions on the reef and to compare with the riverine inputs; sites near Bedarra Island and on a fringing reef near Thorpe Island to see how the physical conditions varied with distance from the coast; and one site at Clump Point was chosen to give more information on coastal conditions and to be used as a comparison with the sites closer to the rivers.

SSC measurements were taken to get an indication of the potential threats from suspended sediments such as light attenuation and deposition on corals, and also of the sediment transport and distribution throughout the area. Fluorescence sensors were used to give a rough indication of nutrient levels, so that a comparison between sites could be made, and also to determine when peak fluorescence events occurred and to compare them with other data such as SSC and river discharge. Analysis of these comparisons can then give some idea of how much nutrient levels around the area are affected by the rivers. Light sensors were used mainly on Lugger Bay Reef to examine the relationship between SSC and light levels reaching the seabed and to determine how regularly light extinction events occurred due to very high SSC. Wave heights were measured to determine which SSC events were due to wave resuspension rather than river discharge.

Two phototransects were recorded, both across the reef between the shore and the seaward side of the reef. They were analysed to determine the percentage cover of coral, algae, sediment, etc. The purpose of this was to examine the current condition of the reef.

Percussion cores of the reef were taken to ascertain the age of the reef and whether the coral species composition had varied over time. Several cores were taken across the reef between the shore and seaward sides.

Prediction of SSC

Dredging and other marine engineering work can cause the resuspension of large quantities of deposited sediment. If this occurs close to reefs it can impact on the heath of the corals. Because of this, environmental monitoring is usually required for any projects that are deemed a potential hazard to corals and other significant marine habitats.

The environmental monitoring usually includes the measurement of SSC. Background monitoring takes place before the marine work commences to develop a profile of normal SSC under a range of weather conditions. The background data can then be compared with measurements taken during the marine work to see if the work is raising SSC above their normal levels. If the increases in SSC are too high then the work may have to stop. The difficulty in this arises from trying to determine exactly what the background SSC would be under the weather conditions if the work was not taking place. It is unlikely that the data from the background monitoring will have a period with precisely the same weather conditions as those that occur during the marine engineering work. Using a control site is not a good solution as the variability of SSC between sites is too high (Orpin et al, 2004).

One solution is to develop a model, which predicts SSC based on the weather conditions. This can be done from first principles, measuring all the relevant parameters for each site such as bathimetry, wave and current boundary conditions, sediment fall velocities and erosion thresholds. However this is not always possible and even when it is, the results can be very poor due to the complex topography of reef environments. In this work an alternative approach is examined. The SSC data and wind data from the background monitoring period are used to generate a site-specific relationship between wind and SSC, which can then be used to predict SSC for given wind conditions. This has the advantage of only requiring wind data, which is readily available from meteorological bureaus.

The model was developed and tested using the SSC data collected at Lugger Bay, and Thorpe and Bedarra Islands. Data from other locations was also used to test the model's accuracy under a range of different conditions. The other locations were at Port Douglas and Nelly Bay on Magnetic Island, near Townsville.

Development of an Algal Growth Sensor

In order to give some information regarding nutrient concentration in the water a sensor was developed to measure the growth of algae on a glass plate. A potential difficulty with such a technique is that algal growth is not just dependent on nutrient concentrations. Factors like light, temperature and type of algae are also important. This means that in order to be certain that the algal growth related completely to nutrient concentrations, the sensor would need to be isolated so that the algae type and light levels could be controlled. In this work the use of an instrument without such isolation is investigated. The reasons for this are firstly to see how strongly the sensor is affected by these other factors and whether it will give a reasonable approximation of nutrient concentrations without the need for a complex isolation system. Secondly if it is not a useful tool for measuring nutrient concentrations it may still be useful to measure algal growth. Algal growth is a potential threat to coral reefs and it is dependent on light and temperature as well as nutrient concentrations. Therefore, an instrument designed purely to measure nutrient concentrations will not be able to detect whether the nutrients are causing levels of algal growth that could threaten corals, whereas this algal growth sensor will give a good indication of how likely algal over growth is in a particular area.

Thesis Layout

The following 4 chapters are divided into papers that have either been submitted or are in the process of being submitted to journals, with each paper dealing with a different aspect of the thesis. The first paper (Chapter 2) examines the SSC and the fluorescence in the study area around Lugger Bay Reef and the effects of the rivers on fluorescence and SSC. The current data and net sediment transport calculation that appear in this paper are not in the journal version and have instead been added to a separate paper (Marissa et al, unpublished work). The second paper (Chapter 3) focuses on Lugger Bay Reef, focusing on coral cover, light levels on the reef and core data. The third paper (Chapter 4) deals with the development of the SSC prediction model and the fourth (Chapter 5) with the algal growth sensor.

2 – Paper on:

Suspended Sediment Concentrations and Fluorescence in an Inshore Reef Region of the Great Barrier Reef Lagoon

To be submitted to the Journal of Marine and Freshwater Research

Suspended Sediment Concentrations and Fluorescence in an Inshore Reef Region of the Great Barrier Reef Lagoon

James C. Whinney and Peter V. Ridd
School of Mathematical and Physical Sciences, James Cook University, Townsville, Queensland, Australia.

Abstract

Sediments and nutrients can have an adverse effect on coral reefs. In the Great Barrier Reef Lagoon the reefs that are particularly at risk from changes in sediment and nutrient levels are those in the inshore region especially those close to river mouths. This work examines an area containing reefs and several river mouths. Suspended sediment concentrations (SSC), fluorescence and currents were measured at various sites in the region. This was done in order to study sediment and nutrient inputs from the rivers, sediment transport through the region and the SSC levels to which these inshore reefs were subjected. It was found that sediment transport through the region was greater than the sediment inputs from local rivers, indicating that sediment was coming from outside the region. For each site there was a strong relationship between SSC and fluorescence, and this relationship did not change significantly at times of high river discharge, such as flood plumes. This indicated that river discharge did not cause a significant phytoplankton or algal bloom. At the site of reef closest to the shore (also the largest reef in the study) SSC had a mean value of 185 mg/l. Resuspension of material from the seabed produced SSC levels that were often greater than literature values of peak SSC within the rivers discharging into region, and far higher than river plumes SSC values. In conclusion, the local rivers did not appear to have a major impact on the SSC and fluorescence levels on the reefs in the study area.

Keywords: Sediment, Fluorescence, Reef, Coral.

Introduction

The potential impact of increases in sediment and nutrient inputs into the Great Barrier Reef Lagoon (GBRL) due to land use changes features prominently in popular and scientific literature. For example the State of the Marine Environment Report for Australia listed the "declining marine and coastal water/sediment quality, particularly as a result of inappropriate catchment land use practices" as a primary concern for Australia's marine environment (Zann 1995). The effects of sediment discharge from the catchment areas adjacent to the GBRL are a significant area of scientific study (e.g. Done 1982, Gagan *et al.* 1987, Hopley 1982, Isdale 1984, Larcombe *et al.* 1996, Larcombe and Woolfe 1999a, Neil *et al.* 2002, Wasson 1997, Wolanski and van Senden 1983). The distribution of the reefs in the lagoon has been shown to be affected by suspended sediment concentrations (SSC) and sedimentation (Done 1982, Larcombe and Woolfe 1999, Larcombe and Woolfe 1999a, Woolfe and Larcombe 1998, Woolfe and Larcombe 1999). Cross shelf transport of sediment originating from the river catchments could also lead to problems for reefs in the GBRL (Alcock 1995, Brodie 1996, Brodie and Furnas 1996, Neil *et al.* 2002, Zann 1995). To study the significance of riverine sediment and nutrient inputs, it is important to look at those reefs most at risk: inshore reefs close to river mouths. Reefs a few kilometres from the coast can also give an indication of the effect of cross shelf sediment transport.

This work examines one of the reefs (Lugger Bay Reef) that is closest to the mouth of a major river in the GBRL by analysing sediment concentrations and fluorescence which can be used to infer the presence of organic material in the water, particularly chlorophyll. The proximity of the reef to the mouth of the Tully River, an intensively farmed catchment, potentially makes the reef at Lugger Bay one of the most susceptible reefs in the GBRL to anthropogenic changes in land use. Field measurements allowed for broad spatial comparisons to be made between fluorescence and suspended sediment levels, sediment transport in the coastal zone, and the significance of fluvial inputs.

Materials suspended in the water column such as sediments and nutrients can in some cases have a detrimental effect on the survival of some coral reef species (Fabricius and Wolanski 2000, Fabricius et al. 2003, Devlin and Brodie 2005). Nutrients are an important part of the ecosystem as they are required by both plants and animals (including corals). However excessive levels of nutrients have the potential to harm corals both directly and indirectly (Ferrier-Pages 2000, McCook 1999, Smith et al 1981, Williams 2001). Direct impacts are usually non-fatal and incorporate changes to growth and calcification rates, and to reproduction (Ferrier-Pages 2000). Indirect impacts by abnormally high levels of nutrients can allow macroalgae to grow faster and thus out-compete the corals for light and substrate. In addition, nutrient-rich water could allow phytoplankton to bloom, increasing turbidity and reducing light levels (Williams 2001, Smith et al 1981). These indirect effects could be amplified if there is also a shortage of herbivorous fish in the area due to over-fishing since the herbivorous fish would normally control the growth of the algae through grazing (Williams 2001, McCook 1999).

Suspended sediments in the water column reduce the light reaching corals and so decrease the energy gained by the coral from photosynthesis (Stafford-Smith 1993, Williams 2001, Anthony et al. 2004). When sediments land on corals, the filter-feeding organism must remove the sediments or risk being smothered. The removal is achieved by either excreting mucus or by physical action (Marshall and Orr 1931). If the sediments settle faster than they can be removed, the corals may die by smothering or a bacterial infection (Fabricius and Wolanski 2000, Marshall and Orr 1931). Corals that do survive have to use significant energy in order to remove the sediment, so they have less energy available for growth (Anthony and Fabricius 2000). If high levels of both nutrients and sediments are present then they can combine together to form large sticky particles called marine snow. Because of the large size and the adhesive nature of these particles it is much harder for the corals to remove them and so it increases the chance that the corals will be smothered (Fabricius and Wolanski 2000).

Sediments can have an adverse effect on coral reproduction. In laboratory experiments elevated suspended sediment concentrations (SSC) levels of 50 and 100 mg/l led to a decrease in fertilisation, larval survival and settlement for *Acropora digitifera* (Gilmour 1999).

However sediments have also been shown to be beneficial to corals as the nutrients and energy they contain are a food source (Anthony 2000).

General statistics of the Great Barrier Reef can be found in Furnas (2003). The catchment area of the rivers flowing into the Great Barrier Reef is 423,070 km^2 which is twice the area of the Barrier Reef itself. The most significant contribution comes from the Burdekin and Fitzroy river basins which account for 64% of the total area. Approximately 1.1 million people live within the catchment where the main land use is agriculture. By land area, cattle grazing is the most important industry taking up about 76% of the area. Annually the rivers discharge into the lagoon a combined total of 14,000,000 tonnes of fine sediment, 7,000 tonnes of phosphorus, and 40,000 tonnes of nitrogen.

Over millennia sediments have built up in the lagoon creating a shore attached wedge in the inshore region up to 5m thick (Maxwell 1968, Belperio 1983, Johnson and Searle 1984). The presence of this wedge means that a large amount of sediment is available on the seabed for resuspension by waves and currents. The deposition of more sediment onto the wedge does not increase the amount of resuspension possible since there is already more sediment available than the waves can resuspend (Larcombe and Woolfe 1999). For this reason, it has been proposed that increases in riverine sediment inputs will not lead to greater SSC during periods of time when wave resuspension is the dominant mechanism causing high SSC (Larcombe and Woolfe 1999, Belperio 1983).

In the central GBRL, the primary source of energy for sediment transport is the South East trade winds that blow from April to September. The trade winds tend to drive the sediment northward along-shore and also produce swell waves which resuspend material (Belperio 1983, Larcombe et al. 1995, Orpin et al. 1999). In local areas, tides can also be an important factor in generating turbidity (Larcombe et al. 1995, 2001). On short time scales cyclones can lead to turbidity and also movement of sediment (Larcombe and Carter 2004).

River plumes have a short-term and local influence on turbidity (Wolanski 1994, Taylor 1996). If winds are favourable, river plumes can reach the mid and outer reef shelves (Brodie 1996, Brodie and Furnas 1996), however plumes tend to be only a few metres thick and carry a small load of sediment (Taylor 1996). For example a major plume from the Barron River, which stretched over an area of 45km by 10km only contained about 9000 tonnes of suspended sediment (Larcombe and Woolfe 1999) whereas swell waves in Cleveland Bay acting over a 200 km^2 are able to disturb 50 000 tonnes of sediment (Larcombe and Woolfe 1999).

A study of nutrients fluxes in the GBRL by Furnas et al (1996) shows the relative importance of the different sources of nitrogen. One source is from rivers which input 40,000 tonnes of nitrogen yearly. Rainfall, upwelling from the ocean, reefal production and production by trichodesium each contribute about half the river input. Benthic release contributes around five times the nitrogen input of the rivers and sediment resuspension and deposition causes the circulation of 100 times the river nitrogen input. It is thus clear that river nitrogen fluxes do not dominate other nitrogen fluxes and are likely to be minor in many locations. Nevertheless on local scales close to river mouths draining agricultural land, it is possible that river derived nutrient have a significant affect on the nutrient balance and may alter the concentrations of algae, phytoplankton and other organic material in the water column.

This study focused on the reef at Lugger Bay just 8 km to the North of the Tully River (Figure 2.1), a significant sediment and nutrient source draining one of the highest rainfall catchments in Australia. The work has three aims. The first is to determine the relationship between SSC and fluorescence and to determine if this changes during periods of significant river discharge. The input of large quantities of nutrients from the rivers could be expected to produce major spikes in fluorescence due to phytoplankton blooms. The second aim is to quantify the sediment transport in the coastal zone and compare this to local river inputs to determine if river inputs are a major contributor to the sediment budget of the region. The third aim is to determine the relative influence of river plumes and wave resuspension sediment in generating high SSC events. The difference between the second and third aim is that the second aim examines the flow of sediments in and out of the region, while the third aim examines the causes of periods of high SSC that may not lead to a flow of sediment, for example a resuspension event may be followed by a deposition event, with little net flow occurring.

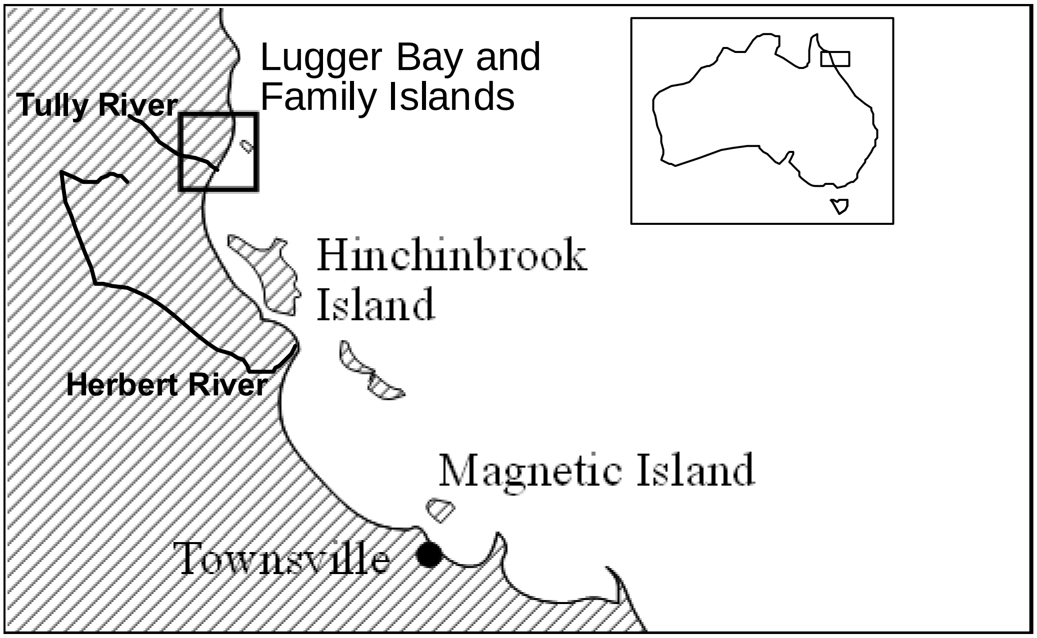

Figure 2.1: Location of Lugger Bay and Family Islands region in North Queensland.

Study Site

Lugger Bay is located in the northern portion of the central GBRL, immediately south of two significant tourist destinations, Mission Beach and Dunk Island (Figures 2.1 & 2.2). The nearby river catchments are predominately used for cane and banana plantations. The largest local river, the Tully, has an annual input into the GBRL of 0.1×10^6 tonnes of fine sediment, 100 tonnes of phosphorus and 1,000 tonnes of nitrogen. The smaller Murray River is the second largest with an output of 0.04×10^6 tonnes of fine sediment, 40 tonnes of phosphorus and 400 tonnes nitrogen per year (Furnas 2003). The Hull River, an inlet, does not input a significant amount of sediments or nutrient into the GBRL. The closest river of significant size, the Herbert, is about 60 km to the South of this location and produces an annual output of 0.50×10^6 tonnes of fine sediment, 200 tonnes of phosphorus and 2,000 tonnes of nitrogen (Furnas 2003). Most of the particulate material from the Herbert River is carried along the coast to the north, and some of this is then trapped in Missionary Bay and the Hinchinbrook Channel (Woolfe and Larcombe 1998).

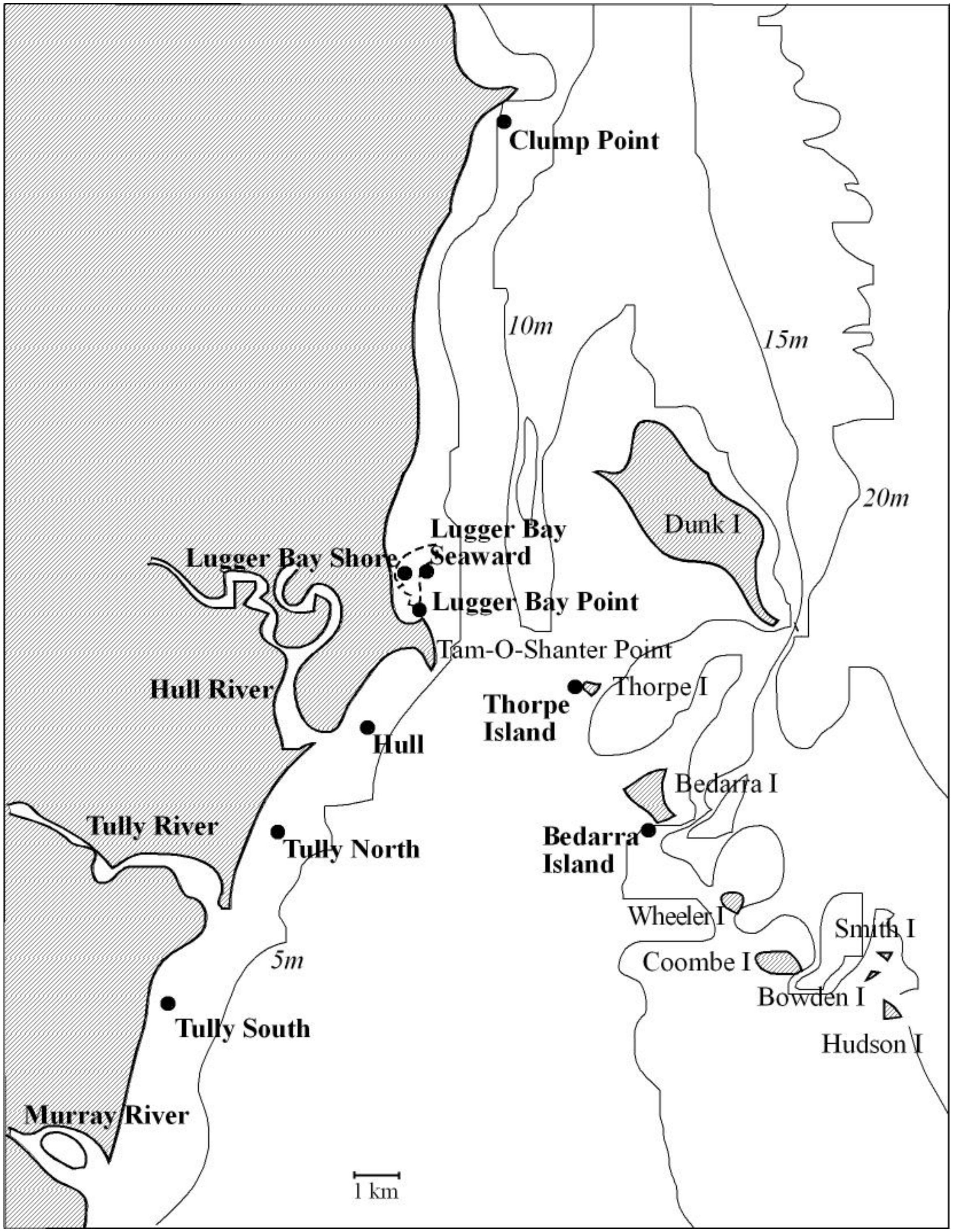

Figure 2.2: Instrument locations in Lugger Bay and in the surrounding area.

The locations chosen for study within the area are shown Figure 2.2. The sites at Lugger Bay (17° 57.7' S, 146° 05.7' E) were selected proximal to the coral reef. The reef at Lugger Bay is about 800 m long by 400 m wide and contains only a few species of corals, dominated by *Porites Australiensis* that form large bombies that merge together in the central part of the reef. The reef is located 300 m east of the shoreline and 500 m north of Tam-O-Shanter point and is partially sheltered by both Tam-O-Shanter point and Dunk Island, 4.5 km to the east (Figure 2.2). Three sites were selected around the reef. Lugger Bay Shore site was situated in an area of sand and bombies at the back of the reef about 200 m from the shore. Lugger Bay Seaward site was on the seaward side of the reef opposite Lugger Bay Shore site. Lugger Bay Point site was at the edge of the reef nearest to Tam-O-Shanter point.

The sites of Thorpe and Bedarra Island were selected because they also contain fringing reefs but were further from the coastline and so would show how the SSC varied with distance from the shore. Thorpe Island is about 5 km to the south east of Lugger Bay (17° 59.0’ S, 146° 07.9’ E). The site selected near this island was on a small fringing reef on the side of the island facing the mainland sheltered from winds coming from the east. Bedarra Island is a further 3 km to the south east (18° 00.4’ S, 146° 09.2’ E). A site position was chosen 50 m from a rocky headland on the south side of the island close to some isolated coral colonies. The site was exposed to the prevailing winds from the south east.

Sites along the coastline were used to determine how the SSC varied along-shore from the point of sediment input from the Tully and Hull Rivers and to see how much material was entering the area from the south. All three sites were just under a kilometre from the shoreline. The bottom type at all sites was sandy and there is slight shelter from the south easterly tradewinds from the Family Islands group to the east and from Hinchinbrook Island further to the south.

Another site was located 10 km along the coastline to the north of Lugger Bay at Clump Point. The Clump Point site was situated about 200 m to the south of Clump Point in a sandy area with rocky outcrops.

Methods

Data collection

A combination of turbidity loggers, fluorescence sensors and a current logger were deployed in the Mission Beach - Tully region. The turbidity loggers used optical backscatter as described in Ridd and Larcombe 1994. The conversion between the turbidity loggers NTU output and SSC was achieved by using an average calibration for all sites. The calibration was determined from *in-situ* turbidity measurements and water sampling over a wide range of weather conditions. This technique does not take into account changes in sediment types between sites. An alternative method is to take sediment samples from each site and analyse them in a laboratory, however, this method also has its problems as it does not account for the changes in sediment types that are resuspended during different weather conditions.

The fluorescence sensors, developed by Dupont (2003), work by emitting blue light, from an LED covered by a filter, at the correct wavelength to excite chlorophyll *a*, i.e. about 460 nm. The chlorophyll *a* then fluoresces, emitting infra red light at about 685 nm (Hall and Rao 1994). The instrument then detects the amount of infra red light emitted and compares it to a background level, i.e. how much infra red light was detected before the blue LED was turned on. This comparison should give an indication of how much chlorophyll a is in the water column. However other molecules, such as chlorophyll *b*, pheophytin *a* and pheophytin *b* have excitation and emission spectra that overlap with chlorophyll *a*'s (Dupont 2003, Jeffrey et al. 1997). This overlap means that the instrument measures the combined concentration of many different molecules rather than the concentration of chlorophyll *a*. Since the molecules detected by this method are organic in nature, the instrument produces a relative measurement of the concentration of organic material in the water column. The level of organic material present is related to the amount of nutrients available, and thus the instrument gives an indirect relative measurement of the nutrient concentration. However, as different organic material contain different amounts of chlorophyll, a fluorescence sensor is dependent on the type of organic material as well as the concentration. While this method does not have the accuracy of taking water samples it has the advantage of being able to take readings continuously over periods of months. The fluorescence instruments used are calibrated against each other so that the outputs of different instruments will be the same when measuring the same event; however, the measurements are not in any standard units. The readings from the instruments are linearly related to fluorescence, but will only be linearly related to the concentration of organic material if the relative quantities of the different types of organic material present remain constant.

The loggers were placed 30cm above the sea floor for periods of several months, with the sensors activating every 10 minutes taking an average from 8000 readings. Current was measured using a WHISL current logger deployed about 1 km from the coastline, between the Hull and Tully rivers at the North of Tully site to determine the net current in the region. Wave heights were measured using a WHISL at the Hull site, the sample interval was 0.25 s and bursts were recorded every 2 hours. The dates of deployment at the various sights and the environmental parameters measured are shown in Table 2.1.

	Date					
Site	20/11/03 - 20/12/03	20/12/03 - 26/01/04	26/01/04 - 23/03/04	23/03/04 - 29/04/04	29/04/04 - 14/07/04	16/07/04 - 03/10/04
Lugger Bay Shore	SSC & fluorescence	-	-	SSC & fluorescence	-	-
Lugger Bay Point	SSC	-	SSC	SSC	-	-
Lugger Bay Seaward	-	SSC & fluorescence	SSC	-	SSC & fluorescence	-
Clump Point	SSC & fluorescence	SSC & fluorescence	SSC & fluorescence	SSC & fluorescence	SSC & fluorescence	-
Hull	-	SSC & Wave	-	-	-	-
North of Tully	-	SSC	-	-	SSC	SSC, fluorescence & Current
South of Tully	-	-	-	-	SSC & fluorescence	-
Thorpe Island	SSC	SSC	SSC	SSC	-	-
Bedarra Island	SSC & fluorescence	SSC & fluorescence	SSC & fluorescence	-	-	-

Table 2.1: Deployment times at the various locations.

Results

SSC and Fluorescence Statistics

Basic statistics for SSC data for the various sites is shown in Figure 2.3. The lowest medians and inter-quartile ranges occurred at the island sites showing an expected decrease in SSC with distance from the coast. The sites at Lugger Bay and close to the Tully River were all within a few hundred metres of the shoreline and have the medians and inter-quartile ranges.

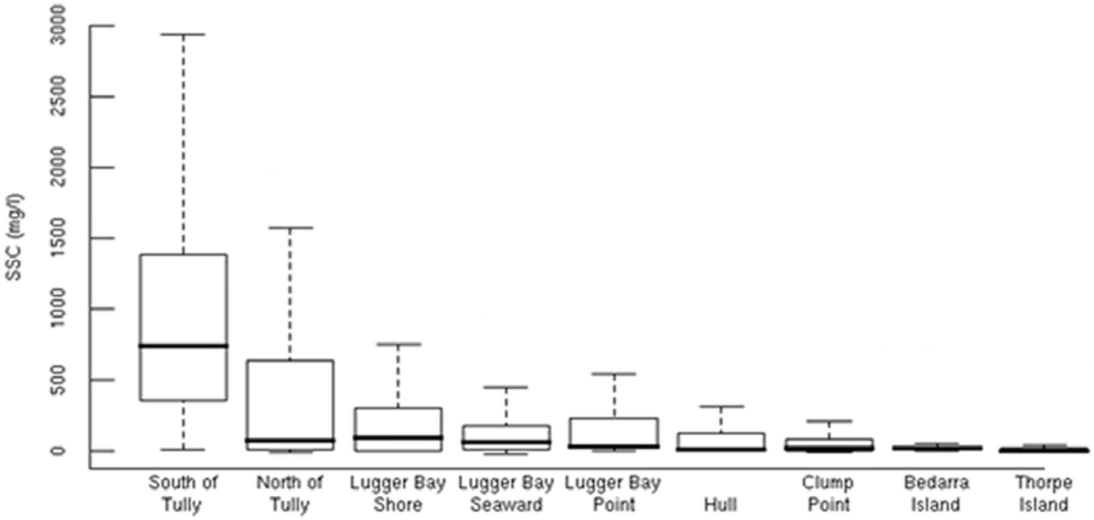

Figure 2.3: Box plots of the SSC data. Maximum and minimum are the maximum and minimum data points excluding the outliers. Outliers are defined as being more than 1.5 times the inter-quartile range above the upper quartile boundary.

The fluorescence statistical data is shown in Figure 2.4. The fluorescence data has arbitrary units as it is only a relative fluorescence between the different instruments used. The medians and inter-quartile ranges for this data correspond reasonably well with the values for the SSC with the inshore sites having larger medians and inter-quartile ranges than those further offshore, showing that high levels of SSC and fluorescence usually occur together.

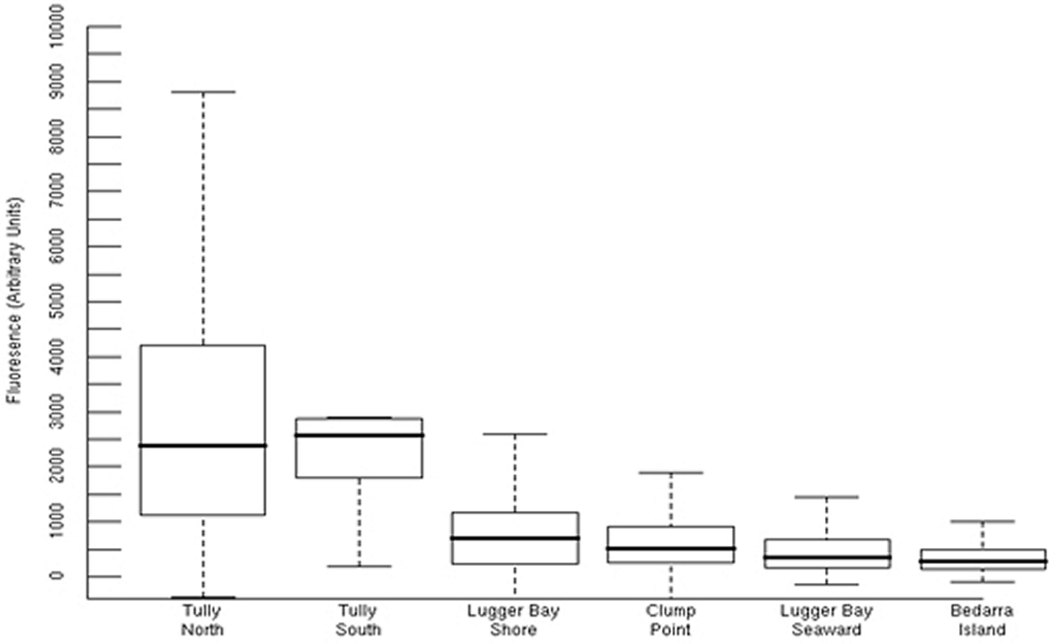

Figure 2.4: Box plots of the fluorescence data. Maximum and minimum are the maximum and minimum data points excluding the outliners. Outliners are defined as being more than 1.5 times the inter-quartile range above the upper quartile boundary.

Temporal Distribution of SSC and Fluorescence Levels

Figures 2.5 and 2.6 show examples of the data taken at the different sites. The discharge from the Tully River has been added for comparison, this data is from the Queensland department of Natural Resources and Water. Figure 2.5 also shows the wave data recorded at the Hull site.

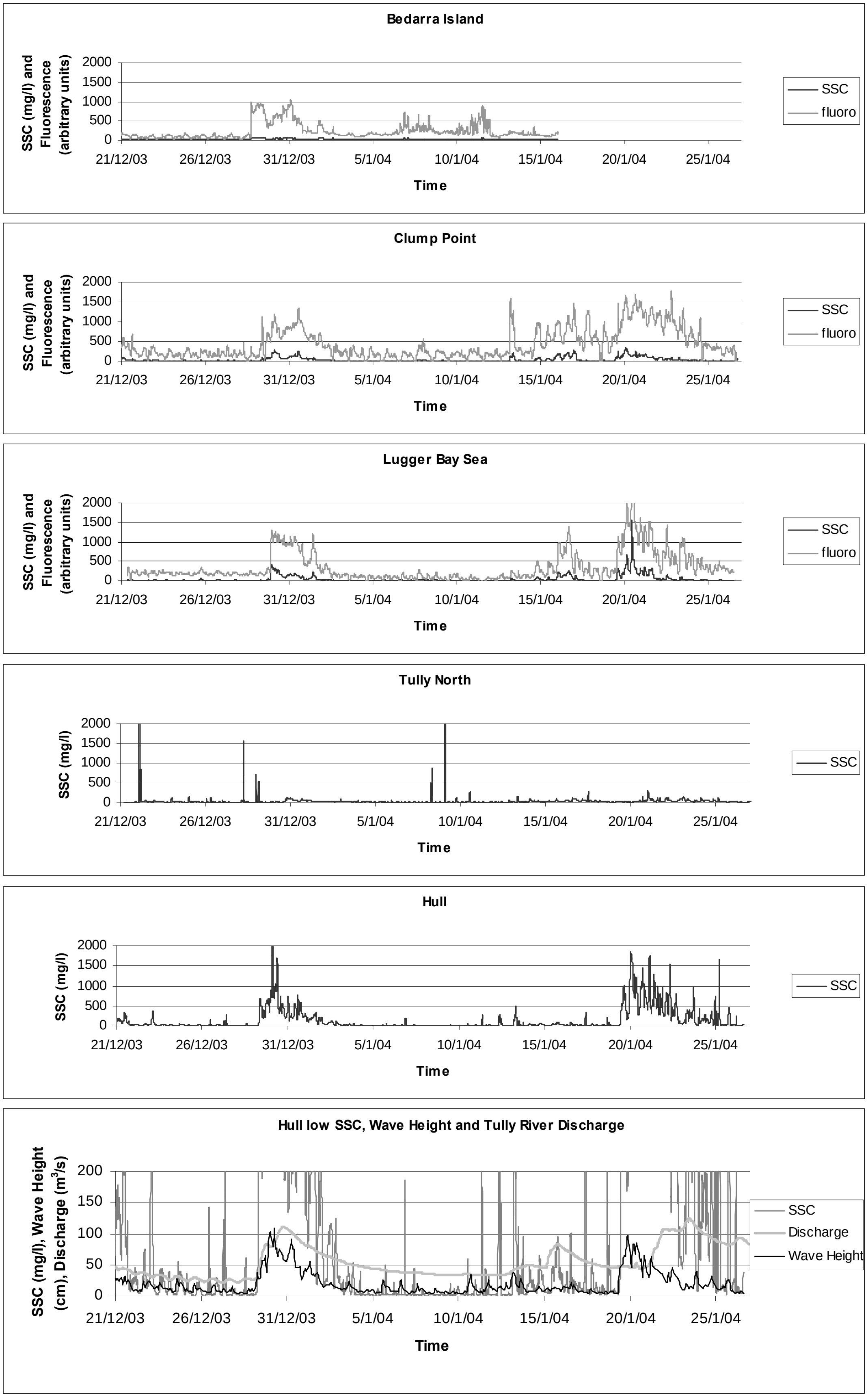

Figure 2.5: Time series from 21/12/03 to 25/01/04 of SSC and Fluorescence for (from top to bottom) Bedarra Island, Lugger Bay Sea, Clump Point, Tully North and Hull. The bottom graph shows wave data and Tully River Displacement with the low SSC values from the Hull for comparison.

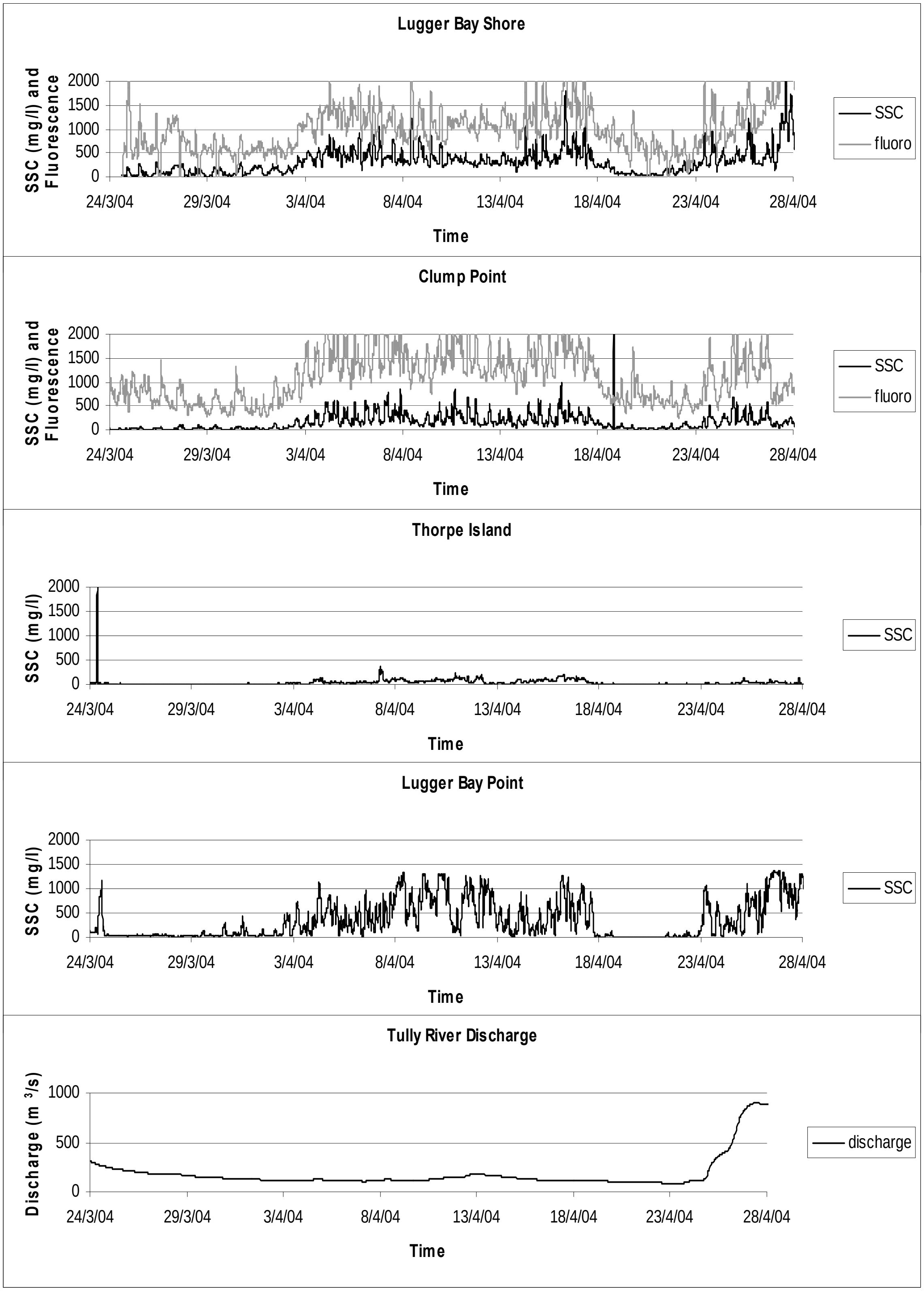

Figure 2.6: Time series from 24/03/04 - 28/04/04 of SSC and Fluorescence data for (from top to bottom) Lugger Bay Shore, Clump Point, Throe Island and Lugger Bay Point and Hull. The bottom graph shows Tully River Displacement.

Spatial Distribution of SSC and Fluorescence Levels

Table 2.2 displays the average SSC and fluorescence levels for the various sites as well as the average of the ratio between them. The ratio is important because a proportion of the suspended sediment will be fluorescing organic particles and so a high SSC will lead to a high fluorescence. However if the ratio between them changes, it indicates that the mix of the suspended particles has changed. A change in the mix of particles could indicate a change in the source of the sediment. For example, sediment from a river might have more fluorescing particles in it than resuspended sediment due to a higher nutrient concentration.

	Mean Values		
Site	SSC (mg/l)	Fluorescence (arbitrary units)	Ratio of fluorescence to SSC
Lugger Bay Shore	200	718	77
Lugger Bay Point	205	-	-
Lugger Bay Seaward	105	480	10
Clump Point	76	630	130
Hull	136		
Tully North	1300	3000	35
Tully South	990	2300	6
Thorpe Island	34	-	-
Bedarra Island	37	340	15

Table 2.2: Mean SSC, Fluorescence levels and of the ratio of fluorescence to SSC at the different sites in the area.

To further analyse the ratio of fluorescence by SSC, the SSC data was divided into 3 terciles with the lowest third of the data in the 1st tercile, the middle third of the data in the 2nd tercile and the highest third of the data in the 3rd tercile. The fluorescence to SSC ratio for each SSC in each tercile was found and then the mean fluorescence to SSC for each tercile was calculated (Table 2.3). A comparison of the mean ratio of fluorescence to SSC for the different terciles of SSC indicates whether high SSC events lead to a higher or lower percentage of fluorescent particles in the suspended sediment. The table shows that as the SSC increases fluorescence by SSC decreases, i.e. when SSC increases the fluorescence increases by a smaller factor. For example, at Clump Point for low levels of SSC the fluorescence to SSC ratio is 190, for medium SSC levels the ratio is 26 and for high SSC levels the ratio is only 8.

	Mean of the Ratio of Fluorescence to SSC		
Site	1st tercile (low SSC)	2nd tercile (medium SSC)	3rd tercile (high SSC)
Lugger Bay Shore	227	8	3
Lugger Bay Seaward	19	7	4
Clump Point	190	26	8
North of Tully	150	17	3
South of Tully	14	3	2
Bedarra Island	25	12	8

Table 2.3: Fluorescence by SSC for the different terciles of SSC.

Current Data

The longshore current data with a 7 day rolling mean (to remove tidal effects) from the Tully North site is shown in Figure 2.7. There are both periods when the current flows predominantly up the coast, and down the coast with a mean longshore speed of 0.5

cm/s and with a speed of less than 1.5 cm/s for 96% of the time. During the 2 months of observation the net movement of the longshore current was small, about 0.5 cm/s in the direction of 205°. The lack of any large net current appears to contradict previous theories of a persistent northward flow in the region (Belperio 1983, Larcombe et al. 1995, Orpin et al. 1999), but concur with the theory by Pringle (1986) that due to the presence of the Islands the wind driven currents are split at the Tully River, some going North and some South.

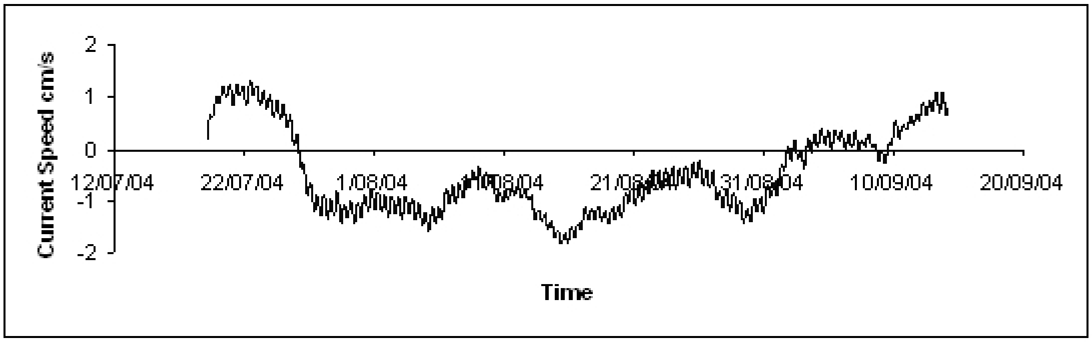

Figure 2.7: Longshore current at north of Tully site with a 7 day rolling mean. Positive current speed is represents northward movement along the coast and negative represents southward movement.

Discussion

Spatial Variation in SSC and Fluorescence

In Table 2.2 the SSC and fluorescence tend to vary together, with areas that have a high average SSC also having a high average fluorescence. The sites closest to the shore of the mainland had higher SSC than those further out to sea at Thorpe and Bedarra Islands. SSC vs distance from the coast (Figure 2.8) shows high but variable SSC close to the shore and consistently lower SSC further from the coast. On average the SSC was 12 times higher near the shore than it was at the islands about 5 to 8 km from the shore while the fluorescence was 4 times higher. The highest SSC averages were found close to the Tully River. These sites had an average SSC that was 7 times higher than those at Lugger Bay and Clump Point. The fluorescence at the sites closest to the Tully River was also 4 times higher than at the other coastal sites. Some of the sites on the coast, particularly those nearest to the Tully River, were very close to shore so there is a possibility of surf driven resuspension at low tides, which would increase the average SSC of these sites.

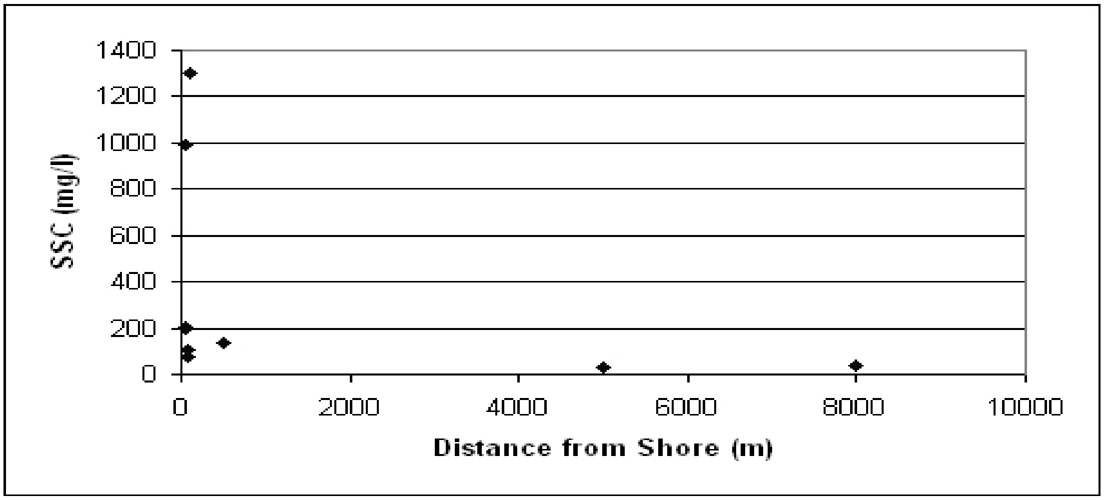

Figure 2.8: SSC vs. distance from shore for the various sites.

Relationship between SSC and Fluorescence

For all the sites, a rise in SCC corresponded to a rise in fluorescence. The changes occurred simultaneously with increases and decreases happening at the same time for both the SSC and the fluorescence. However the ratio between SSC and fluorescence does not remain constant. As SSC rises, fluorescence by SSC decreases showing that SSC increases more than fluorescence (Table 2.3). The correlation between SSC and fluorescence can be seen in Figure 2.9. In most cases the relationship between fluorescence and SSC could be modelled using a quadratic equation except in the case of Bedarra Island where noisy data made it harder to fit an equation to the correlation. The non-linear ratio between fluorescence and SSC suggests that in rough weather conditions, the inorganic portion of the suspended sediments is increased.

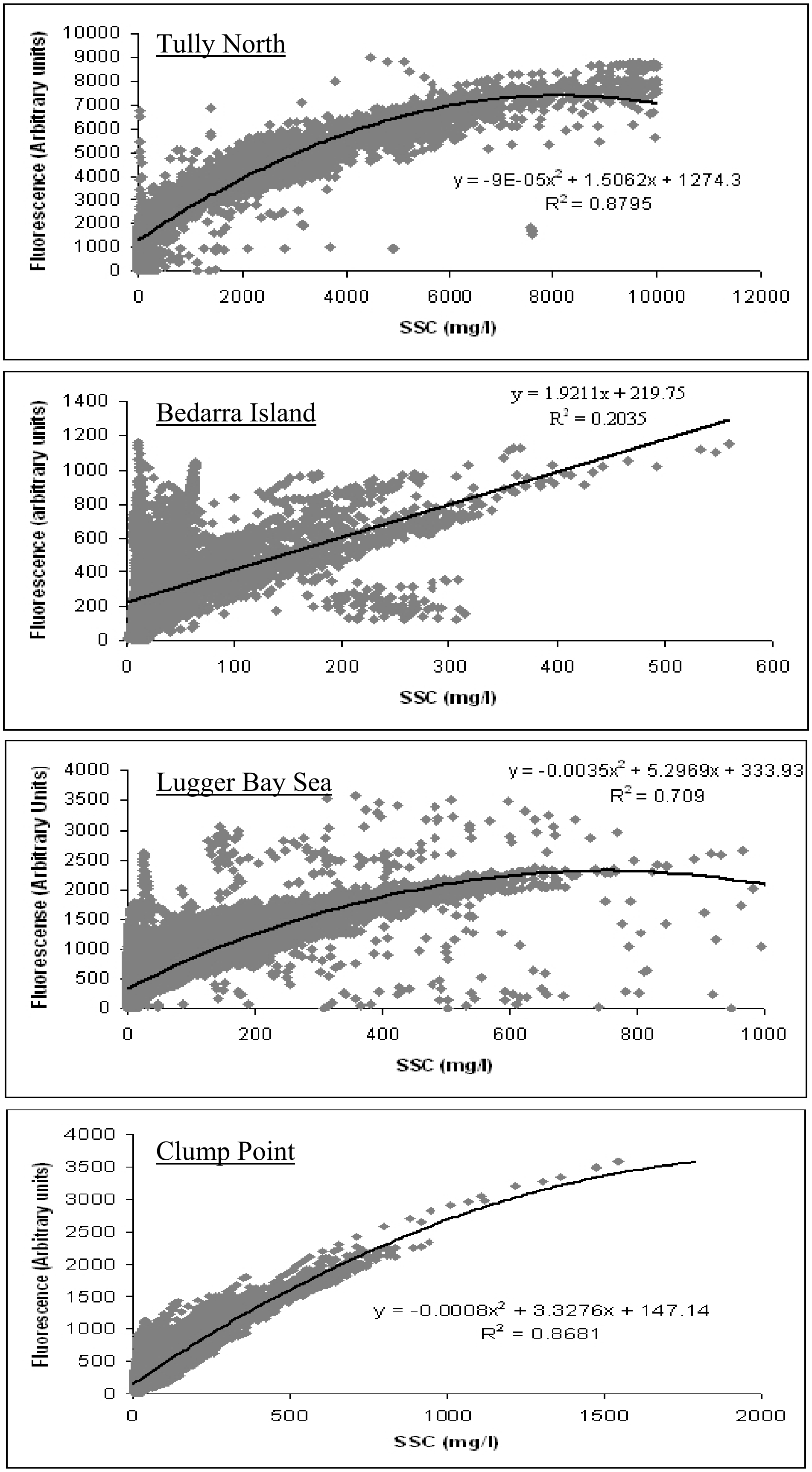

Figure 2.9: Correlation between fluorescence and SSC, for sites, from top to bottom: Tully North, Bedarra Island, Lugger Bay Seaward, and Clump Point.

Flood Plumes and Wave Resuspension

In the wet season (between December and April) the Tully River has an average SSC of 23 mg/l and a maximum SSC of 230 mg/l (both calculated from a decade of data) (Furnas 2003). The measurements taken on the reef at Lugger Bay, about 10 km from the mouth of the Tully River, gave an average SSC of 185 mg/l. This shows that even during events where large amounts of sediment are being discharged from the Tully River the SSC at Lugger Bay Reef is unlikely to rise much above commonly occurring levels. The implication is that floods and plumes do not represent an impact to the turbidity at Lugger Bay.

Figure 2.10 shows how fluorescence and SSC vary with river discharge using Bedarra Island and Lugger Bay Shore sites as examples. Both figures show only a very weak correlation of either fluorescence or SSC to river discharge with R^2 values between 0.1 and 0.3. The correlations in all cases have small positive gradients indicating a slight increase of fluorescence and SSC with increase in river discharge.

It should be noted that high river discharge events such as flood plumes tend to occur during periods of strong winds or storms, when high rainfall and thus high river discharge is likely. These conditions generate waves that drive sediment resuspension. Hence it is difficult to determine how much of the positive correlation is due to the river discharge and how much is due to wind driven resuspension. A comparison between the effects of waves and river discharge on SSC can be seen in Figure 2.5. Here the wave height data shows a strong relationship with SSC, particularly at the Hull site where the wave logger was located. The linear relationship between SSC and wave height has an R^2 value of 0.55, whereas for SSC and river discharge during the same period the R^2 was 0.13 (Figure 2.11).

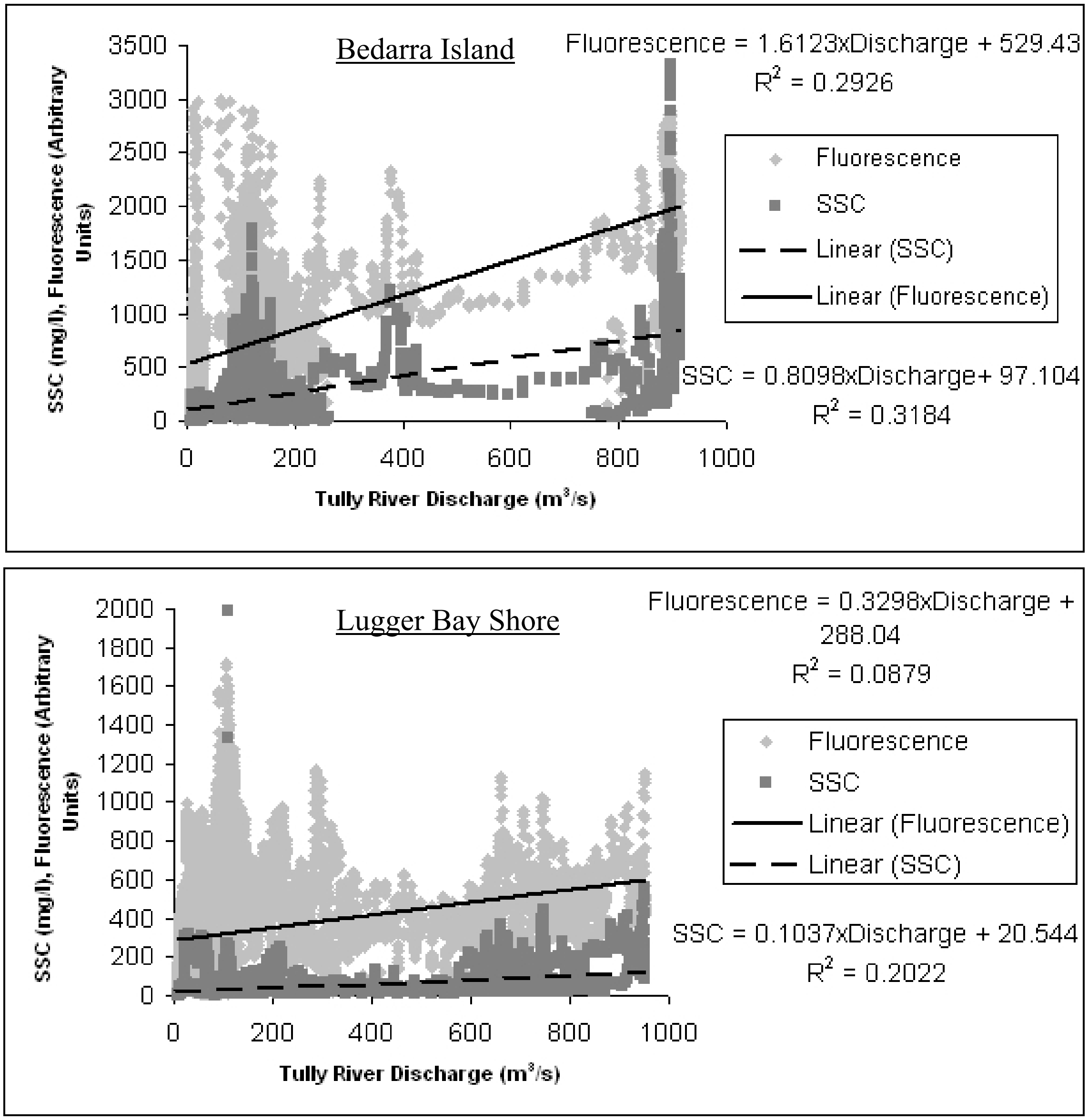

Figure 2.10: Correlation between SSC and river discharge and between fluorescence and river discharge for Bedarra Island (top) and Lugger Bay Shore (bottom) sites.

The two high SSC events from 29/12/03 to 03/01/04 and from 19/01/04 to 25/01/04 (Figure 2.5) correspond to an increase in wave heights starting at the same time and continuing for the same period. There are increases in river discharge during these periods however for the event from 19/01/04 to 25/01/04 the increase in discharge starts about 2 days after the increase in SSC. For the event from 29/12/03 to 03/01/04, the increase in discharge does begin at the same time as the increase in SSC, but the increase is gradual unlike the rapid increase in both SSC and wave height. This indicates that for these two SSC events wave resuspension is the most likely cause of the raised SSC.

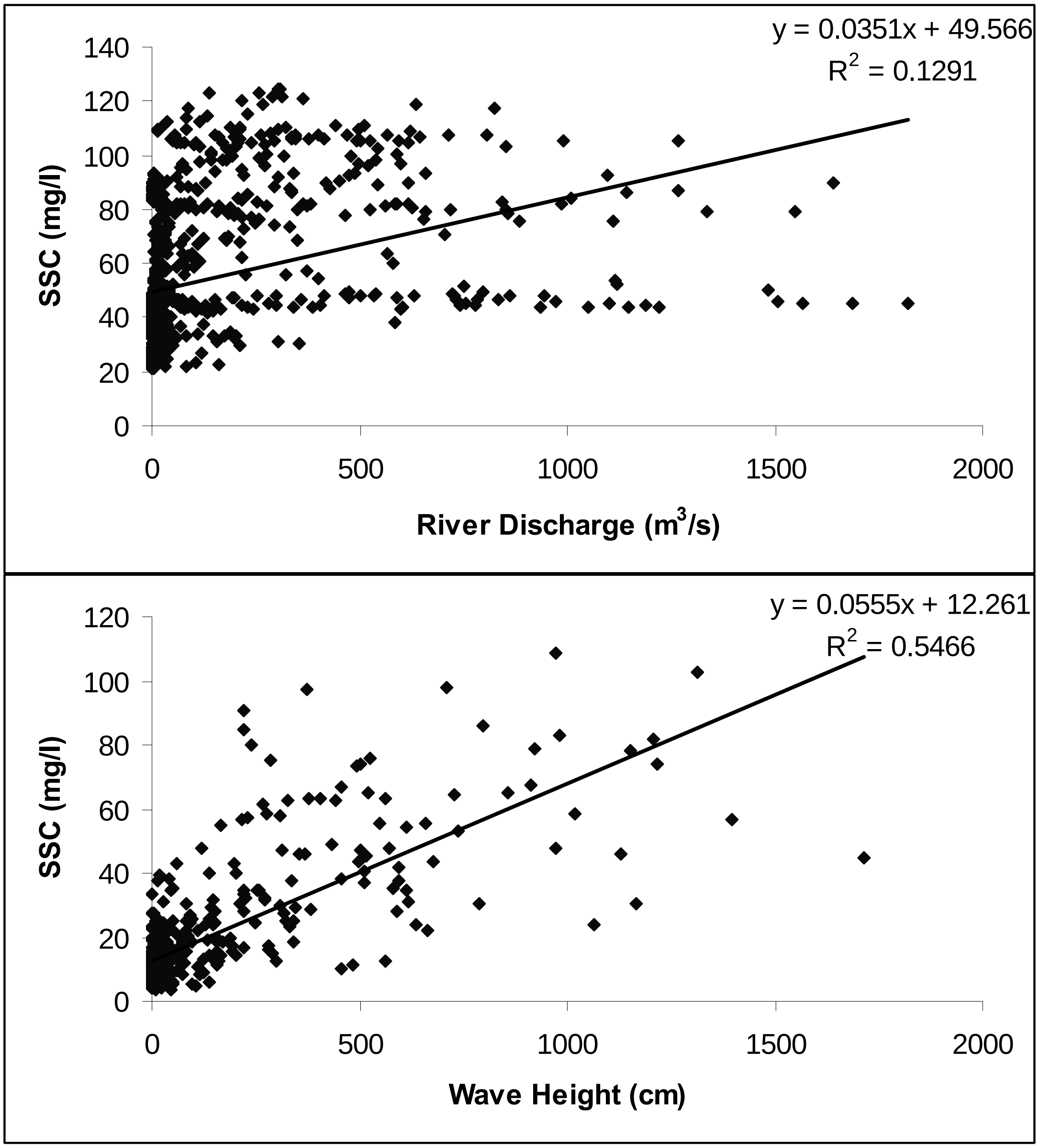

Figure 2.11: Correlation between SSC at the Hull site and Tully River discharge (top), and between SSC at the Hull site and wave height (bottom).

A more minor SSC event occurred between 13/01/04 and 18/01/04, however this event is not accompanied by an increase in wave height but there is an increase in river discharge at this time suggesting that river discharge is responsible for this event. The river discharge during this event is of a similar magnitude to the discharges during the 29/12/03 to 03/01/04 and 19/01/04 to 25/01/04 SSC events but the SSC peak is an order of magnitude smaller than the peaks for the other events (about 100 mg/l compared to over 1000 mg/l for the other events). This suggests that the river discharge during the 29/12/03 to 03/01/04 and 19/01/04 to 25/01/04 SSC events is not large enough to cause the observed SSC peaks, indicating again that these two events are caused by wave resuspension rather than river discharge.

When studying peak SSC events that occurred at the same time as large discharges from the Tully River and those that occurred when there was no corresponding discharge, there was little change in the relationship between fluorescence and SCC. Figure 2.12 shows the correlation between fluorescence and SSC at the Lugger Bay Shore site for peak SSC events (over 200 mg/l) during times of high discharge (over 200 m^3/s) from the Tully River and at times of low discharge (less than 200 m^3/s). The correlations for the two levels of discharge are very similar showing that the river discharge has very little effect on the relationship between fluorescence and SSC.

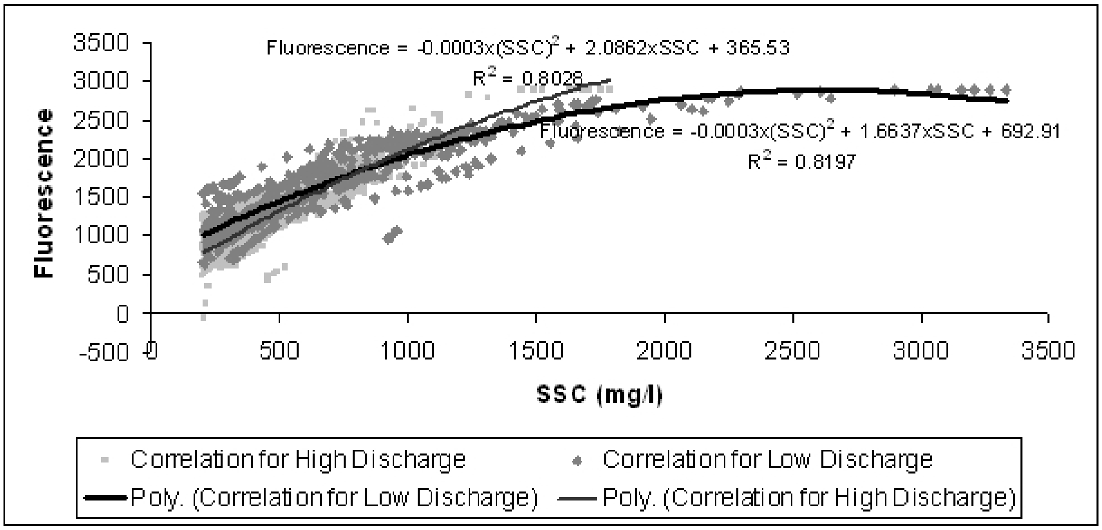

Figure 2.12: Correlation between fluorescence and SSC during Tully River high discharge events (over 200 m3/s) and for Tully River low discharge events (under 200 m3/s) for SSC events of over 200 mg/l for Lugger Bay Shore.

Net Sediment Flow

Using the observed SSC for the various sites and the current data, a rough calculation of the flow of sediments through the region can be made. Figure 2.8 shows a high variability of SSC close to the shore and a more continuous gradient in SSC further from the shore. Therefore an average SSC for the first 500 m from the shore was calculated by averaging the mean SSC from the sites within this area. The depth in this area was also averaged. The change in SSC between 500 m and 8 km was approximated as a linear gradient as was the change in depth. Therefore the approximate average value suspended sediment in the cross-sectional area between the coast and the islands is 4400 Kg/m. This is a large sediment load and even with small net currents as suggested by the current data it can lead to a large net transport of sediment. For example taking a net current of 0.5 cm/s would make the net sediment flow through the region 630,000 tonnes per year. Given that the combined sediment input from the Tully and Murray rivers is 170, 000 tonnes per year it is clear than even a small net current may well be sufficient to remove sediments added to the region from river discharge.

Sediment Input from Outside the Region

Since the sediment flow through the region is likely to be much larger than the local sediment inputs from the Tully and Murray Rivers, it is possible that sediment is entering the region from other sources. A possible source is the Herbert River to the south that has an annual input of 540,000 tonnes of fine sediment and has been found to export sediment into the Hinchinbrook Channel (Belperio 1983, Moss et al. 1992), between Hinchinbrook Island and the mainland (Figure 2.1).

SSC Levels on the reefs

The measurements showed that Lugger Bay Reef exists in highly turbid conditions with SSC less than 25 mg/l for 35% of the time, less than 50 mg/l for 48% of the time, less than 100 mg/l for 58% of the time, and less than 200 mg/l for 74% of the time. The reef at Thorpe Island was less turbid with SSC less than 25 mg/l for 80% of the time, less than 50 mg/l for 91% of the time, less than 100 mg/l for 96% of the time, and less than 200 mg/l for 99% of the time. In comparison Gilmour found that SSC of more than 50 mg/l significantly decreased the fertilisation, larval survival and settlement of the coral species *Acropora digitifera* (Gilmour 1999). The corals at Lugger Bay appear healthy (Whinney and Ridd unpublished work) indicating the species represented on this reef are more resilient to elevated SSC. This suggests that 50 mg/l is too low to be used as an indicator of potential reduction of fertilisation in some inshore coral species.

The SSC at Lugger Bay Reef was high compared with other inshore reefs in the region. For example reefs in the bays of Magnetic Island were less than 5 mg/l 60-70% of the time and rarely exceeded 40 mg/l and at Rattle Snake Island SSC was less than 5mg/l for 87% of the time and rarely exceeded 10 mg/l (Larcombe et al 1995). Lugger Bay has much higher SSC than this and Thorpe Island is also subjected to slightly high concentrations than those at Magnetic Island.

Conclusion

Measurements of SSC and fluorescence in the Tully River/Lugger Bay area show major variations both temporally and spatially. SSC concentrations were on average 12 times higher near the mainland than they were 5 to 8 km from the mainland. Fluorescence levels were 4 times higher near the shore than they were 5 to 8 km from the mainland. SSC varied temporally at all sites by at least 2 orders of magnitudes with highest concentration occurring during periods of high wave activity.

A clear relationship was established between SSC and fluorescence, but this relationship is site specific. High SSC occurred simultaneously with high fluorescence. However the relationship was non-linear and indicated that changes in SSC would be accompanied by a relatively smaller change in fluorescence. The ratio between fluorescence and SSC was lower for high SSC events. This indicated that organic material, to which the fluorescence sensor is sensitive, becomes relatively less abundant compared to the inorganic material.

The ratio between fluorescence and SSC varied little between periods of high river flow and low river flow. Nutrient input from the rivers may have been expected to give rise to a phytoplankton and algal blooms which would have been recorded as a spike in fluorescence. However this did not occur and indicates that river plumes did not cause a significant change in the balance between inorganic and organic material in the water at Lugger Bay.

The average SSC for water leaving the Tully River during the wet season, 23 mg/l, is much less than the average SSC on Lugger Bay Reef, 185 mg/l. In fact the maximum SSC for the water in the Tully River, 230 mg/l (Furnas 2003), is close to the average SSC for Lugger Bay Reef and the maximum SSC for Lugger Bay is over 1500 mg/l. This shows that resuspension appears to be the dominant process in generating increases of SSC on Lugger Bay Reef, and is by far overwhelming the river discharge effect.

The net sediment flow through the region could be as much as 630,000 tonnes per year and considering that the Tully and Murray rivers have a combined sediment input into the GBRL of 170, 000 tonnes per year it is likely that there are sediment inputs from outside the region, for example from the Herbert River.

Considering the fact that Tully River discharge events do not appear to increase the quantities of fluorescing material on Lugger Bay Reef and that the suspended sediment levels in the river are lower than those on the reef it seems likely that the Tully River does not have a great impact on Lugger Bay Reef in terms of sediment and nutrient inputs.

Acknowledgements

We would like to thank the following people for their invaluable contribution to this paper: Janice Lough, Martial Depczynski, Tim Hancock, David McNaughton and Tamika Tihema.

References

Alcock, D., 1995. 1920s Research Sheds Light on a Potential Coral Reef Calamity. GEO Australia 17, p100-108.

Anthony, K. R. N., 2000. Enhanced Particle-Feeding Capacity of Corals on Turbid Reefs (Great Barrier Reef, Australia). Coral Reefs 19, p59-67.

Anthony, K. R. N., Fabricius, K. E., 2000 Shifting roles of Heterotrophy and Autorophy in Coral Energy Budgets at Varying Turbidity, J Exp. Mar. Biol. Ecol. 252, p221-253.

Anthony, K.R.N., Ridd, P.V., Orpin, A.R, Lough, J., Larcombe, P., 2004. Temporal Variation in Light Availability for Benthos in Coastal Marine Habitats: Effects of Cloud Cover, Turbidity and Tides. Limnology and Oceanography, p2201-2211.

Anthony, K. R. N., 2006. Enhanced Energy Status of Corals on Coastal, High-Turbidity Reefs. Mar Ecol Prog Ser 319, p111-116.

Belperio, A. P., 1983. Terrigenous Sedimentation in the Great Barrier Reef Lagoon: A Model from the Burdekin Region, BMR Jour. Of Aust. Geol. And Geophysics 8, p179-190.

Brodie, J., 1996. River Flood Plumes in the Great Barrier Reef Lagoon, In Larcombe, P., Woolfe, K., Purdon, R. G. (eds), Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts, CRC Reef Research Centre, Research Symp. Proc., Townsville, p33-39.

Brodie, J., Furnas, M. J., 1996. Cyclones, River Flood Plumes and Natural Water Quality Extremes in the Central Great Barrier Reef. In: Hunter H. M., et al. (eds), Downstream Effects of Land Use, Department of Natural Resources, Brisbane..

Done, T., 1982. Patterns in Distribution of Corals Communities Across the Central Great Barrier Reef, Coral Reefs 1, p201-209.

Devlin, M. J. & Brodie, J., 2005. Terrestrial discharge into the Great Barrier Reef lagoon: nutrient behaviour in coastal waters. Marine Pollution Bulletin 51, 9-22.

Fabricius, K. E., Wolanski E., 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow, Est. Cos. Shelf Sci. 50, p115-120.

Fabricius, K. E., Wild, C., Wolanski, E., Abele, D., 2003. Effects of Transparent Exopolymer Particles and Muddy Terrigenous Sediments on the Survival of Hard Coral Recruits. Estuarine, Coastal and Shelf Science, 57, Number 4, p613-621.

Ferrier-Pages, C., et al., 2000. Effect of Nutrient Enrichment on Growth and Photosynthesis of the Zooanthellate Coral Stylophora Pistillata, Coral Reefs 19, p103-113.

Furnas, M., 2003. Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef, AIMS and CRC Reef Research Centre.

Furnas, M., Mitchell, A. W., Skuza, M., 1996. Nitrogen and Phosphorus Budgets for the Central Great Barrier Reef Shelf, A Report to the Great Barrier Reef Marine Park Authority, Research Publication No. 36.

Gagan, M. K., Chivas, A. R., Herczeg, A. L., 1990. Shelf-Wide Erosion, Deposition, and Suspended Sediment Transport During Cyclone Winifred, Central Great Barrier Reef. Journal of Sedimentary Petrology 60, p456-470.

Gilmour, J., 1999. Experimental Investigation into the Effects of Suspended Sediment on Fertilisation, Larval Survival and Settlement in a Scleractinian Coral, Mar. Bio. 135, p451-462.

Hall. D. O., Rao, K. K., 1994. Photosynthesis Fifth Edition. Cambridge University Press: Cambridge.

Hopley, D., 1982. 'The Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs.' Wiley and Sons, New York.

Isdale, P., 1984. Fluorescent Bands in Massive Corals Record Centuries of Coastal Rainfall. Nature 310, p578-579.

Jeffrey, S. W., et al., 1997. Phytoplankton Pigments in Oceanography, United Nations Educational: Paris.

Johnson, D.P., and Searle, D.E., 1984. Post-glacial seismic stratigraphy, central Great Barrier Reef, Australia. Sedimentology 31, p335-352.

Larcombe, P., Ridd, P.V., Prytz, A., and Wilson, B., 1995. Factors controlling suspended sediment on the inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14, p163-171.

Larcombe, P., Woolfe, K. J., Purdon, R. G., (Eds), 1996. Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts. Second Edition. CRC Reef Research Centre, Research Symposium Proceedings: Townsville, Australia.

Larcombe, P., Woolfe, K. J., 1999. Increased Sediment Supply to the Great Barrier Reef will not Increase Sediment Accumulation at Most Coral Reefs, Coral Reefs 18, p163-169.

Larcombe, P., Woolfe, K. J., 1999a. Terrigenous Sediments as Influences upon Holocene Nearshore Coral Reefs, Central Great Barrier Reef, Australia. Australian Journal of Earth Sciences 46, p141-154.

Larcombe, P., Costen A., and Woolfe, K.J., 2001. The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48, p811-836.

Larcombe, P., Carter, R. M., 2004. Cyclone Pumping, Sediment Partitioning and the development of the Great Barrier Reef Shelf System: A Review. Quaternary Science Reviews 23, p107-135.

Marshall, S. M., Orr, A. P., 1931. Scientific Report of the Great Barrier Reef Expedition 1, p94.

Maxwell, W. G. H., 1968. ‘Atlas of the Great Barrier Reef.’ (Elsevier: Amsterdam.).

McCook, L. J., 1999. Macroalgae, Nutrients and Phase Shifts on Coral Reefs: Scientific Issues and Management Consequences for the Great Barrier Reef, Coral Reefs 18, p357-367.

Moss, A. J., et al., 1992. A Preliminary Assessment of Sediment and Nutrient Exports from Queensland Coastal Catchments, Queensland Department of Environment and Heritage Technical Report No. 4, Brisbane.

Neil, D. T., Orpin, A. R., Ridd, P. V., Yu, B., 2002. Sediment Yield and Impacts from River Catchments to the Great Barrier Reef Lagoon. Marine and Freshwater Research 53, p733-752.

Orpin, A.R., Ridd, P.V. and Stewart, L.K., 1999. Assessment of the relative importance of major sediment transport mechanisms in the central Great Barrier Reef lagoon. Australian Journal of Earth Sciences 46, p883-896.

Pringle, A.W., 1986. Causes and Effects of Changes in Fluvial Sediment Yield to the North-East Queensland Coast, Australia: Townsville, James Cook University.

Ridd, P. V., Larcombe, P. 1994. Biofouling Control of Optical Backscatter Suspended Sediment sensors. Mar. Geol. 116, 255-258.

Smith, S. V., et al., 1981. Kanhoe Bay Sewage Diversion Experiment: Perspectives on Ecosystem Responses to Nutritional Perturbation, Pac. Sci 35, p270-395.

Stafford-Smith M. G., 1993. Sediment-Rejection Efficiency of 22 Species of Australian Scleractinian Corals, Mar. Bio 115, p229-243.

Taylor, J., 1996. Sediment Input to the Great Barrier Reef Lagoon via River Discharge: the Barron River, In Larcombe, P., Woolfe, K., Purdon, R. G. (eds), Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts, CRC Reef Research Centre, Research Symp. Proc., Townsville, p152-154.

Wasson, R. J., 1997. Run-Off From the Land to the Rivers and the Sea. In ‘The Great Barrier Reef, Science, Use and Management. Proceedings of a National Conference’. P23-41 (Great Barrier Reef Marine Park Authority: Townsville, Australia).

Williams, D., 2001. Impacts of Terrestrial Run-off on the Great Barrier Reef World Heritage Area, AIMS.

Wolanski, E., van Senden, D., 1983. Mixing of Burdekin River Flood Waters in the Great Barrier Reef. Australian Journal of Marine and Freshwater Research 34, p49-64.

Wolanski, E., 1994. Physical Oceanographic Processes of the Great Barrier Reef, CRC Press, Boca Raton, p194.

Woolfe, K. J., Larcombe, P., 1998. Terrigenous Sediment Accumulation as a Regional Control on the Distribution of Reef Carbonates. Special Publications of the International Association of Sedimentologists 25, p295-310.

Woolfe, K. J., Larcombe, P., 1999. Terrigenous Sedimentation and Coral Reef Growth: a Conceptual Framework. Marine Geology 155, p331-345.

Zann, L. (Ed), 1995. Our Sea, Our Future: Major Findings of The State of the Marine Environment Report for Australia. Ocean Rescue 2000, Department of Environment, Sport and Territories: Canberra, Australia.

3 - Paper on:

A Case Study of Lugger Bay Reef

To be submitted to the Journal of Coral Reefs

A Case Study of Lugger Bay Reef

James C. Whinney and Peter V. Ridd
School of Mathematical and Physical Sciences, James Cook University, Townsville,
Queensland, Australia.

Abstract

Sediments and nutrients can have numerous impacts on corals, particularly in inshore regions where sediment and nutrient concentrations are greatest. Studying inshore coral reefs can therefore increase understanding of these potential threats, and of what role local river systems can play. The reef selected for this study was in Lugger Bay, near Mission Beach in the Great Barrier Reef Lagoon. It is close to the mouths of the Tully and Murray Rivers, in an area where high suspended sediment concentration (SSC) events are common. Loggers were deployed throughout one year to determine what the levels of light extinction on the reef were, the peak and duration of SSC events and how they corresponded with light attenuation. Phototransects were used to evaluate the health of the reef, and percussion cores provided information about of its age. The results showed very high SSC levels, exceeding 200 mg/l for 28% of the time, and light extinction occurring on 49% of the days that data was recorded. Coral cover was 57% of the area surveyed, and algal encroachment was not a significant problem with only 12% of coral having algal cover. Coral species biodiversity on the reef was very low, as one species of *Porites* accounted for 85% of the coral cover. The results show that such reefs are a niche area where some coral species can survive well, under extreme SSC conditions and with limited light, and are able to compete with algae.

Keywords: Reef, Coral, Light, Sediment, Phototransect.

Introduction

Inshore reefs are judged to be some of the reefs most at-risk in the Great Barrier Reef Lagoon (GBRL) (GBRMPA 2001). This is due to their proximity to river estuaries, which can discharge pollutants, nutrients and sediments into the Lagoon. The concentrations of these materials in rivers are dependant on river catchment use and therefore can be anthropogenic in origin. For example land used for cattle grazing or cane farming will produce higher amounts of sediment and nutrients from run off than rainforest.

Sediments can harm corals in a number of ways. The sediment in the water column may settle on corals. When this occurs corals are able to remove the sediment either by excreting a mucus or by physical action. However if sediment settles on them faster than they can remove it they can be smothered (Fabricius and Wolanski 2000, Marshall and Orr 1931). Even if the corals do succeed in removing the sediment the act of removal costs energy. Suspended sediments can also reduce the energy available to corals by preventing light from reaching the corals (Williams 2001, Stafford- Smith 1993). High suspended sediment concentrations (SSC) can also affect coral reproduction, decreasing fertilisation, larval survival and settlement (Gilmour 1999).

Nutrients can influence corals both directly and indirectly. Direct affects occur when both sediments and nutrients are present in the water column. The sediments can combine with organic matter produced by biological activity as a result of high nutrient concentrations, to create large sticky particles. If these particles fall on the coral, the large size and cohesiveness of the particles make them much more difficult for the coral to remove than single sediment particles and increase the likelihood of smothering (Fabricius and Wolanski 2000).

Nutrients are required by algae for growth, and as such there is a commonly held view that excessive nutrient levels will lead to a dominance of macroalgae over corals (Bell 1992, Lapointe 1997, Adey 1998). However, it is important to note that other factors also limit algal growth, such as light, temperature and nutrient uptake and so increases in nutrients will only lead to an increase in growth if these factors are not already limiting it. Nutrient uptake is more important than the nutrient concentrations (Atkinson 1988, Larned & Atkinson 1997). Tests have shown that while the growth of *Sargassum baccularia* does increase as nutrient concentrations are raised, this effect does saturate at moderately high levels of nutrients (Schaffelke and Klumpp 1997, 1998a, b).

When increased algal growth occurs it will not necessarily lead to an increase in algal biomass (Carpenter 1988; Hatcher 1997). A conceptual model by Littler & Littler (1984) showed large crops of algae only occurring in areas of low herbivory. Other studies have also shown algal cover to depend strongly on levels of herbivory and that large increases in nutrient concentrations do not necessarily lead to an increase in the size of the algal standing crop (McCook 1996, 1997, Russ & McCook 1999, Scott & Russ 1987).

Field Site

Lugger Bay (Figure 3.1) contains an inshore reef in a highly turbid environment. It is within about 10 km of the Murray River and Tully River, both of which have been designated medium/high risk to inshore reefs (GBRMPA 2001). The Tully is the largest with an annual discharge of 0.13×10^6 tonnes of fine sediment, 140 tonnes of phosphorus and 1,300 tonnes of nitrogen (Furnas 2003). Lugger Bay's inshore location and the close proximity of the river mouths mean that the reef is very marginal with high SSC, nutrients, and deposited sediments. All these factors make Lugger Bay Reef one of the most at-risk inshore reefs in the GBRL.

The reef at Lugger Bay is in an L-shape about 400 m long by 150 m wide and contains only a few species of corals, dominated by a species of *Porites,* which forms large bombies that merge together in the central part of the reef (Figure 3.2a-c). The reef is located 400 m east of the high tide-line and about 100m from low tide-line. It is 500 m north of Tam-O-Shanter point and is partially sheltered by both the point and Dunk Island, 4.5 km to the east. If wind conditions are moderate or higher the reef becomes completely hidden by resuspended sediment (Figure 3.2d)

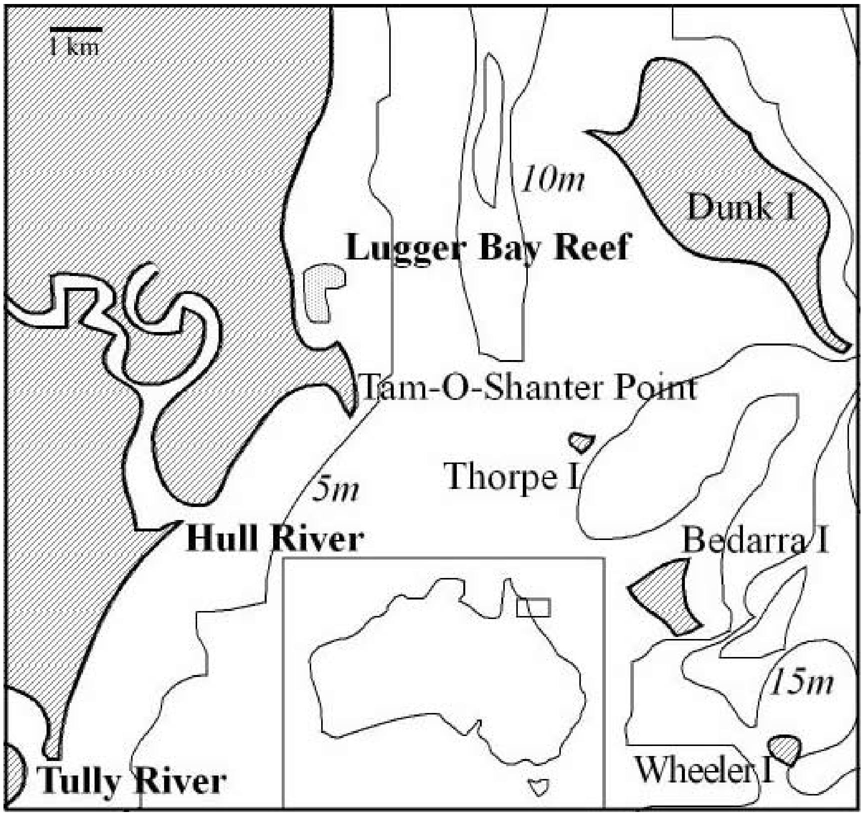

Figure 3.1: Location of Lugger Bay Reef in the North Queensland region.

Figure 3.2: Photographs of Lugger Bay Reef. Top left: (a) Lugger Bay Reef with Tam-O-Shanter Point and Lugger Bay behind it. Top Right: (b) The reef at extreme low tide, the main coral here is *Porites australiensis*. Bottom left: (c) The seaward side of the reef, here the bombies are more spread out. Bottom left: (d) the reef after a moderate wind event, the reef is very difficult to see, a small part of it is just visible in the bottom centre of the photograph.

Methods

A combination of SSC loggers and light sensors were deployed in Lugger Bay. The SSC loggers used optical backscatter as described in Ridd and Larcombe (1994). The light sensors were of standard design but were mounted facing horizontally rather than pointing upwards which is the usual direction. The reason for this horizontal positioning was due to a limitation in the instruments available. These particular instruments had light and turbidity sensors facing in the same direction, so if the light sensors were facing upwards the turbidity sensor would be facing the wrong direction to collect valid data. The horizontal direction of the light sensors means that they cannot be compared to light readings from other works where vertical downwelling light is recorded, but instead they can be used to examine when light attenuation occurs. The loggers were placed 30cm above the sea floor for periods of several months, with the sensors activating every 10 minutes.

The instruments were deployed at three locations in Lugger Bay (Figure 3.3). Lugger Bay Shore site was situated in an area of sand and bombies at the back of the reef about 200 m from the shore. Lugger Bay Seaward site was on the seaward side of the reef opposite Lugger Bay Shore site. Lugger Bay Point site was at the edge of the reef nearest to Tam-O-Shanter point, a light sensor was also deployed at this site.

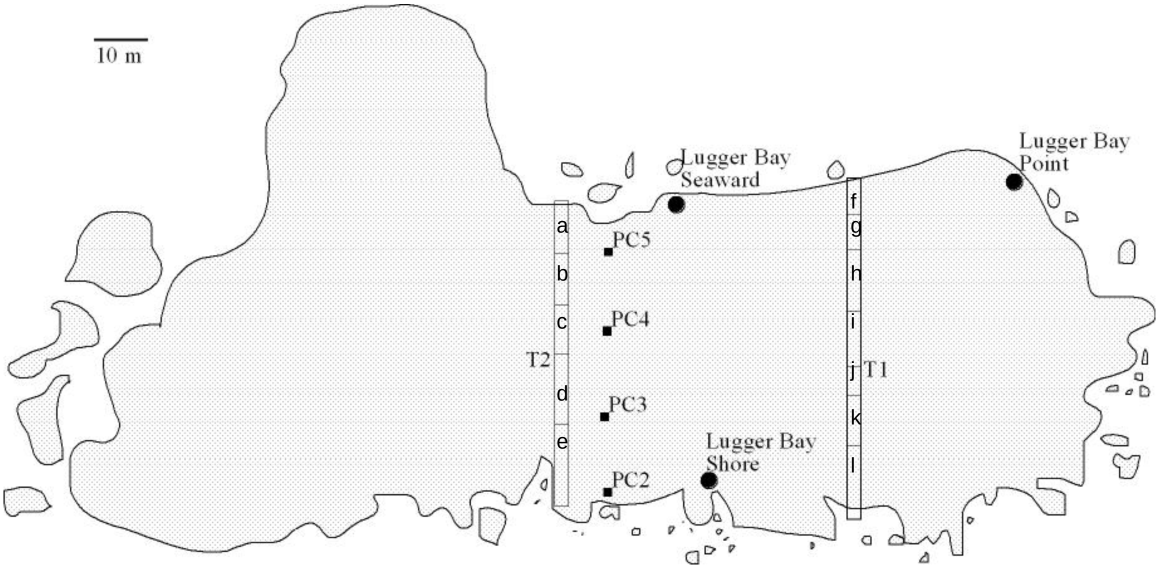

Figure 3.3: Lugger Bay Reef with the three instrument sites (indicated by the circles), four percussion core sites (PC2 to PC5) and two phototransects (T1 and T2) shown. The divisions in T1 and T2 show the areas that the phototransects were divided into for the purpose of analysis.

Percussion cores were taken at four locations (PC2, PC3, PC4 and PC5) in a transect from the shore side of the reef to the seaward side (Figure 3.3). The percussion core technique involves hammering aluminum piping (of 9.5cm internal diameter in this case) into the sediment close to the reef. The open end of the pipe is then capped and the pipe is removed from the sediment. This technique was chosen instead of drilling since the high levels of unconsolidated sediment present in the cores make the recovery rate from drilling too low. The compression in the cores was calculated to be about 25%. The cores were sawn in half lengthwise with a circular saw and photographs of each half were taken. The contents of the cores were analysed and the results were published in

Perry and Smithers (2006). Two samples were taken from the cores and carbon dated at the Radiocarbon Dating Laboratory, University of Waikato. One sample was from the top of sand layer in PC2, and was one of the lowest, and therefore oldest coral fragments found in the core. The other sample was from just above the layer of pleistocene clay at the bottom of PC4, which makes it more significant as the pleistocene clay indicates an era prior to coral settlement.

Phototransects were taken from the shore side to the seaward side of the reef at two locations along the length of the reef (Figure 3.3: T1 and T2). These were done at very low tide (0.1m LAT) when the majority of the top of the reef was above the water and those parts that were still submerged were in shallow enough water to be seen clearly from above the surface. They were achieved by taking a series of photographs with the camera pointing perpendicular to the reef from the height of 1m above the water level; a tape measure was laid along each transect as a guide. The photographs were then merged together using a computer program to remove any overlap and to ensure the scale remained consistent and the tape measure in the photographs was used to confirm that this had been achieved. The photographs were analysed by measuring the number of pixels with a computer program for each feature so that a percentage cover could be calculated. The transects were divided into the areas shown in Figure 3.3, and again in Figure 3.7, by selecting areas of similar bottom type to enable a comparison between different parts of the reef to be made.

Results

SSC and Light Data

Box plots for the SSC data for the three sites are shown in Figure 3.4. Lugger Bay Shore site had the highest median, 95 mg/l, and also the greatest variation with an interquartile range of 299 mg/l. Lugger Bay Point site had the lowest median 31 mg/l while Lugger Bay Seaward site had the smallest interquartile range, 185 mg/l.

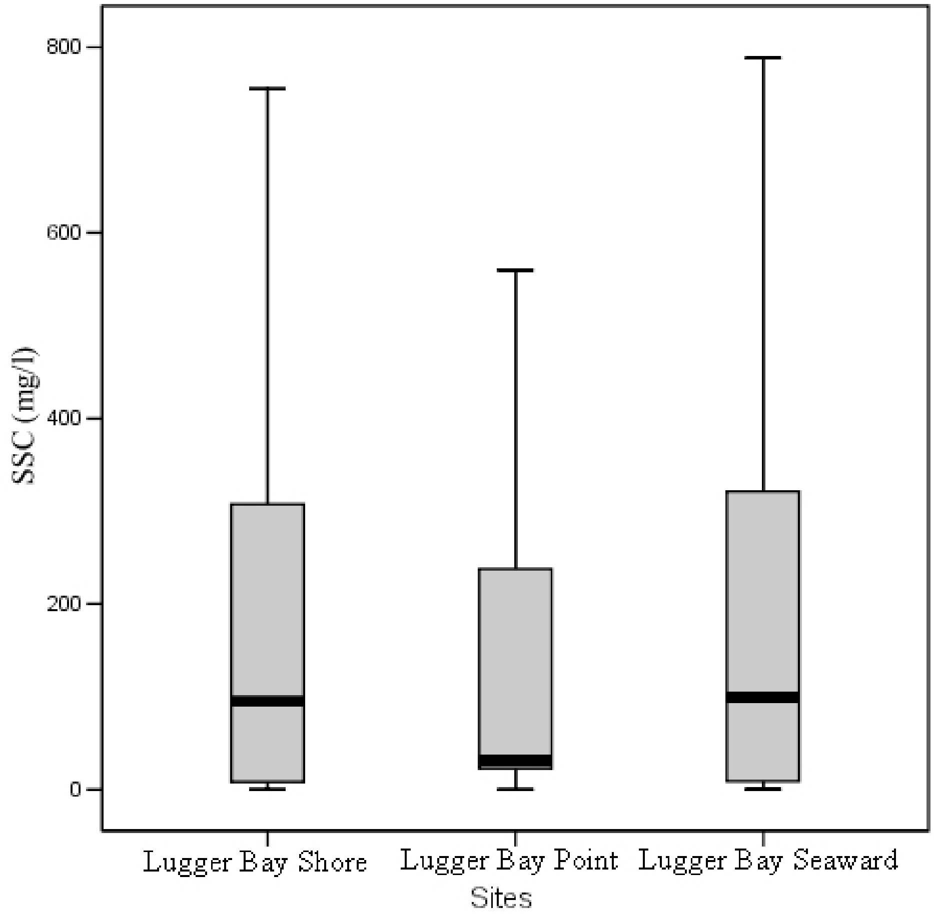

Figure 3.4: Box plots of SSC data from the three Lugger Bay instrument sites.

Figure 3.5 displays the SSC and light data in a time series. The SSC data has a baseline level of less than 10 mg/l with peaks occurring about every two weeks. These peaks vary in size and duration from about 200 mg/l to 1000 mg/l and from 1 day to 10 days.

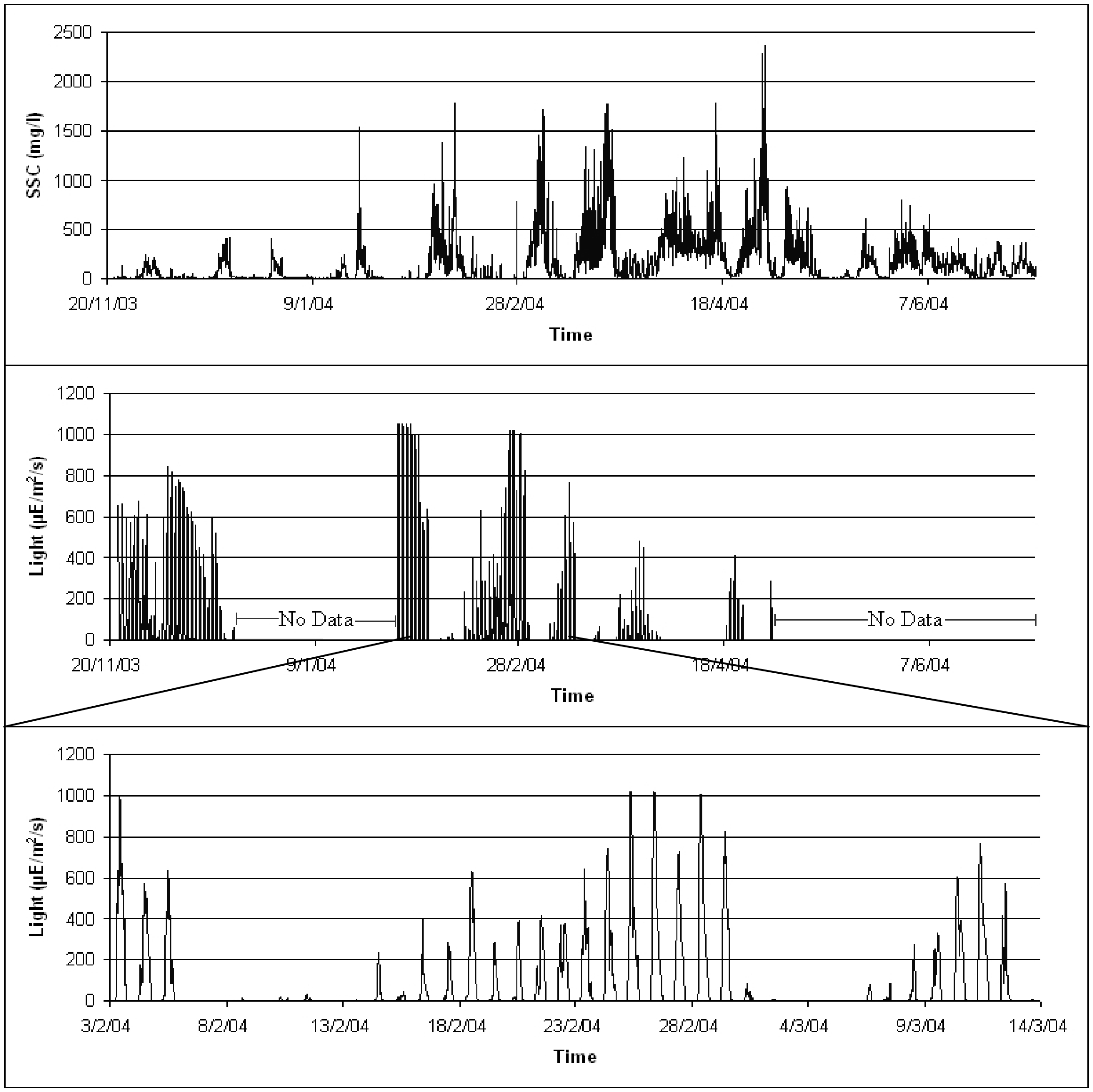

Figure 3.5: Light and SSC time series for Lugger Bay. An expanded section of the light data is shown at the bottom so that the diurnal pattern can be seen.

The light data has daily peaks centred around noon; the size of the peaks varies in a tidal pattern when SSC is close to its baseline of between 0 and 15 mg/l. However when SSC rises above baseline the resulting light attenuation becomes more significant than the tidal influence. When SSC increases above 50 mg/l light extinction occurs, with no light reaching the seabed even at noon. Over the period when light data was recorded (122 days) total light extinction occurred on 49 % of the days.

Phototransects

Analysis of the phototransects, Figures 3.6 and 3.7, shows a coral cover of 57%, 85% of which is free of mud and algae and 12% is covered with algae. 91% of the coral cover was *Porites australiensis*. 31% of the area surveyed was sediment and 18% had algae growing on it. In the different sections of the transects coral cover free of mud and algae varied from 22% to 72%.

Figure 3.6: Example sections of the phototransects.

Figure 3.6: Example sections of the phototransects.

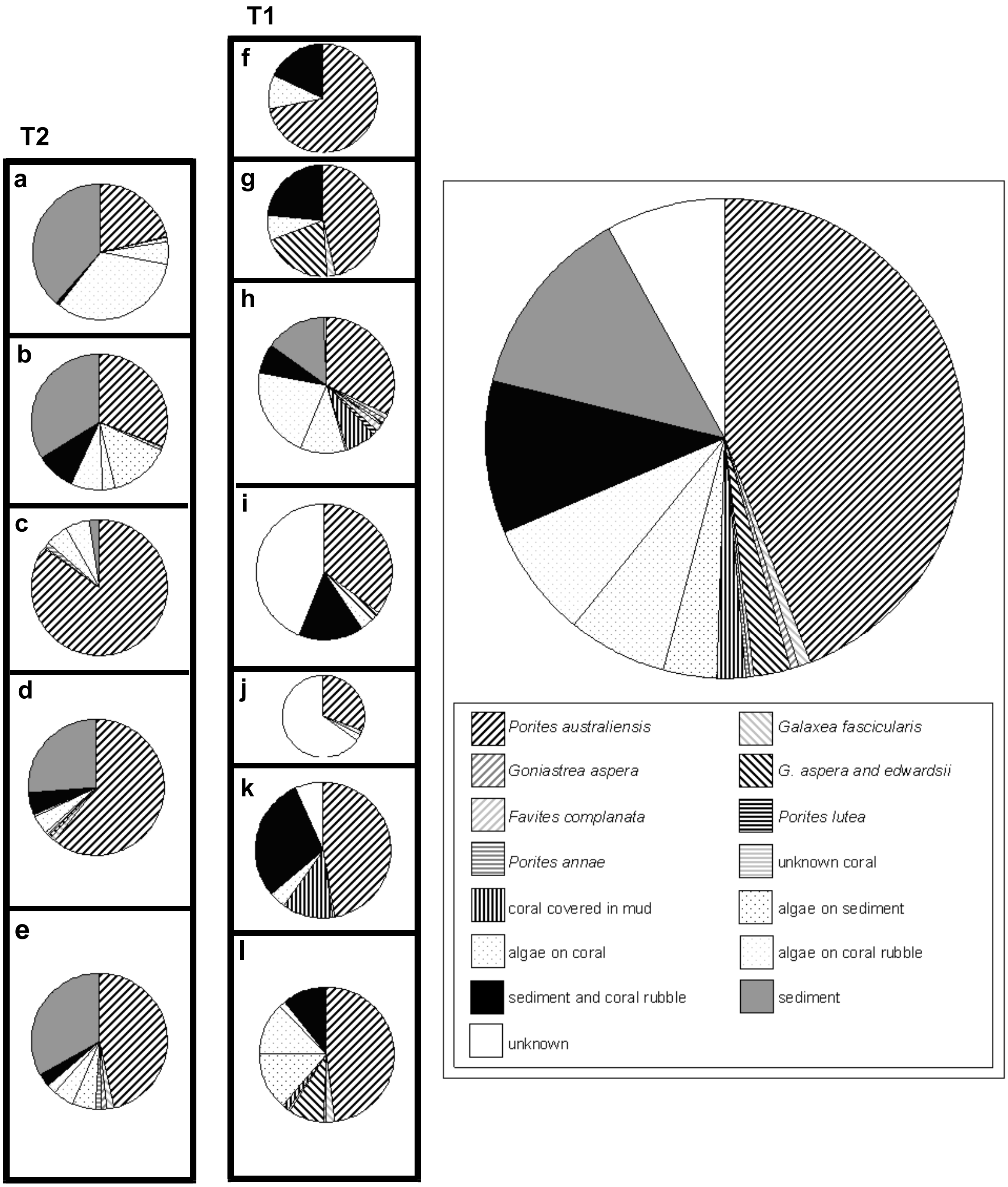

Figure 3.7: Phototransect analysis**.** Left**:** Pie charts for the different sections of the two transects. Right: combined pie chart for both transects, and key.

Core Data

The positions and depths of the 4 percussion cores are shown in Figure 3.8. PC2 reached a depth of 1.4 m. Coral fragments were found in the top 0.9 m whilst below that sand and clay were found. PC3 and PC5 reached depths of 0.7 and 0.9 m respectively with coral fragments found throughout both cores. PC4 reached a depth of 2.7 m with coral fragments found to a depth of 2 m and the top of a layer of Pleistocene clay starting at a depth of 2.5m.

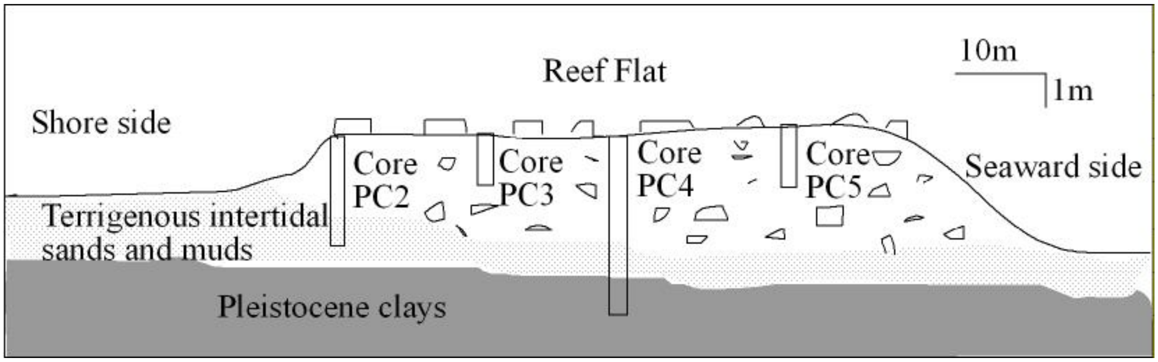

Figure 3.8: Reef cross section with the locations and depths of the percussion cores included.

Carbon dating on the deepest corals found in PC4 gave an age of 3, 993 years. Coral at the deepest part of the core on the seaward side of the reef, PC5, was dated at 738 years (Perry and Smithers 2006).

Discussion

SSC and Light

SSC readings show a large range in values for Lugger Bay. During calm periods the SSC is low, staying at a low baseline level of less than 10 mg/l for 21% of the time. However, when SSC events occur there tend to be large increases above the baseline. The SSC is greater than 50 mg/l for 55% of the time and greater than 200 mg/l for 28% of the time. There are also some very high SSC events with 19% of the readings being above 500 mg/l and 9% of the readings above 800 mg/l. SSC is also high compared to other inshore reefs in the GBRL. For example the mean SSC on Lugger Bay Reef is 170 mg/l while on a reef by Thorpe Island, 5 km offshore from Lugger Bay, it is 20 mg/l, on a reef at Port Douglas it is 67 mg/l, and on a reef in Nelly Bay, Magnetic Island, it is 6 mg/l (Whinney and Ridd unpublished work).

Light data for Lugger Bay shows that SSC is the dominant factor affecting light levels reaching the seabed. While SSC remains close to its baseline levels some effects of the fortnightly tidal pattern on the light levels can be seen with low tides closer to noon leading to increases in light reaching the seabed. However peaks in SSC have a greater influence on the light levels than the tidal signal, and SSC values of more than 50 mg/l lead to light extinction. During the study period complete light extinction occurred on the seabed for 60 out of 122 days showing that the reef is often subjected to periods without light. There were also 5 occasions when almost no light (less than 5% of peak daytime, where peak daytime level is estimated by comparing unattenuated peaks on the surrounding days and adjusting for the tidal pattern) reached the seabed for more than 5 consecutive days, the longest time with almost no light being 18 days.

The influence of SSC on light levels is evident in their correlation. The relationship between light reaching the seabed and SSC can be described using the equation:

$$I = I_0 e^{-(k + f_S S)d}$$

where I is the light reaching depth, d, I_o is the light incident on the water surface, k is the attenuation due to clear water, $f_s S$ is the attenuation due to suspended sediments (f_s is a coefficient of attenuation due to SSC and S is the SSC). If k is assumed to be small compared to $f_s S$, which is reasonable considering the high SSC concentrations present, and d is assumed to be constant, then S should have a linear relationship with *ln(I)*. A plot of SCC against *ln(I)* for noon hour light levels shows some linear relationship (Figure 3.9). All light values less than 1 $\mu E/m^2/s$ have been removed since they are below the sensitivity of the sensor and errors in these values would be expanded by the logarithmic scale. A linear equation fitting the data has an R^2 value of 0.62 showing that 62% of the variation in light levels at midday can be explained by SSC alone. Considering that the incident light level, I_o, is unknown and assumed constant this is a reasonable correlation as variations in incident light due to the season and cloud cover could account for much of the remaining variation. If an averaged depth of 1m is assumed then the attenuation due to SSC, f_s, is 0.02 per mg/l of SSC.

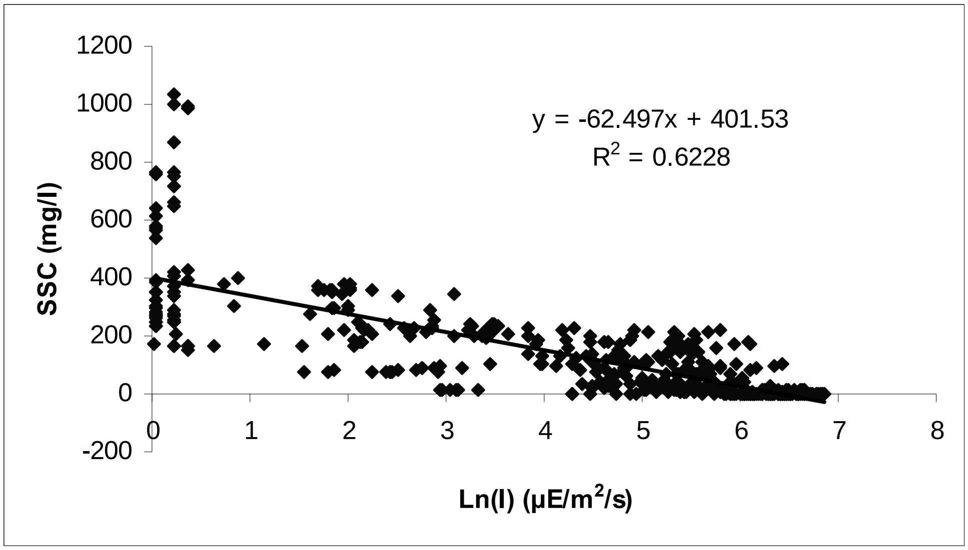

Figure 3.9: Correlation between SSC and light at noon, with light values of less than 1 µE/m^2/s removed.

Both SSC and light data indicate a reef where the water ranges from very clear to very dirty and that for a high percentage of the time SSC is very high and no light reaches the seabed.

Phototransects

The results of the phototransects suggest that Lugger Bay Reef is healthy, with over half the area surveyed (57%) covered in hard coral rising about half a metre above the sediment. Algae was significant but not dominant, with 18% of the area covered in algae, in 11% of the area the algae was growing on sediment and coral rubble and in 7% of the area the algae was growing on top of corals. So while algae is competing with corals for space it does not appear to be an immediate major threat to the coral community. The transects show a reef area dominated by *Porites*. Uncovered sediment constitutes most of the rest of the area (32%).

The different sections of the transects were reasonably consistent with one another. The ratio between coral and sediment varied slightly between the reef flat areas and the spaces between them. Slightly more algae was found towards the edges of the reef. Other than the *Porites,* the corals were evenly spread throughout the sections covering only a small percentage of each area.

Coring

Coral fragments in the sediments indicate that there has been deposition of coral debris for about 4000 years. This in turn suggests a very approximate upper age on the reef. At about 4000 years old the reef is young, older than Paluma Shoals (1657 years old, Smithers and Larcombe (2003)), but younger than reefs near inshore islands such as: Rattlesnake Island (7010 years, Hopley (1982)), Pioneer Bay, Orpheus Island (6610 years, Hopley *et al.* 1983) and Fantome Island (5910 years, Johnson and Risk 1987). Analysis of the cores by Perry and Smithers (2006) found only small quantities of *Porites* which indicates that *Porites* was not always the dominant species on the reef, therefore it must have increased in abundance overtime, possibly becoming more important as the reef reached sea level.

Conclusion

The reef is subjected to a large range of SSC including long periods of very high concentrations, higher than 200 mg/l for 28% of the time. Due to the high SSC, light extinction occurs regularly on the reef (on 49% of the days when data was recorded).

Coral cover is reasonably high, at about 57% of the area surveyed and it is dominated by *Porites,* which constitute 85% of the coral. While encroachment on corals by algae does occur (12% of the coral was covered in algae) it does not appear to be an immediate threat to the reef.

The reef is probably less than about 4000 years old and it appears that *Porites* may not have been dominant for all that time.

These results indicate a reef that appears healthy and does not seem to be threatened by algal overgrowth. However, biodiversity is very low, with one coral type dominating the reef.

Acknowledgements

We would like to thank the following people for their invaluable contribution to this paper: Scott Smithers, David McNaughton and Zhen Bao.

References

Adey W. H., 1998. Coral reefs: Algal structured and mediated ecosystems in shallow, turbulent, alkaline waters. J Phycol 34, p393-406

Atkinson, M. J., 1988. Are coral reefs nutrient-limited? Proc 6th Int Coral Reef Symp 1 p157-166.

Bell, P.R. 1992. Eutrophication and coral reefs-some examples in the Great Barrier Reef lagoon. Water Research 26, p553-568.

Carpenter, R.C., 1988. Mass mortality of a Caribbean sea urchin: Immediate effects on community metabolism and other herbivores. Proc Natl Acad Sci 85, p511-514

Fabricius, K. E., Wolanski E., 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow, Est. Cos. Shelf Sci. 50, p115-120.

Furnas, M., 2003. Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef, AIMS and CRC Reef Research Centre.

Gilmour, J., 1999. Experimental Investigation into the Effects of Suspended Sediment on Fertilisation, Larval Survival and Settlement in a Scleractinian Coral, Mar. Bio. 135, p451-462.

Hatcher, B.G., 1997. Organic production and decomposition. In: Birkeland C (ed) Life and death of coral reefs. Chapman & Hall, New York, pp 140-174

Hopley, D., 1982. Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs. New York: John Wiley-Interscience, 453p.

Hopley, D.; Slocombe, A.; Muir, F., and Grant, C., 1983. Nearshore fringing reefs in North Queensland. Coral Reefs, 1, 151–160.

Johnson, D. and Risk, M.J., 1987. Fringing reef growth on a terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia. Sedimentology, 34, 275–287.

Lapointe, B.E., 1997. Nutrient thresholds for eutrophication and macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42, p1119-1131.

Larcombe, P., Woolfe, K. J., 1999. Increased Sediment Supply to the Great Barrier Reef will not Increase Sediment Accumulation at Most Coral Reefs, Coral Reefs 18, p163-169.

Larned, S.T., Atkinson, M.J. 1997. Effects of water velocity on NH4 and PO4 uptake and nutrient-limited growth in the macroalgal Dictyosphaeria cavernosa. Mar Ecol Prog Ser 157 p295-302

Littler, M. M., Littler, D. S., 1984. Models of Tropical Reef Biogenesis: The Contribution of Algae, Prog. Phycol. Res. 3, p323-363.

Marshall, S. M., Orr, A. P., 1931. Scientific Report of the Great Barrier Reef Expedition 1, p94.

McCook L.J., 1996. Effects of herbivores and water quality on the distribution of Sargassum on the central Great Barrier Reef: cross-shelf transplants. Mar Ecol Prog Ser 139, p179-192

McCook L.J., 1997. Effects of herbivory on zonation of Sargassum within fringing reefs of the central Great Barrier Reef. Mar Biol 129, p713-722

Perry, A., Smithers, S. G., 2006. Taphonomic signatures of turbid-zone reef development: Examples from Paluma Shoals and Lugger Shoal, inshore central Great Barrier Reef, Australia. Palaeo 242, p1-20.

Ridd, P. V., Larcombe, P., 1994. Biofouling Control of Optical Backscatter Suspended Sediment sensors, Mar. Geol. 116, p255-258.

Russ, G.R. and McCook, L.J., 1999. Potential effects of a cyclone on benthic algal production and yield to grazers on coral reefs across the central Great Barrier Reef. J Exp Mar Biol Ecol 235, p237-254.

Schaffelke, B. & Klumpp, D. W., 1997b. Biomass and productivity of tropical macroalgae on nearshore fringing reefs in the Central Great Barrier Reef, Australia. Botanica Marina 40, p373-383.

Schaffelke, B. and Klumpp, D. W., 1998a. Nutrient-limited growth of the coral reef macroalga Sargassum baccularia and experimental growth enhancement by nutrient addition in continuous flow culture. Mar. Ecol. Prog. Ser. 164 p199-211.

Schaffelke, B. & Klumpp, D. W., 1998b. Short-term nutrient pulses enhance growth and photosynthesis of the coral reef macroalga Sargassum baccularia. Mar. Ecol. Prog. Ser. 170 p95-105.

Scott, F.J., Russ, G.R., 1987. Effects of grazing on species composition of the epilithic algal community on coral reefs of the central Great Barrier Reef. Mar Ecol Prog Ser 39, p293-304.

Smith, S. V., et al., 1981. Kanhoe Bay Sewage Diversion Experiment: Perspectives on Ecosystem Responses to Nutritional Perturbation, Pac. Sci 35, p270-395.

Smithers, S. and Larcombe, P., 2003. Late Holocene initiation and growth of a nearshore turbid-zone coral reef: Paluma Shoals, Central Great Barrier Reef, Australia. Coral Reefs, 22, 499–505.

Stafford-Smith M. G., 1993. Sediment-Rejection Efficiency of 22 Species of Australian Scleractinian Corals, Mar. Bio 115, p229-243.

Williams, D., 2001. Impacts of Terrestrial Run-off on the Great Barrier Reef World Heritage Area, AIMS.

4 – Paper on:

Predicting Suspended Sediment Concentrations on Coral Reefs Using Meteorological Data

To be submitted to the Journal of Coral Reefs

Predicting Suspended Sediment Concentrations on Coral Reefs Using Meteorological Data

James C. Whinney and Peter V. Ridd
School of Mathematical and Physical Sciences, James Cook University, Townsville,
Queensland, Australia.

Abstract

High suspended sediment concentrations (SSC) around coral reefs can have an adverse effect on coral growth and reproduction. Engineering construction or dredging activity close to reefs has the potential to raise the SSC, and environmental monitoring is often required so that management decisions can be taken to reduce the impact of such work. This necessitates measuring SSC at the site to see if it has been elevated above what would normally be expected at that site and under those physical conditions if construction work were not taking place. A judgement can then be made as to whether the work has elevated the SSC to a point where significant environmental impact would occur. The difficulty in this process is to estimate what the normal SSC at the site would be if no work was taking place.

It is generally not feasible to use control sites to establish the expected SSC due to high spatial variability around coral reefs. So an alternative approach is to predict the natural SSC for that site. While some modelling (e.g. DELFT 3D) packages are available to do this, they are very complex requiring many parameters about the site to be known and it has yet to be shown if they can perform well on a site with such complex bathymetry as a coral reef. This work investigates a simpler method of SSC prediction using just wind data as a parameter, which is easily available and inexpensive. Wind is responsible for generating waves, which in turn causes resuspension and an increase in SSC. In this work a model was developed and tested using data from 6 locations on, or close to, inshore reefs. Using category fit tests the model performed more than 50%

better than a random selection of the categories. The performance of the models for different sites depended upon what method was used to evaluate them.

Keywords: Coral Reef, Suspended Sediment, Modelling, Turbidity.

Introduction

Suspended sediments in the water column can have a significant influence on benthic coral communities. The turbid water reduces the intensity of the light reaching the sea floor and so decreases the energy available for photosynthesis (Williams, 2001; Stafford- Smith, 1993). In addition, suspended particles in the water column that settle on corals must be removed by either a physical motion or by the coral excreting mucus. Mucus excretion costs the coral energy, while at the same time the amount of energy it receives has been reduced by the decrease in light levels (Anthony and Fabricius, 2000). This can disturb the coral's energy balance preventing growth and causing starvation in extreme cases.

If the sediment settling rate is too high, and the coral cannot remove the particles, the result is coral smothering, which may ultimately cause coral mortality (Fabricius and Wolanski, 2000; Marshall and Orr, 1931). This problem can be amplified if large quantities of marine snow are present together with sediments. This occurs when high levels of both sediments and nutrients are present in the water column. Muddy sediments can combine with organic matter produced by biological activity as a result of high nutrient concentrations, to create large sticky particles. If these particles fall on the coral, the particles large size and cohesiveness make them much more difficult for the coral to remove than single sediment particles and increase the likelihood of smothering (Fabricius and Wolanski, 2000).

Another side effect of increased suspended sediment concentration (SSC) levels is a possible reduction in reproduction for some corals. Laboratory experiments have shown a decrease in coral fertilisation, larval survival and settlement when SSC are increased to more than 50 mg/l (Gilmour, 1999).

Some marine engineering activities such as construction of new harbours are likely to cause temporary increases in SSC. When this occurs close to sensitive areas, such as coral reefs, environmental impact studies are often required. Recent examples of construction activity in the Great Barrier Reef Lagoon (GBRL) that have occurred close to fringing reefs are channel dredging at Port Douglas, the construction of Nelly Bay Harbour on Magnetic Island, and the laying of a pipeline in West Channel, Magnetic Island. To control the impact of the engineering work, a maximum permissible SSC for the site needs to be established. SSC can then be monitored, and if it rises above the threshold level, the construction work may be required to cease until SSC drops. However a major problem is calculating what the threshold level for a particular site should be. The simplest solution is to set a fixed threshold value based on historic data, but this does not take account of weather or wave conditions, which affect the natural SSC. For instance when the sea-state is calm, the SSC would normally be low, but a fixed threshold chosen as the average of historic values is likely to be much higher than the expected SSC for such calm conditions. Conversely, in rough weather the historic average threshold will be lower than natural SSC. Therefore a practical solution should have a threshold that varies according to variations in the expected natural SSC.

A site that is close enough to undergo the same SSC conditions but far enough from the engineering work not to be affected by it could be used as a control site. However spatial variability in SSC is naturally very high, which makes it very difficult to find a site that will react in the same way as the work site to different weather conditions (Orpin et al, 2004). A better approach is to predict what the SSC would be if no construction was occurring, and compare these values with measurements.

Ideally SSC could be predicted by a model based on the physical process occurring at the site. Such a model would take account of the tidal hydrodynamics and the wave dynamics in order to predict the bottom shear stresses, turbulent energy and transport rates. It would thus require a detailed wave model, a hydrodynamic model and the boundary conditions with which to run the model. A detailed knowledge of the sediment properties would also be needed in order to determine how the sediment would respond to the physical forcings such as bottom stress. In particular the sediment fall velocity, degree and variability of flocculation, threshold shear stress and bed erodibility would all be required.

Suspended sediment modelling packages that attempt to take account of all physical processes, such as DELFT3D (Delft Hydraulics 2006), can be difficult to apply because of insufficient input data of, for example, wave and current boundary conditions, sediment fall velocities and erosion thresholds. Purely physical models have also not been well tested for coral reef environments where the complex bathymetry makes such purely theoretically based approaches very difficult.

In most instances where there is concern about the impact of construction work on coral reefs, financial constraints do not allow the collection of sufficient data to enable a fully theoretical model to be developed. Usually there will be no data available about water currents or waves that will be collected simultaneously with water turbidity. The only data that is routinely available, at little cost, over large areas, is meteorological data, particularly wind speed. This study thus investigates the possibility of using cheaply available wind data as an input to a model that uses a combination of statistical and physical approaches in its formulation

Wind is a primary forcing of water SSC through its influence on waves, which in turn predominantly control SSC levels in the areas of this study (Larcombe and Woolfe, 1999). Indeed, SSC in the inshore region of the GBRL is mostly caused by resuspension of sediment from the sea floor rather than by river plumes due to the presence of large amounts of sediment on the seafloor in most areas (Larcombe and Woolfe, 1999). This ensures that resuspension is not limited by sediment supply, resulting in the total increase in SSC due to waves generally greatly exceeding the total increase due to river plumes. It then follows that approximate SSC levels can be calculated by focusing on resuspension alone. Aside from wind-waves, tides may also be an important factor in resuspending sediment due to tidally induced currents and the fact that water depth affects bottom shear stress due to waves.

Generally, resuspension is caused by waves and currents generating a shear stress on the seabed, which if sufficiently high, can stir up sediment particles into the water column. Shear stress caused by waves is a function of the square of the near bottom wave orbital velocity (Grant and Madsen 1979, Lou and Ridd 1996). Shear stress is also related to a friction coefficient, which depends on the bottom type, and thus varies from location to location for the same wave conditions. Nevertheless knowing the bottom type is not enough to determine the theoretical shear stress threshold for resuspension because the presence of algal films growing on the sediment can significantly alter bottom characteristics (Wright et al. 1991, Lou and Ridd 1998).

The waves gain energy from the wind in proportion to the wind stress on the surface of the water that is in turn approximately proportional to the square of the wind speed (WMO 1998). From linear wave theory the height of a wave is proportional to the square root of the wave energy density and the orbital velocity varies linearly with the height (Wright et al. 1991). This means that the orbital velocity of a wave is roughly proportional to velocity of the wind and therefore the bottom shear stress is approximately proportional to the square of the wind speed. However, the relationship between shear stress and resuspension rate is not always a simple linear one (Wright et al. 1991). As a consequence theoretically predicting resuspension due to wind generated waves from physical principles for a particular location would require very complex site specific calculations using a large variety of data such as topography, fetch area for each wind direction, sediment type, and threshold shear stresses that account for algal cover.

Rather than theoretical calculations, the approach taken in this work to predict SSC from wind data used existing SSC data for a particular site to tailor the constants of an empirical model. This model can then be employed to predict future SSC at the site. Such site specific models were developed in this study for 6 different locations based on a similar approach to that of Anthony et al. (2004), who used wind speed to predict light attenuation coefficients due to SSC. These authors developed a model that relates the attenuation coefficient to a daily averaged wind speed and takes account of the wind history. The model, summarised in equation 1, was tailored to a specific site using light and wind data.

$$\bar{k}_D(\bar{U},t) = k_0\left(\frac{\bar{U}(t)}{U_m}\right)^b + k_1\left(\frac{\bar{U}(t-1)}{U_m}\right)^b + \ldots k_n\left(\frac{\bar{U}(t-n)}{U_m}\right)^b + \bar{k}_b \quad (1)$$

where $\bar{k}_D$ is the daily average light attenuation coefficient of day t; $\overline{U}$ (t) is the wind speed averaged over the previous 24 hours before day t; U_m is the maximum wind introduced to non-dimensionalise the wind. k_0, k_1 and k_n are coefficients that weigh the importance of past and present winds on the current SSC levels, and $\bar{k}_b$ accounts for the background attenuation. The parameters to be determined in this equation are k_0, k_1, ... k_n, b, and $\bar{k}_b$.

This simple model does not account for wind direction, which can be important for wave generation. For example if a site is sheltered on one side, then a wind from that direction is unlikely to generate large waves, and therefore will not produce a large rise in SSC. It also uses a daily average of the wind data, disregarding the fact that the time taken for a flat sea to become close to its full height may vary from hours to days depending on wind strength (WMO, 1998).

This paper develops the ideas used by Anthony et al. (2004) applied to SSC data but considers wind data for each hour instead of each day. It also includes wind direction and uses a more elaborate scheme than that of Anthony et al. (2004) to take account of the wind history. The data set described in this work represents the largest set of turbidity data so far presented in the literature of nearshore fringing reefs and is thus an good data set with which to test the model.

Field Sites

SSC data were taken from three areas in the GBRL (Figure 4.1): Port Douglas, Lugger Bay/Family Islands and Nelly Bay. All sites were within a few kilometres of the coast and close to inshore coral reefs. At two of the positions (Port Douglas and Nelly Bay), marine engineering work had occurred close by and the data from these sites had been previously used as baseline data for environmental monitoring.

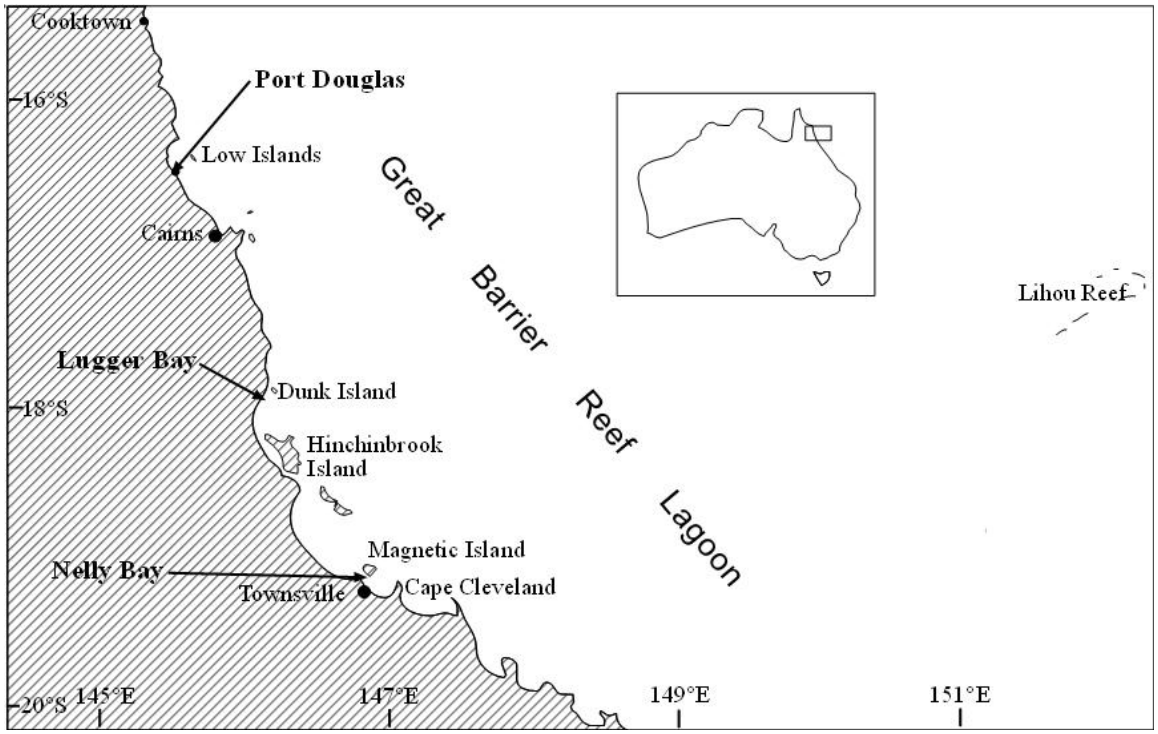

Figure 4.1: Map of data collection locations: Port Douglas, Lugger Bay/Family Islands and Nelly Bay. Fringing coral reefs grow at all 3 locations.

The first location was at Port Douglas (Figure 4.2a). Here the coastline runs along the southern and western edges of the study area. The town itself is on the southern shoreline, and a channel from the port runs out to the north east, in which dredging took place in 2004. Corals and seagrass beds grow north west of this channel, and join with a mangrove shoreline on the southern and western sides. Natural SSC levels were monitored at 2 sites prior to the dredging work. One of these sites (site y, 16° 28.8’ S, 145°27.5’ E) was close to the seaward end of the channel near where dredging would later occur. The other site, (site z, 16° 29.0’ S, 145°27.4’ E), was located close to seagrass beds and corals adjacent to the mangrove shoreline. Both sites were sheltered from the west and the south by the coastline.

The second location was at Lugger Bay/Family Islands (Figure 4.2b) where several sub-sites were chosen: an inshore reef in Lugger Bay, Bedarra Island and Thorpe Island. The reef in Lugger Bay (17° 57.7’ S, 146° 05.7’ E) is about 300 metres to the east of the shoreline, and about 500 m north of Tam-O-Shanter Point. Lugger Bay is also protected by Dunk Island about 4.5km to the east affording some protection from waves emanating from that direction. With both the Murray and Tully River mouths a few kilometres to the south, the area is subjected to occasional river plumes (Furnas 2003). The Hull River shown in Figure 4.2b is an inlet with little freshwater outflow and does not have any significant influence on the local SSC. The reef contains only a few coral species and is dominated by one species of *porites*, which form large bombies that merge together in the central part of the reef. The reef is about 800m long and 400m wide. Thorpe Island (17° 59.0’ S, 146° 07.9’ E) is 5 kilometres offshore from Lugger Bay. A small reef grows a few hundred metres from the beach on the sheltered side facing the mainland coast. The reef is smaller than at Lugger Bay (about 200m wide and 300m long), and also has low species diversity. Bedarra Island (18° 00.4’ S, 146° 09.2’ E), also called Richard’s Island, is about 3 kilometres to the south east of Thorpe Island. The site is on the south side of the island, about 50 metres from a small rocky headland. It is partially exposed to the prevailing winds from the south-east. There are a few isolated coral colonies in the area.

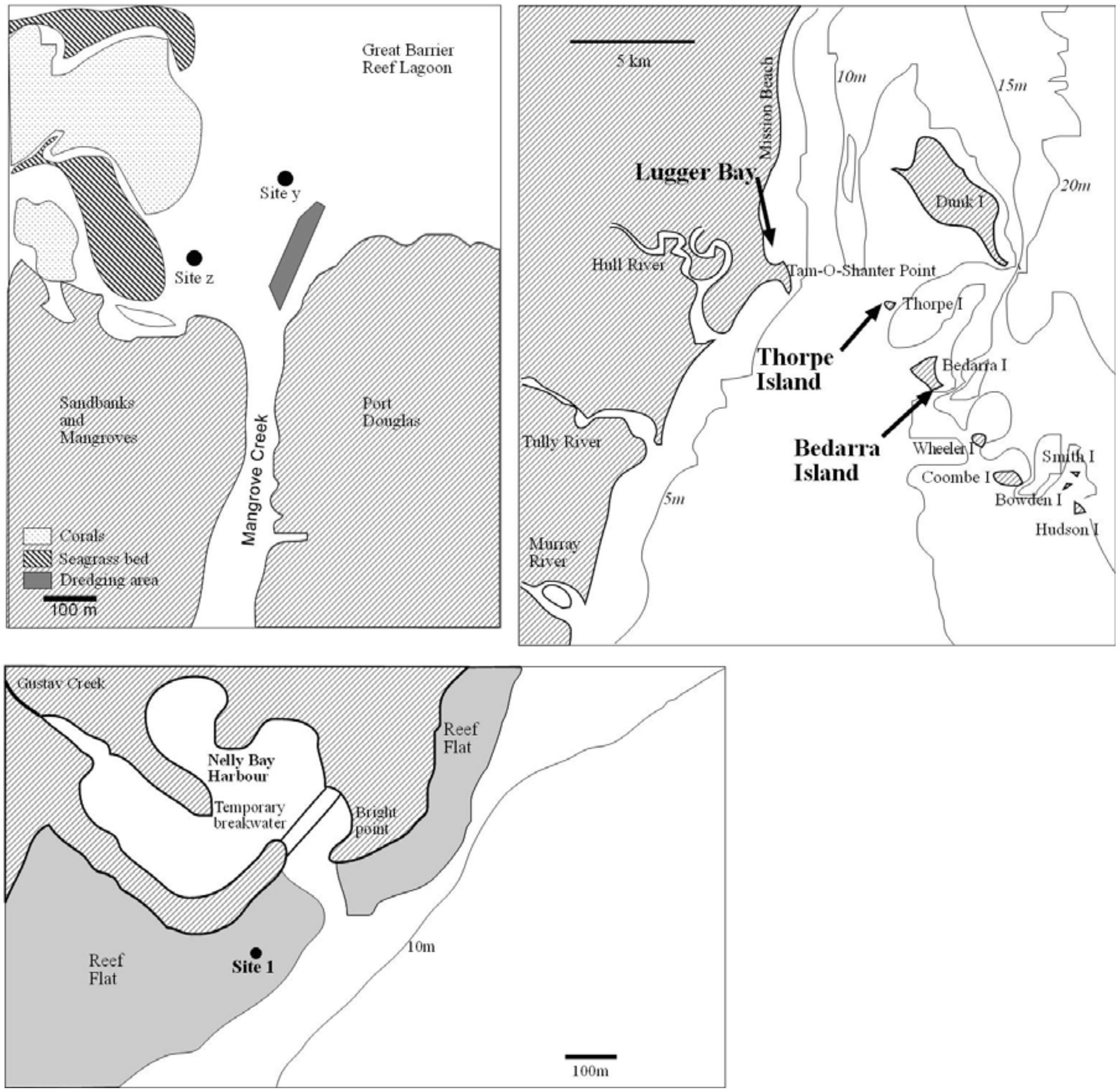

Figure 4.2: SSC measurement sites, clockwise from top left: (a) Port Douglas. The area that was dredged after the SSC data was collected is shown in grey. (b) Lugger Bay/Family Islands. Data was used from 3 locations in this area: the fringing reef in Lugger Bay, a small reef on the sheltered side of Thorpe Island, and the south side of Bedarra Island. (c) Nelly Bay Harbour. Site 1 is to the west of the Harbour entrance on the fringing reef. This map shows the harbour at the time of construction, but the current site does not look exactly like this.

The third location was at Magnetic Island, in Cleveland Bay, 8km from Townsville (Figure 4.2c). Construction of a new harbour took place in Nelly Bay, (19° 10.0' S, 146° 50.1' E) on the east side of the island. Nelly Bay is sheltered from the predominant south-easterly winds by Cape Cleveland on the mainland, however the waves diffract around Cape Cleveland and thus south east winds still create significant waves at this location. A fringing reef grows a few metres from the harbour sea wall, where SSC monitoring took place before and during construction of the harbour. This reef has a larger variety in species than at the other sites described above, and the water is usually much clearer.

Methods

SSC Measurements

The SSC data were collected from all three locations with the use of optical backscatter SSC loggers as described in Ridd and Larcombe (1994). The instruments were all placed 30cm above the sea floor and left for periods of approximately 1 month between servicing, logging at intervals of 10 minutes. At Port Douglas, data were collected over a period of 3 months, from May to July 2004. At Lugger Bay/Family Islands, instruments were deployed from October 2003 to March 2004. The information from Nelly Bay was gathered between May and October in 2001. After the data were collected, any obvious artefacts were removed and it was calibrated and then converted into SSC in units of mg/l using a conversion factor developed specifically for these loggers (Dupont 2003).

Wind Data

Hourly wind data were provided by the Australian Bureau of Meteorology (BOM) and the Australian Institute of Marine Science (AIMS). Different wind data stations were used for the various reef locations. It was considered important to use wind data, which would give wind magnitudes and directions similar to those actually occurring at the sites and in the regions offshore where wave generation would occur. Land based weather stations were not used because topographical features such as hills can shelter from some directions as well as cause other localised meteorological effects including large diurnal fluctuations that may not be present over the sea. Instead, off-shore stations were used, with preference given to those close to the SSC observation site and those in the direction of the prevailing wind and with complete data sets.

For Port Douglas, the wind data used was from Low Isles which is about 15 km to the north-east (BOM). For the sites near Lugger Bay, the wind data were used from Lihou Reef (BOM) which is about 600km to the east. This weather station was very far away from the sites, however all nearby stations were either on land, sheltered, or had data which contained too many missing points so there was no choice but to use this wind data if for no other reason than to evaluate the models performance given poor quality wind data. For Nelly Bay, the Cleveland Bay weather station used is on Cape Cleveland to the south east of Magnetic Island (AIMS).

Model

The model described below uses hourly wind data to predict SSC. Important aspects of this model are as follows:

- The model takes account of present and past wind speeds using hourly wind data and gives the wind data from each hour a weighting factor to represent the lag between a change in wind speed and a change in wave height.
- Wind speed data is also weighted according to the direction of the wind since each site will be sheltered from winds from certain directions.
- The site-specific model parameters are determined by training the model with real SSC data to find the values of the parameters that give the best fit between modelled and real SSC values.
- SSC is then predicted using these parameter values.

While the model is run using hourly wind data, the output is generally presented as predicted daily SSC averages, because short time scale variations in SSC are unlikely to be successfully modelled. In addition, provided the corals are not smothered by sediment, elevated SSC values over short time scales are unlikely to affect the coral significantly because energy stored within corals usually allows them to survive for at least a few days of reduced light (Gilmour, 1999).

The equation used to model the concentration of suspended sediment, C (in mg/L) is as follows:

$$C(t) = M\begin{pmatrix} k_t(t_{w0})[w(t)]^b + k_t(t_{w1})[w(t-\Delta t)]^b + \dots \\ +k_t(t_{wn})[w(t-n\Delta t)]^b + \gamma + LH_t \end{pmatrix} \quad (2),$$

where M is a coefficient to adjust the magnitude of the result, $w(t)$ is the wind speed at time t, which has been weighted according to its direction, $k_t(t_{wn})$ is a temporal weighting, which controls the significance of the wind speed for each data point from the present to $n\Delta t$ hours before present. Δt is the time interval between wind data points. The constant γ adjusts the background SSC level. b is the power to which the wind speed is weighted. H_t is the difference between the highest and lowest tidal elevation of the day at time t and L is a constant.

$K_t(t_{wn})$ – Temporal Wind Weighting Function

When a wind blows on a calm sea, there is a delay before the waves reach a maximum height. For wind speeds of less than 25 knots that are usually encountered in the GBRL, this fully developed state is reached within 48 hours (Figure 4.3) (WMO, 1998 Gröen and Dorrestein, 1976). Waves generated offshore of the GBRL are dissipated by the Barrier Reef so the only waves affecting the lagoon are those generated inside the GBRL. At the cessation of a high wind speed event, inside the lagoon short waves will dissipate within 48 hours. Longer waves will not, but in that time they would travel across the lagoon reaching either the coast or the Barrier Reef where they will break. Hence wind speeds from times greater than 48 hours ago are not likely to have any effect on the present wave height. Also due to the lag between the change in wind speed and the change in wave height, the present wind speed will not be very significant in determining the present wave height. It is expected that the most significant period of wind data for determining the present wave height will be from a few hours before the present. Therefore the weighting function for the wind speed is chosen such that it starts at zero at time t, climbs steeply to a maximum a few hours before time t and then gradually falls. This is formalised in equation 3.

$$k_t(t_{wn}) = (t_{wn})^c e^{-(t_{wn}+1)^c/a} \quad (3)$$

where t_{wn} is the time before the present. In the implementation of the model, t_{wn} starts at 0 for the present wind data point and increases by increments of 1 for each hour back into the past. Parameters c and a are constants which alter the shape of the function and are determined by the model. It should be expected that c and a will be values that generate a distribution such as that shown in Figure 4.4.

While many other functions would have created the required shape just as well, equation 3 was selected because it only has two parameters that must be determined by the model. To investigate how far back in time it was necessary to go before the wind data became inconsequential to the present SSC, the model was run using 48 and 72 previous hours of wind data.

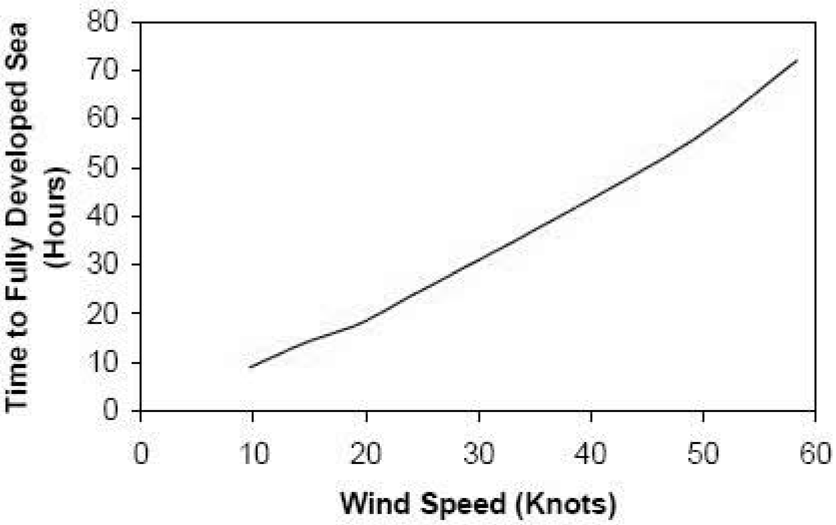

Figure 4.3: Time taken for the generation of a fully developed sea from data in: Gröen and Dorrestein, (1976). This shows how many hours it takes for waves to reach their maximum height for a given wind speed. So if the wind speed is 45 knots the sea will become fully developed in 48 hours.

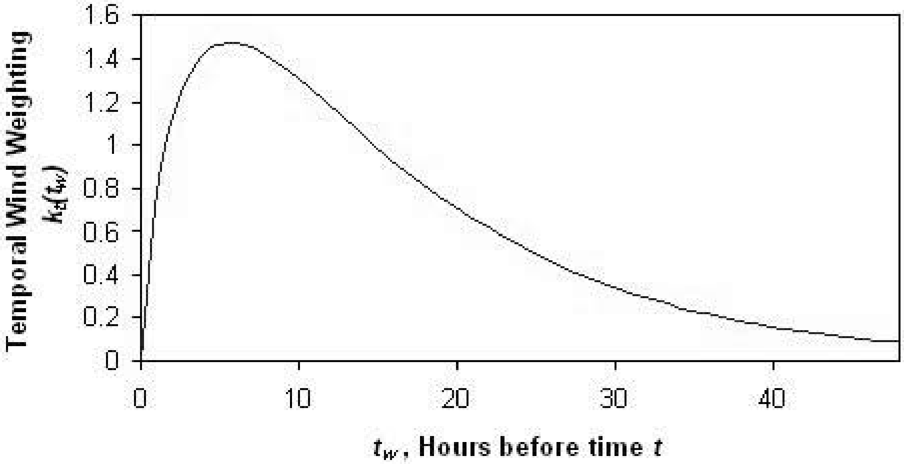

Figure 4.4: Example of an expected $k_t(t_{wn})$ temporal wind weighting function vs time. In this case a is 4 and c is 0.8 which produces a peak 7 hours before time t and then gently decreases so that at 50 hours it is close to zero. t_{wn} is measured using units of hours.

Wind Direction Weighting Function

To allow for the fact that fetch will vary with direction, an adjustment was made to the wind data that gave a bias towards particular directions. Since the North Queensland coastline runs roughly North-South, it is expected that wind coming from the west will not generate waves at the SSC monitoring sites whilst winds originating offshore are most likely to produce larger waves. Thorpe Island and Bedarra Island could experience some waves from the west, but the fetch is small so these waves are not likely to be as significant in comparison to waves from the east A wind direction weighting function in the form of a Gaussian centred on the most significant wind direction was used to modify the wind speed, i.e.

$$w(t) = w_s(t)k_\theta \qquad (4)$$

$$k_\theta = e^{-(\theta(t)-p)^2/2q^2} \qquad (5)$$

where $w(t)$ is the directionally adjusted wind speed, and $w_s(t)$ is the original hourly wind speed data. $\theta(t)$ is the direction of the wind at time t in degrees, p is a coefficient that controls the direction of the peak weighting and q controls the width of the peak. Since this equation gives a discontinuity at 0° and 360° the reference direction for $\theta(t)$ was shifted by placing west at 0° instead of north since due to the orientation of the coast the influence of the wind from this direction would be close to zero. The directional weighting that would be expected for a typical site in North Queensland is shown in Figure 4.5, with a most significant direction of $\theta = 130°$. Note in Figure 4.5, the wind direction is plotted using the usual convention with 0° as wind coming from the north.

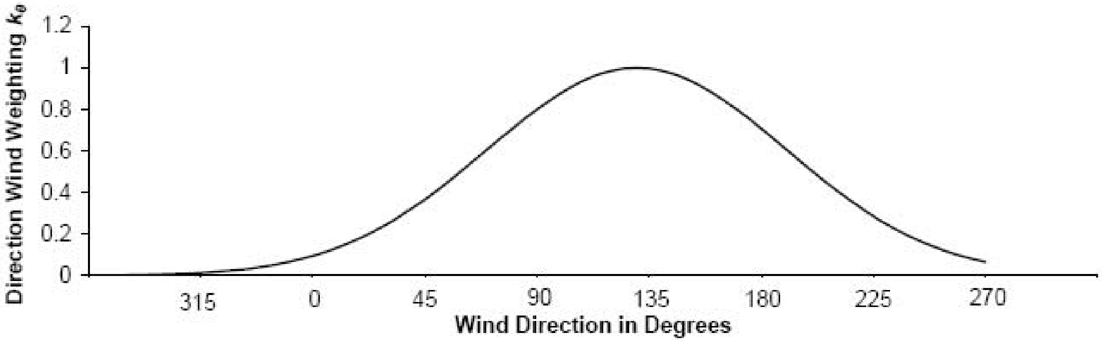

Figure 4.5: Wind direction weighting function k_θ. For $p = 220$ and $q = 60$. p has set the peak of the distribution at 130° and q has controlled the width of the peak. Note, the wind directions is shown with the normal convention with north as zero.

Tidal effects

Tides can affect SSC due to depth changes and tidal current. The influence of tides on the daily average SSC was modelled by using the final term in equation 2, i.e. LH_t, where H_t is the difference between the current day's maximum and minimum tide, and L is a constant, which was determined by the model calibration. Since the model aimed at predicting a daily average SSC, it did not attempt to predict tidal effects of less than one day. Short-term tidal effects on SSC are represented by an increase in the mean of the daily average. To remove the short time scale tidal influences from the SSC data a one-day rolling mean was applied. The model was run both with and without tide data to see the difference on the performance of the model.

Model Calibration and Minimisation Function

The model shown in equation 2 is dependent on 7 parameters, M, b, γ, a, c, p and q, and, in the case where tidal effects are included it contains an extra parameter, L. For each site, the values of these parameters were determined by comparing the SSC results calculated by the model with those recorded at the site and by minimising the difference between the two. This minimisation was done by defining a cost function $\in$ equal to the square of the difference between the real SSC and the calculated SSC for each hour summed for all the hours that the model is run (equation 5).

$$\in = \sum_{t} \left(C(t)_{real} - C(t)_{predicted} \right)^2 \qquad (5)$$

The parameters were adjusted until $\in$ was minimised at which point the model was providing a best fit to the data. This process was done using a MATLAB simplex search method from Lagarias et al. (1998). It is a direct search method using neither numerical nor analytic gradients.

As with all minimisation routines, care must be taken to avoid the algorithm converging on a local minimum rather than a global minimum. To this end, the starting values of the parameters were set to physically realistic values. Tests were also carried out with a selection of different starting values to find which gave the lowest minima.

Model Evaluation

The minimisation was done for each site using several months of data. Once the optimum values for the parameters were found, the remaining SSC data for that site was compared to SSC levels predicted by Equation 2 run with the values of the parameters found in the calibration period. This comparison provided an assessment of the predictive capabilities of the model, and was done at several levels, all based on daily averaged predicted and observed SSC, since the aim of the model was to produce a daily average.

The first model evaluation method involved breaking both the predicted and recorded SSC values into 3 categories representing high, medium, and low SSC ranges. To make the designation of these boundaries objective, the points between low and medium and between medium and high were determined by the 1/3 and 2/3 terciles of the entire of each sites data set respectively. The actual SSC values of the boundaries between these ranges varied from site to site since the data sets were all different. It should be noted that while this is a useful tool for evaluating the performance of the model, the results cannot be taken as absolute as changing the boundaries for the categories can produce different fitting results between recorded and predicted data. A problem also occurs when a recorded reading lies very close to one side of a boundary and the corresponding prediction is close to it, but on the other side of the boundary. In this scenario, the model has actually performed well, but according to the evaluation method it has failed. To counter this, a second method of assessment was employed using the same categories as above but also including a weighting system. The system weights the prediction of the correct category as 1; a prediction that is only wrong by one category, for example predicting medium when it should be low, as 0.5; and if it is wrong by more than one category the weighting is 0. A less coarse approach was also tried using quintiles instead of terciles. For this method a weighting of 1, 2/3, 1/3 and 0 was used for being correct, wrong by one category, wrong by two categories, wrong by more than two categories respectively.

Finally, two other approaches to evaluate the model accuracy that did not use categories were tried. One was to perform an R^2 test on the data. The other was to find percentage of time when the model's prediction was within one standard deviation of the whole data set from the recorded value.

Results

SSC Measurements

Although all the sites from which the data were recorded were inshore reef environments, the magnitude and patterns of the SSC varied greatly. The ranges of SSC can be seen in Table 4.1 and Figure 4.6. For all the sites except for those at Port Douglas the standard deviations were greater than the means indicating that the data sets are highly skewed. The SSC readings from Lugger Bay were by far the highest with a mean of 161 mg/l. The data there was wide-ranging with a standard deviation of 239 mg/l, which was due to periods of approximately two weeks of very low SSC followed by large peaks lasting for several days. The two Port Douglas sites were similar to each other with mean concentrations of around 60 mg/l and standard deviations of 28 and 42. With a mean of 5.7 mg/l, Nelly Bay had by far the lowest SSC and also a very small range of

SSC with a standard deviation of 6.7 mg/l. Table 4.2 and Figure 4.7 show an analysis of the same data after it has been averaged over a 24 hour period, which was used to assess the performance of the model.

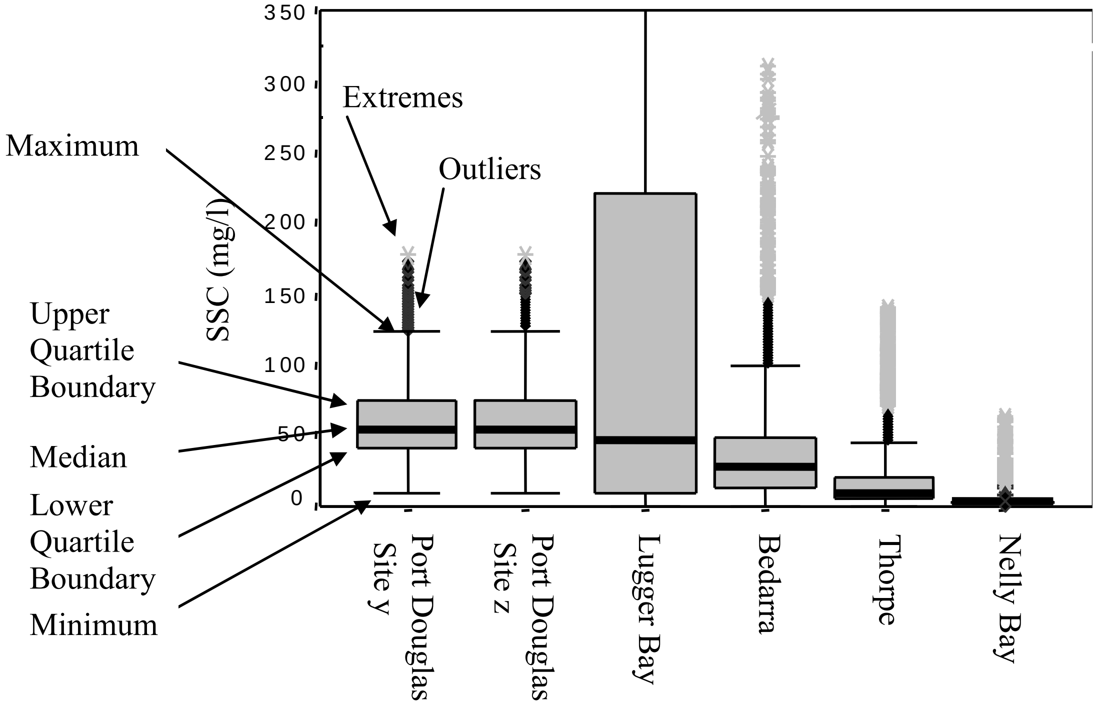

Figure 4.6: Box plots of the hourly SSC data. Maximum and minimum are the maximum and minimum data points excluding the outliers. Outliers are defined as being more than 1.5 times the inter quartile range above the upper quartile boundary and less than 3 times the inter quartile range above the upper quartile boundary. Extremes are anything above this range.

	SSC (mg/l)					
	Lower Tercile Boundary	Upper Tercile Boundary	Mean	Median	Standard deviation	Maximum
Port Douglas Site y	45	66	59	54	28	178
Port Douglas Site z	41	77	67	57	42	231
Nelly Bay	3.6	4.8	5.7	4.5	6.7	62
Lugger Bay	19	166	161	47	239	1542
Thorpe	7.1	17	20	10	24	141
Bedarra	17	47	40	29	41	310

Table 4.1: Statistical information for the hourly SSC data from the different sites.

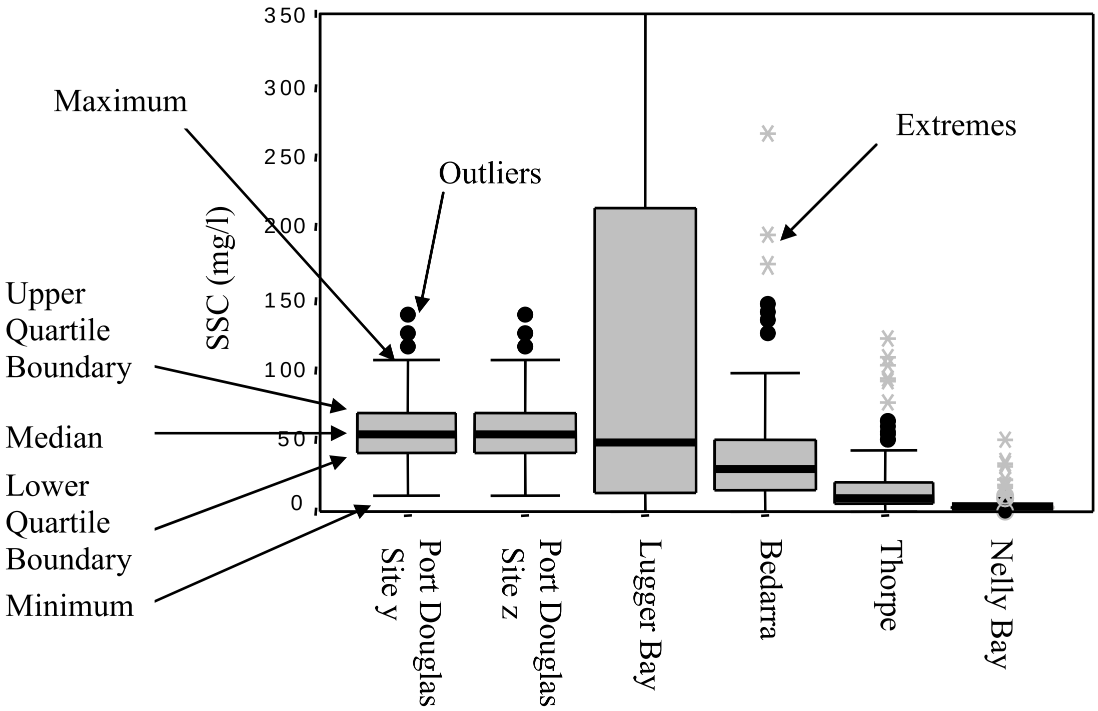

Figure 4.7: Box plots of the daily averaged SSC data. Maximum and minimum are the maximum and minimum data points excluding the outliers. Outliers are defined as being more than 1.5 times the inter quartile range above the upper quartile boundary and less than 3 times the inter quartile range above the upper quartile boundary. Extremes are anything above this range.

	SSC (mg/l)					
	Lower Tercile Boundary	Upper Tercile Boundary	Mean	Median	Standard deviation	Maximum
Port Douglas Site y	43	76	64	54	35	176
Port Douglas Site z	44	62	58	54	25	139
Nelly Bay	3.8	4.9	5.8	4.6	6.0	49
Lugger Bay	23	180	153	48	207	1175
Thorpe	7.3	17	20	11	23	121
Bedarra	18	47	40	30	40	267

Table 4.2: Statistical information for the daily averaged SSC data from the different sites.

Model Results

Tidal Influence

The version of the model that included tidal effects gave results not significantly different to the models that did not include tides. R^2 values for the tidal model were within 5% of the R^2 values of the non-tidal model for all sites. This implies that tidal range has a negligible influence on the daily average SSC at these sites. Hence the non-tidal model was used to reduce the number of parameters in the model, which was important because more parameters produce more local minima in the minimisation function, causing difficulty in finding the global minimum. However, if using a similar model for other some types of locations where the conditions are different from these reefs, for example a river estuary, then a tidal component might be necessary.

Generated Model Parameters

The parameters generated by the minimisation process for each site (Table 4.3) were examined to determine whether the model for the site is physically realistic. *a* and *c*, the two parameters controlling the temporal wind weighting function $k(t_{wn})$, mostly produced functions which reduced to close to zero within 48 hours (Figure 4.8). This justified the use of a 48 hour models and there was no need to extend the cut-off to 72 hours. The exception to this was Thorpe Island, where the weighting decreases very gradually after 2 hours but remains at over 50% of its peak value for winds 48 hours before present. This very slow decrease is not physically realistic for the moderate wind speeds and short fetch characteristic of this region.

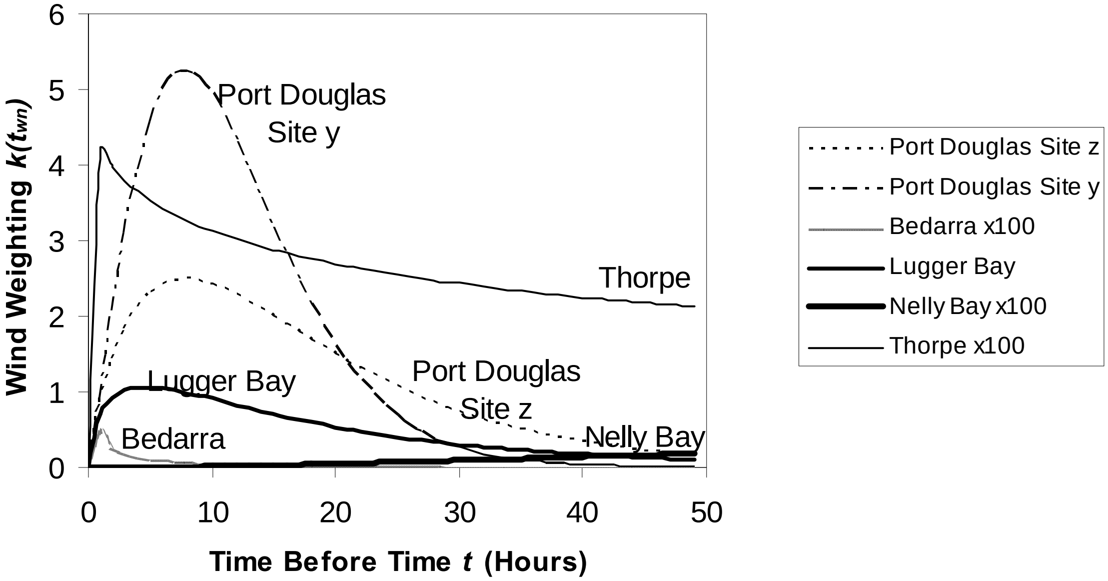

Figure 4.8: Temporal wind weighting, $k(t_{wn})$, for the various sites. The weightings for Bedarra, Thorpe, and Nelly Bay have been multiplied by 100 so they can be seen on the same graph.

Both models for the sites at Port Douglas have parameters that appear physically reasonable. They both give 70 degrees as the most significant wind direction (Figure 4.9). Although in general the strongest winds are from slightly further to the South of this direction the coastline meant that the sites (Figure 4.2a) were sheltered from winds from the south and west. For both Port Douglas sites, the peak in the wind weighting function occurred at 9 hours before present (Figure 4.9). The model parameters for Lugger Bay had similar parameters to the Port Douglas sites with the directional weighting function centred around 45 degrees and the temporal weighting function at 5 hours. Both Lugger Bay and Port Douglas sites have similar parameters as they are geographically similar sites being close inshore on a North-South oriented coastline

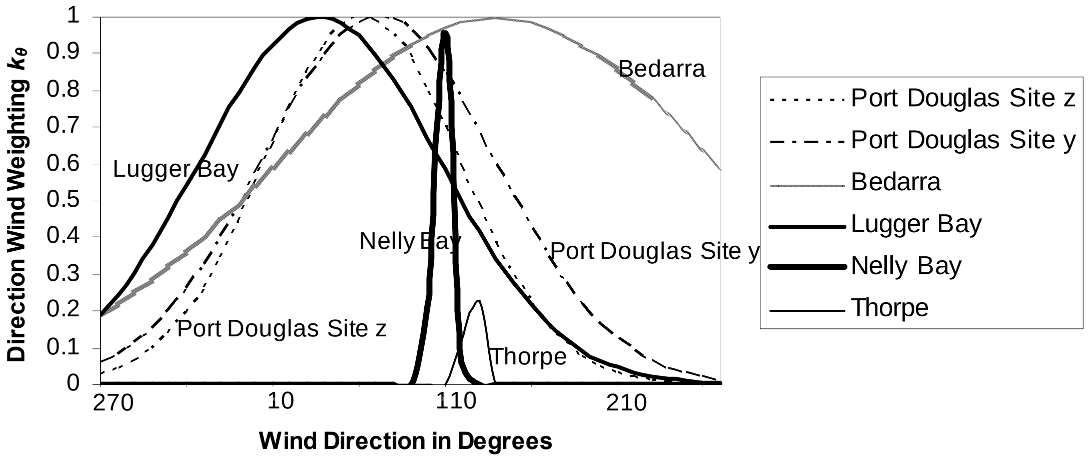

Figure 4.9: Directional wind weighting, k_θ, for the various sites. The wind direction is given with a wind from the north being zero degrees.

The model parameters for Bedarra Island also appeared to be physically reasonable with a peak value for $k_t(t_{wn})$ just a few hours before present and indicating little significance for wind data more than 10 hours before present. The k_θ function for this site has a broad distribution centred around 130°.

As mentioned previously, the model for Thorpe Island generated parameters that seemed physically unrealistic for the temporal wind weighting function. The directional wind weighting function has a very narrow peak implying that only winds from 110^o to 130^o have any influence on generating SSC which does not seem to be physically realistic.

The model for Nelly Bay also appears to be physically unrealistic. The peak of the directional wind weighting function is sharp around 110^o and is zero outside the range 80^o to 120^o. The temporal wind weighting distribution is extremely unrealistic as it increased monotonically, failing to drop with increasing time even after 48 hours. The model was re-run with an extended period for the wind weighting function of 72 hours, however a peak failed to develop even for this extended time. This indicates that the model for this site is fundamentally flawed.

Sites	Parameters						
	c	a	b	γ	M	p	q
Port Douglas Site y	1.2977	14.279	1.2927	10.623	0.03175	161.37	67.701
Port Douglas Site z	0.9277	6.7822	1.1646	-4.284	0.0958	152.1	56.561
Nelly Bay	-0.193	0.0718	1.9468	0.096	53.985	198.52	4.8188
Lugger Bay	0.6803	2.8815	3.011	114.84	0.0014	127.54	69.946
Thorpe	0.1214	0.3156	2.6445	30.262	0.24875	215.46	2.6512
Bedarra	0.1709	0.1863	2.6034	80.297	0.1766	230.51	125.97

Table 4.3: Parameter values for the various sites.

Model Predictions

Figure 4.10 shows an example of the hourly SSC data at Port Douglas before it has been averaged over each day. It also includes the raw wind data and the wind after it has been adjusted by the directional wind weighting function. The daily average predictions of the models are shown in Figures 4.11 to 4.16. These figures show predicted and observed SSC for both the training periods, where the models' parameters were found to best fit the data, and the prediction periods, where the models predicted the SSC. The boundaries between the tercile categories used for two of the model evaluation methods have also been marked on the graphs.

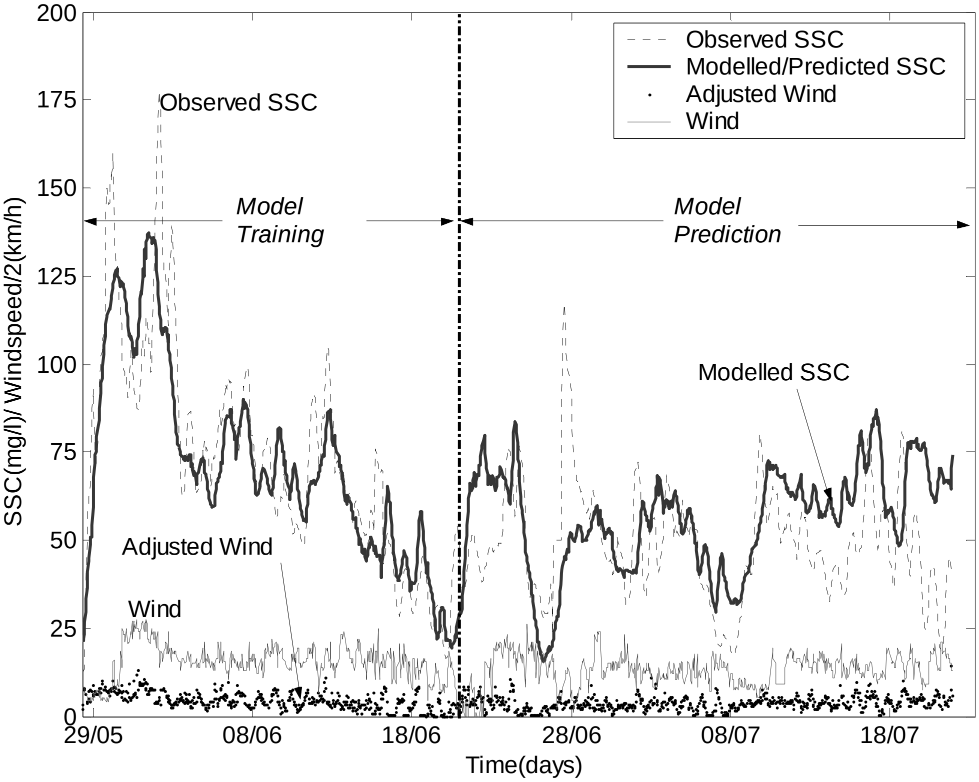

Figure 4.10: Modelled/predicted and observed hourly SSC for Port Douglas Site z, 2004. The wind is the raw wind data, and the adjusted wind is the wind after it has been adjusted by the directional wind weighting function.

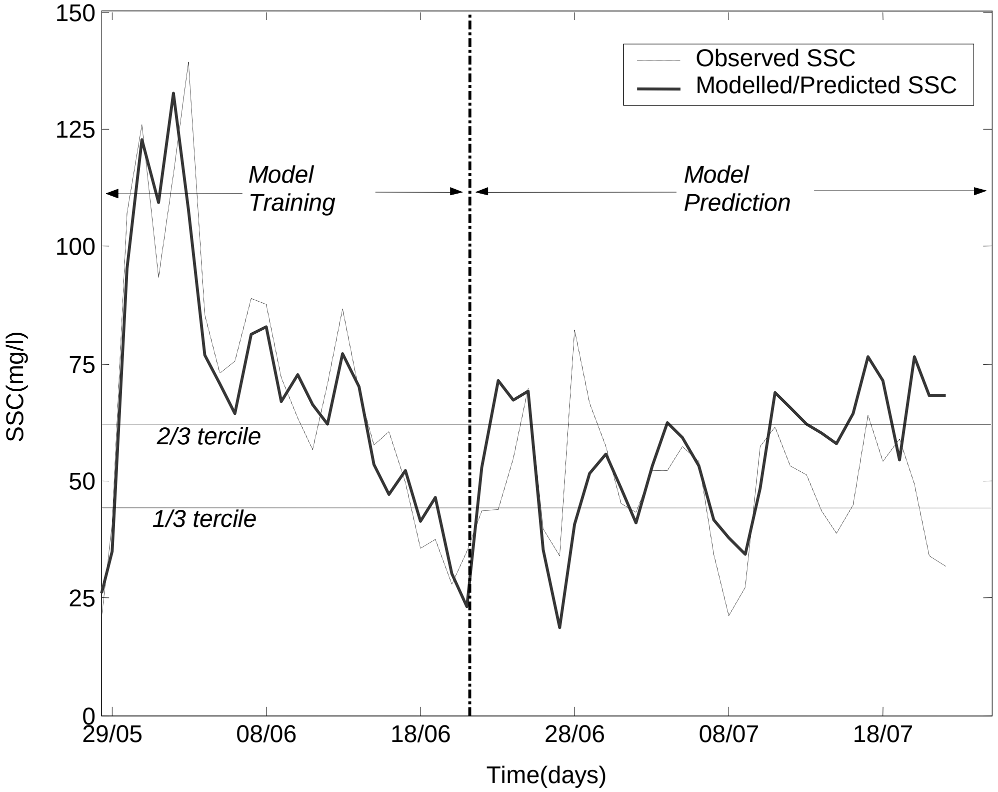

Figure 4.11: Daily average of modelled/predicted and observed SSC for Port Douglas Site z, in 2004.

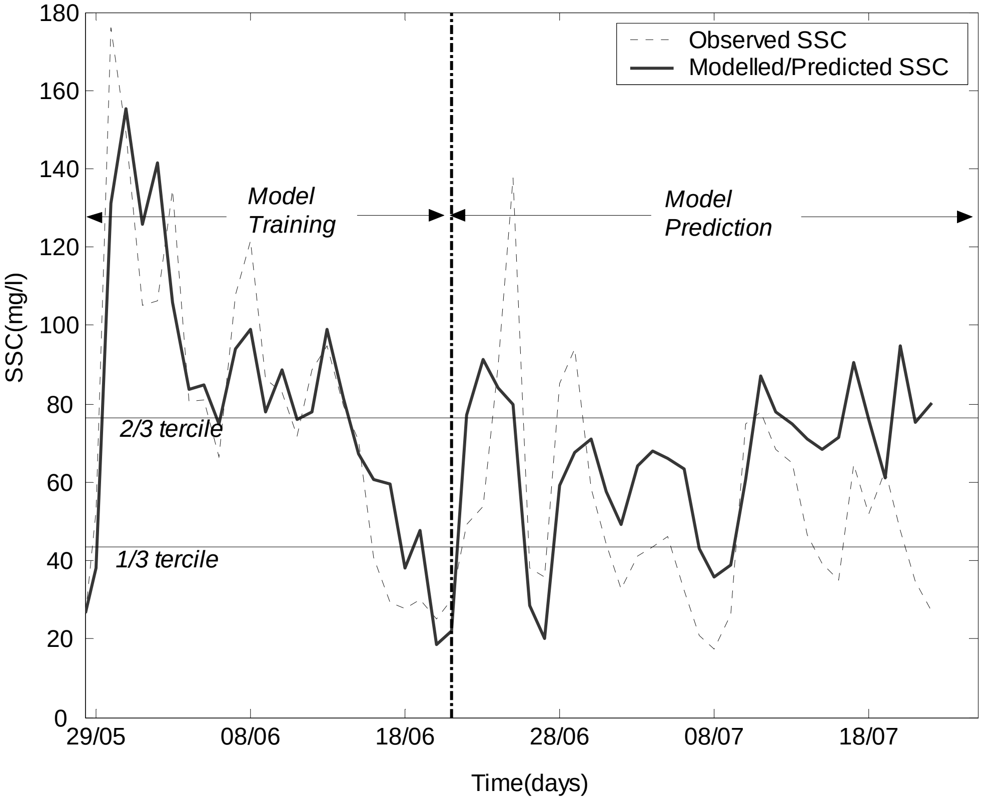

Figure 4.12: Daily average of modelled/predicted and observed SSC for Port Douglas Site y, 2004.

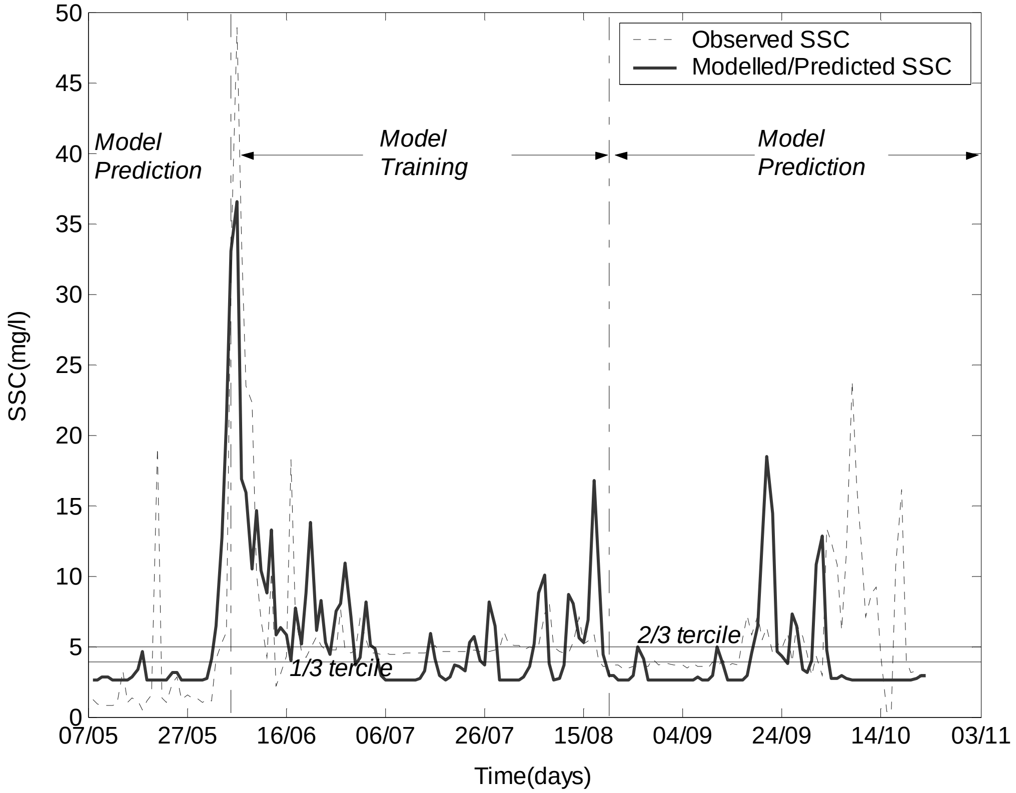

Figure 4.13: Daily average of modelled/predicted and observed SSC for Nelly Bay in 2001.

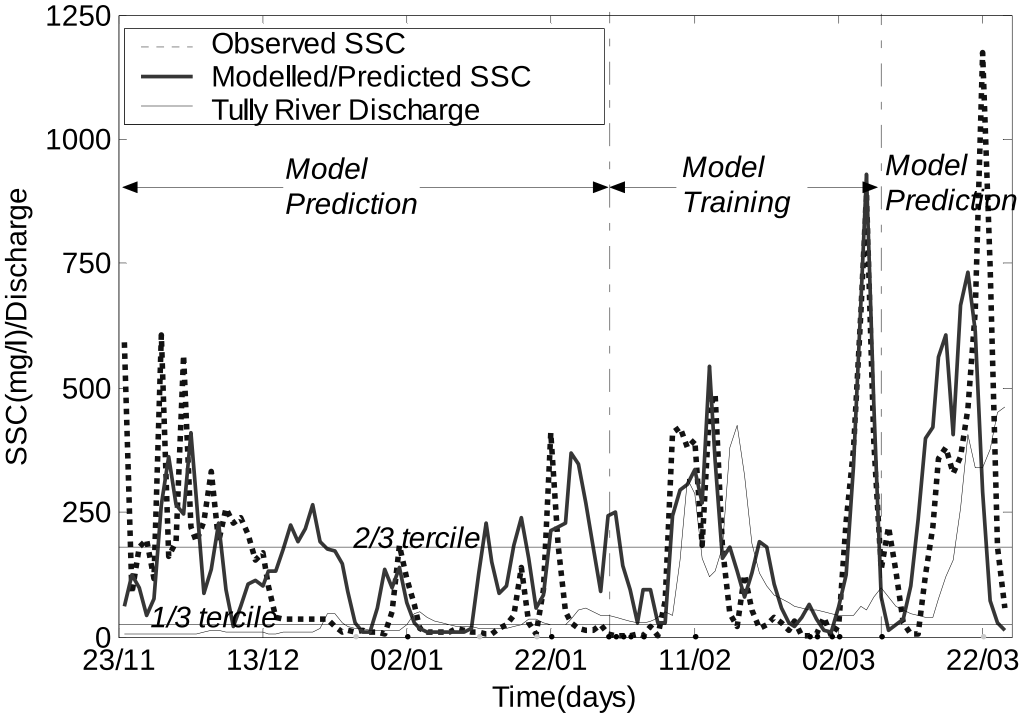

Figure 4.14: Daily average of modelled/predicted and observed SSC for Lugger Bay, and the Tully River discharge in 2003 to 2004.

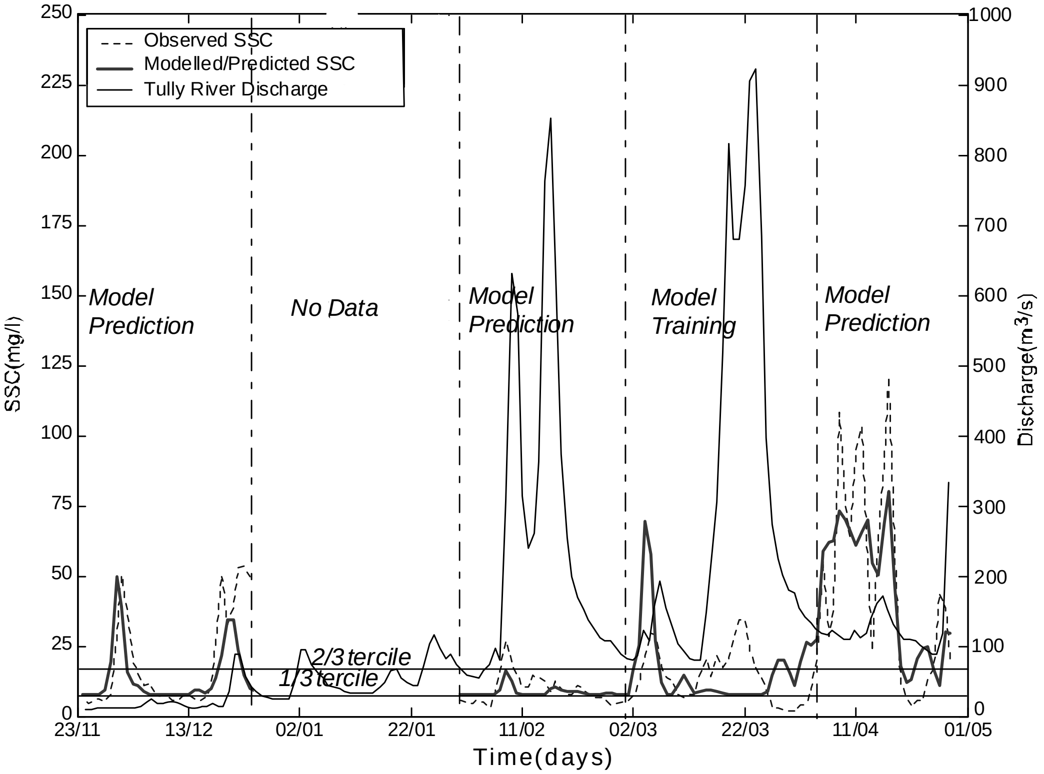

Figure 4.15: Daily average of modelled/predicted and observed SSC for Thorpe Island and the Tully River discharge in 2003 to 2004.

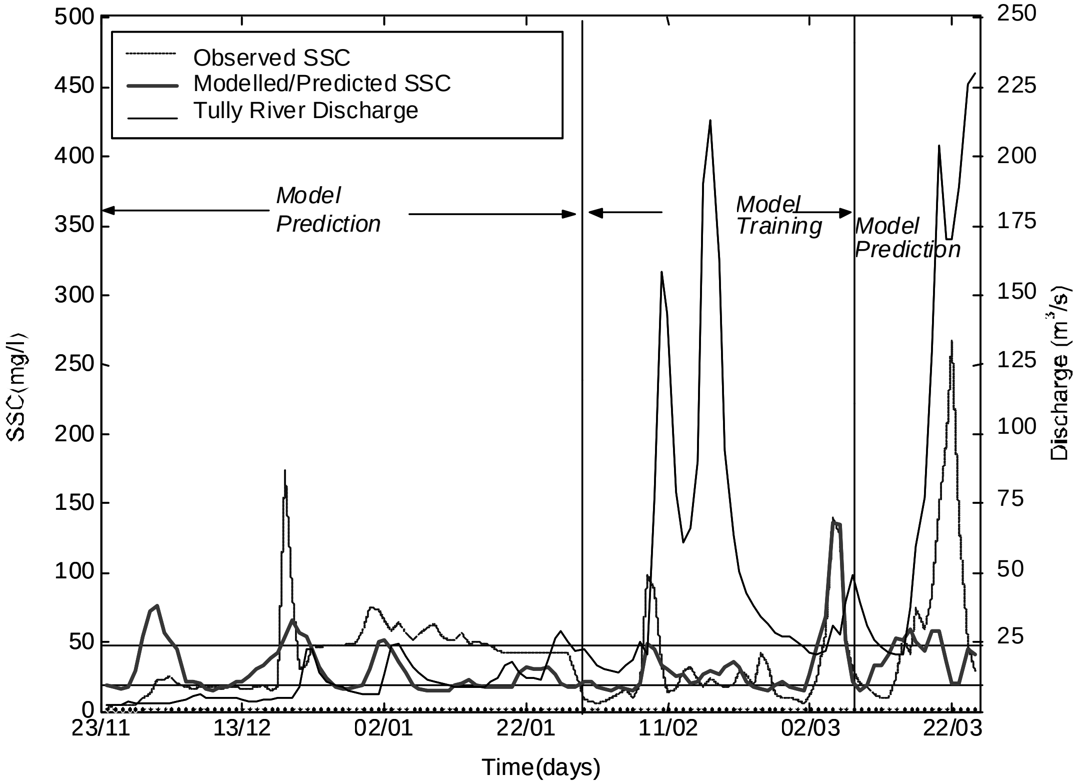

Figure 4.16: Daily average of predicted and observed SSC for Bedarra Island and the Tully River discharge in 2003 to 2004.

The results for the five methods used to evaluate the model are shown in Table 4.4. The row labelled random shows the percentages expected if the categories are predicted by means of a random selection. In general the models performed well in the R^2 test for their training periods, and performed badly when predicting the SSC, except for the Thorpe and Nelly Bay models for which the opposite was true. The standard deviation fit test gave very high percentages for all the sites, even those with unrealistic parameters such as the models for Thorpe and Nelly Bay. All the category fit tests gave results that were better than if the categories had been selected at random, with the exception of the tercile test for Nelly Bay. Averaged over all the sites the model was more than 50% better than random category selection in all the category tests.

Model	R^2		Standard Deviation Test (%)		Tercile Test (%)		Weighted Tercile Test (%)		Weighted Quintile Test (%)	
	T	P	T	P	T	P	T	P	T	P
Port Douglas Site y	0.77	0.19	90	82	72	54	86	73	54	44
Port Douglas Site z	0.85	0.12	93	86	79	54	88	71	84	65
Nelly Bay	0.19	0.46	91	78	31	60	60	70	50	64
Lugger Bay	0.83	0.17	97	77	62	50	78	70	71	59
Thorpe	0.0002	0.72	90	90	40	53	63	75	50	75
Bedarra	0.78	0.013	95	85	70	35	85	60	76	52
Random					33	33	50	50	40	40

Table 4.4: Evaluation results of model predictions for the various locations for both the training (T) and prediction (P) periods.

Discussion

Figure 4.10 and Figure 4.11 show that both Port Douglas models apparently predict the SSC well, capturing all the major features, although the Site y model has a tendency to over predict. The hourly data in Figure 4.10 shows that the model is capable of predicting some of the finer details in the SSC. However for the standard tercile test, the performance results for these models are not very good, achieving a 54% fit for each site. This is mainly due to the predictions often being just on the other side of the tercile boundary from the observed SSC. Use of the weighted tercile method at this site produced some of the best results with percentages of 73% and 71%. But it should be noted that even a random selection using the weighted tercile test will achieve 50%. The model for site z also performs well in the quintile fit test with 65% whilst the model for Site y performs poorly only achieving a 44% fit, barely better than a random selection. As expected, both sites perform well in the standard deviation fit test. This high performance is more significant than it is for the other sites since for both Port Douglas sites, the standard deviations are small compared to the full range of the data because there are few extreme data points. As with most of the sites, the Port Douglas R^2 values are high for the training period but very low for the prediction period.

The model for Nelly Bay, shown in Figure 4.15, did predict the first major peak, on the 01/06/2001. However it performed poorly for the rest of the time. This was to be expected from examining the values of the model parameters, which do not appear to be physically correct. In this case, all the category fit tests seem to produce high values especially for the prediction period. The standard deviation fit test produced percentages that were high, 78% for the prediction periods, considering the unphysical nature of the model. These high values are due to a relatively large standard deviation that was forced up by one or two relatively large peaks in the data. For the R^2 test, the result of 0.46 is higher than for other sites for the prediction period. This appears to be mainly caused by the good prediction of the one high SSC event. It is surprising that the Nelly Bay model performed so well considering the unrealistic model parameters, particularly for the temporal wind weighting function.

For Lugger Bay, a site with much higher SSC levels than any other site, visual inspection of Figure 4.16 indicates that the model appears to have fitted the data well. It has correctly predicted the main features of the test data however it added some extra SSC events that were not recorded by the instruments (Figure 4.16). On Figures 4.16 to 4.18 for the 3 sites near Lugger Bay/Family Islands, data showing the discharge from the Tully River has been superimposed to allow for comparison with the SSC to see if particular events were caused by river plumes or wind generated waves. There is a possibility for some overlap since plumes often occur during periods of strong wind, making it difficult to tell which is the cause of elevated SSC. This is illustrated in the case of Lugger Bay where two such events seem to have occurred. The first was during the modelling phase, between 07/02/2004 and 20/02/2004 when there was a period of raised SSC that also coincided with an increase in river discharge. However the program modelled this SSC quite well using just the wind data. A similar peak occurred in late March 2004, in the test phase of the model, and again the program was able to predict the peak from the wind data alone. It is also worth noting that there are many other peaks in the SSC that occur when the river discharge is very low. For example, during the event starting on the 2nd of March 2004, when there is not a rise in discharge proportional to that of SSC, the wind based model fits the change in SSC well.

According to most of the evaluation methods the Lugger Bay model performed quite well, each time giving slightly better results for the training period than for the prediction period. However compared to the Thorpe Island model, it performed worse in the category tests even though the model parameters for Thorpe Island are somewhat unrealistic.

Referring to Figure 4.15, the model for Thorpe Island seems to have fitted the SSC data quite well, with one notable exception being the peak on the 22nd of March 2004 that the model did not predict. The river discharge data for this period shows a high discharge that corresponds with this peak, suggesting that this event may have been at least partly caused by a river plume. Due to the peak on the 22nd of March in the observed data, the Thorpe Island model gives poor results for the category fit tests in the training period, however its predictive powers are better. For example for the quintile test it scores only 50% in the training phase but gets 75% in the prediction phase. The same result is given by the R^2 test, with 0.0002 in the training period and 0.72 in the prediction period.

Figure 4.16 shows that, as the parameters suggested, the model for Bedarra Island, was not very successful in fitting the observations. The Bedarra Island model performed badly in predicting the SSC due to two events, i.e. the period between the end of December 2003, the end of January 2004 and the peak around 22/3/04. In the first period, the base line of the SSC data is much higher than usual, possibly due to a fault in the calibration of the instrument. Secondly, similar to Thorpe Is., there is a peak around the 22nd of March 2004, which may be partly attributable to river discharge. For Bedarra Is. this peak occurs in the prediction period and contributes to the very low values in all the category fit and R^2 tests for this period. However, even without this event, the model does very badly at predicting the SSC. The results for the standard deviation test are higher than were anticipated, due to a relatively high standard deviation.

The first major discharge, occurring in February, did not coincide with a peak in measured SSC at Thorpe Is. or Bedarra Is., however the second discharge, in March did coincide with significant SSC peak. The Lugger Bay model however successfully predicted or fitted an SSC peak during both these discharge events based upon a moderate elevation in wind speed (Figure 4.19).

On which sites the model performed the best depended to a large degree on which evaluation method was chosen. The sites with more physically reasonable models tended to perform better than others in most of the tests, but in some tests, such as the R^2 test, they did not. There did not seem to be one test which was significantly better than the others, and it would seem that it is necessary to do a number of tests to properly evaluate the models performance. The Quality of wind data did make a difference to how physically realistic the model was. However the sites where the wind data was of good quality did not out perform the others in all the tests.

Conclusion

The model showed some degree of success, with its predictions always being better than random, with one exception for Nelly Bay when using the tercile fit. The relative performance of each of the models varied greatly depending on which evaluation method was used. This indicates that caution should be applied when stating the success of a model and that using multiple evaluation tests is advisable. The results from the R^2 and category tests were usually consistent with each other, but the performance assessed by the standard deviation test was often contradictory to the other tests.

The models for Nelly Bay and Thorpe Island, which used physically unrealistic parameters, did not perform as badly as was expected. In fact, in some tests they did better than other models, for example in the standard deviation fit test.

The quality of the wind data did not always make a difference on the performance of the models. The two sites at Port Douglas had the most representative wind data, in terms of the proximity of the weather station and its unsheltered nature. These sites performed relatively well compared to the others in most of the tests. However on some tests, models based on less relevant wind data performed better.

Prediction of suspended sediment concentrations and water turbidity is very challenging. Large temporal and spatial variations in SSC are common with order of magnitude changes occurring over distances of less than a kilometre and times of a few hours. Compared with predicting gently fluctuating parameters such as water speed, tidal level or water temperature, the prediction of SSC is much more difficult. However this study has shown that a useful degree of predictability of SSC is possible using only wind data as an input. Such models may find application in environmental impact studies of engineering activities that occur close to coral reefs.

Acknowledgements

We would like to thank the following people for their invaluable contribution to this paper. Janice Lough, Martial Depczynski, Tim Hancock, David McNaughton, Severine Thomas, Tamika Tihema.

References

Anthony, K. R. N., Fabricius, K. E. 2000. Shifting roles of Heterotrophy and Autorophy in Coral Energy Budgets at Varying SSC. J Exp. Mar. Biol. Ecol. 252, 221-253.

Anthony, K. R. N., Ridd, P. V., Orpin, A. R., Larcombe, P., Lough, J. 2004. Temporal variation of light availability in coastal benthic habitats: Effects of clouds, turbidity, and tides. Limnology and Oceanography 49, no. 6, 2201-2211.

Delft Hydraulics, 2006. DELFT3D. Retrieved 20/09/2006 from Delft Hydraulics website: http://www.wldelft.nl/soft/d3d/intro/index.html

Dupont, L., 2003. Development of an In-Situ Fluorometer for the Study of Organic Materials on a Fringing Reef, Thesis, JCU.

Fabricius, K. E., Wolanski E. 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow. Est. Cos. Shelf Sci. 50, 115-120.

Grant, W. D., Madsen, O. S. 1979. Combined Wave and Current Interaction with a Rough Bottom. J. Geophys. Res. 84(C4), 1797-1808.

Gilmour, J. 1999. Experimental Investigation into the Effects of Suspended Sediment on Fertilisation, Larval Survival and Settlement in a Scleractinian Coral. Mar. Bio. 135, 451-462.

Gröen, P., Dorrestein, R. 1976. Zeegolven. KNMI Opstellen op Oceanografisch en Maritiem Meteorologisch Gebied, 11, 124.

Larcombe, P., Woolfe, K. J. 1999. Increased Sediment Supply to the Great Barrier Reef will not Increase Sediment Accumulation at Most Coral Reefs. Coral Reefs 18, 163-169.

Lagarias, J.C., Reeds, J. A., Wright, M. H., Wright, P. E. 1998. Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions. SIAM Journal of Optimization, Vol. 9 Number 1, 112-147.

Lou, J., Ridd, P. V. 1996. Wave-Current Bottom Shear Stresses and Sediment Resuspension in Cleveland Bay, Australia. Coastal Eng. 29, 169-186.

Lou, J., Ridd, P. V. 1998. Reply to Comments by J. P. Xu regarding "Wave-Current Bottom Shear Stresses and Sediment Resuspension in Cleveland Bay, Australia". Coastal Eng. 33, 65-67.

Marshall, S. M., Orr, A. P. 1931. Scientific Report of the Great Barrier Reef Expedition 1. p94.

Orpin, A. R., Ridd, P. V., Thomas, S., Anthony, R. N., Marshall, P., Oliver, J. 2004. Natural Turbidity Variability and Weather Forecasts in risk Management of Anthropogenic Sediment Discharge Near Sensitive Environments. Marine Pollution Bulletin 49, 602-612.

Ridd, P. V., Larcombe, P. 1994. Biofouling Control of Optical Backscatter Suspended Sediment sensors. Mar. Geol. 116, 255-258.

Stafford-Smith M. G. 1993. Sediment-Rejection Efficiency of 22 Species of Australian Scleractinian Corals. Mar. Bio 115, 229-243.

Williams, D. 2001. Impacts of Terrestrial Run-off on the Great Barrier Reef World Heritage Area. AIMS.

World Meteorological Organization. 1998. Guide to Wave Analysis and Forecasting, 2nd edition.

Wright, L. D., Boon, J. D., Kim, S.C., List, J. H. 1991. Modes of Cross-Shore Sediment Transport on the Shoreface of the Middle Atlantic Bight, Mar. Geol. 96, 19-51.

5 – Paper on:

The Algal Growth Sensor

To be submitted to The Marine Pollution Bulletin.

Algal Growth Sensor

Abstract

Nutrients can affect corals in a number of ways, both directly and indirectly. For example they can contribute to the formation of marine snow which has the potential to smother corals. High concentrations can also enable algae to grow more rapidly and possibly out-compete corals for living space. For such an important parameter, techniques for measuring nutrient concentrations are limited; water sampling only provides data with a limited frequency, and fluorometers, which measure nutrient indirectly through organism concentrations, indicate nutrient levels where the organisms grew rather than the level at the location of the instrument. The purpose of this work was to investigate an alternative technique using algal growth as a surrogate for nutrients.

The growth of algae on a glass plate was measured by placing a fluorometer behind the plate. The changes in algal growth are reflected in the fluorometer output. The advantage of this technique is that it should relate to nutrient concentrations at the location of the instrument. The potential problem, which this work was to investigate, is that other factors influence algal growth, such as temperature, light and algal type. The instrument was constructed and tested at an aquarium and on an inshore reef.

Results showed that temperature and light had too great an influence on algal growth to allow the instrument to give an accurate indication of nutrient concentrations. However, the instrument's ability to measure the algal growth rate could make it useful in determining the threat to corals from algal encroachment.

Keywords: Nutrients, Algae, Reef, Coral.

Introduction

Changes in nutrient concentrations have the potential to have major impacts on coral reefs. One source of nutrients is river discharge that is affected by land use in the river catchment and is therefore susceptible to anthropogenic changes (Furnas 2003). Therefore when monitoring the impact of human activity on coral reefs, it is important to be able to measure nutrient levels.

Nutrients can impact on corals directly by combining with sediments to create large particles called marine snow. When these particles settle on a coral they can be too large for the coral to remove which can lead to smothering (Fabricius and Wolanski 2000). It is also possible for excess nutrient concentrations to slow coral growth (Ferrier-Pages 2000).

As algae require nutrients to grow, an increase in nutrient concentrations can lead to an increase in algal growth. If the algae is in the same habitat as corals, this increase in growth could lead to algae covering all areas suitable for coral recruitment and even the corals themselves (Bell 1992, Lapointe 1997, Adey 1998).

Increasing nutrient concentrations do not always lead to increases in algal growth. If algal growth is already limited by another factor such as light or temperature, then an increase in nutrients will not mean an increase in algal growth. This makes the nutrient uptake more significant than the nutrient concentration when assessing algal growth (Atkinson 1988, Larned & Atkinson 1997). For example tests by Schaffelke and Klumpp (1997, 1998a, b) showed that while growth of *Sargassum Baccularia* did increase with nutrient concentrations there was a saturation point where more nutrients did not lead to more growth.

Even when an increase in algal growth does occur, it may not lead to an increase in the standing crop of algae (Carpenter 1988, Hatcher 1997). Studies have shown that the algal biomass is strongly dependent on herbivory and increases in nutrient concentrations may not lead to increases in the amount of algae crop (Littler & Littler 1984, McCook 1996, 1997, Russ & McCook 1999, Scott & Russ 1987).

The measurement of nutrient concentrations can be carried out in a variety of ways. The traditional method is to take water samples for analysis in a laboratory. The advantage of this technique is that very accurate measurements of nutrient concentrations can be made. It is also possible to measure the specific concentrations of many different parameters such as nitrates, phosphates and chlorophyll. All these advantages make sampling the best method in many cases; however, it does have a number of disadvantages. Collecting a long time series of data requires many trips to the same location over a long period of time. This can become very expensive, particularly if the location is in a remote area. Safety also prevents samples from being taken in rough weather, which prevents important data from being recorded especially because runoff events tend to occur during rough weather. Some automated samplers do exist that take water samples at predetermined intervals that can later be analysed in a laboratory. However, the number of samples that can be taken is limited, and while the total nitrogen in the sample will remain constant it is likely that the delay before the sample is analysed will mean that the nitrogen will not be in the same form as it was when the sample was taken. It is also impossible to record with an automated system every few minutes or hours continuously over periods of months.

Using an automated sensor instead avoids the disadvantages associated with water sampling, although some accuracy will be lost and the number of parameters that can be measured will be reduced. One automated system which has started being used recently is diffusive equilibration in thin film plates (DETs) (Davison et al. 1994, Krom et al. 1994, Mortimer et al. 1998). DETs consist of a polyacrylamide gel covered by a millipore filter and can be used to absorb nitrates such as ammonia, which can then later be examined in a laboratory to give concentration measurements. This will measure the average nutrient concentration over the time deployed so it will not give any time series information.

Another automated method is to measure water fluorescence. Fluorescence will give an indication of how much *chlorophyll a* is present, which will relate to the concentrations of phytoplankton and algal blooms. The advantage of using fluorescence is that it measures the response of the system to nutrient inputs, and it is the results of the nutrient input, i.e. algal blooms, macroalgal growth and production of marine snow, that are potentially harmful to corals. Fluorescence loggers are also capable of recording detailed time series data over long periods and are already used in many areas of oceanography e.g. Turnewitsch and Graff (2003). The disadvantage of these loggers is that chemicals other than *chlorophyll a* fluoresce at similar optical wavelengths making it hard to determine how much of the fluorescence signal comes from phytoplankton and algae. It has also been found that in rough weather resuspended sediment will produce high fluorescence readings due to organic material in the sediment (Whinney and Ridd, unpublished work). Since this material was produced previously it is not an indication of the present inorganic nutrient levels. High fluorescence readings could also be the result of phytoplankton or algal blooms growing elsewhere in a nutrient rich environment and then drifting to the logger's location. In this case the readings do not relate to the *in situ* nutrient concentrations.

A more advanced fluorescence sensor uses Pulse-Amplitude-Modulation (PAM) (Heinz Walz GmbH, 2002), which works by emitting a saturating pulse of light before measuring the fluorescence. This allows photochemical and non-photochemical de-excitation to be distinguished from one another, since photochemical de-excitation will become zero during the saturation pulse. The advantage of this is that the sensor will be able to measure the photosynthetic performance of the organic material rather than just fluorescence.

In this work a sensor to measure algal growth was investigated as an alternative to a fluorescence sensor to try to solve some of the problems associated with fluorometers. The algal growth sensor uses similar technology to the conventional fluorescence loggers but instead of measuring phytoplankton in the water column it measures the amount of algae growing on a glass plate (periphyton). This will have the advantage that it will be related to the current *in situ* nutrient concentration and while the algae will feed, to some extent, on resuspended old organic matter, the sensor will be less affected by resuspension than a fluorescence sensor is. As a measure of algal growth, it may also give a rough qualitative indication of nutrient intake by algae and perhaps the likelihood of whether algal growth could be a problem for any coral present.

One potential problem with this technique is that algal growth is not just related to nutrient concentrations so the results from the sensor will also be dependent on light, temperature and the type of algae growing on the plate. Whether this is a problem or not will depend on whether those using the sensor are interested in nutrient concentrations or nutrient intake and its effects on algal growth. A more complex algal growth sensor could be constructed that would isolate the plate, in order to control factors like type of algae and light levels, while allowing water and the nutrients present within it to flow past the plate. The goal of this work is to investigate how well an algal growth sensor will work without such isolation, whether it can be used to measure nutrient concentrations if some offset for light and temperature is applied, or whether it can only be used to determine nutrient intake and algal growth. The advantages of a non isolated sensor is that its simplicity of design makes it easier and more reliable to deploy and that it can be a better indication of nutrient intake since it also takes into account other limiting factors such as light.

Methods

Instrument Design and Construction

The technology for the algal growth sensor was based on fluorescence sensors developed by Dupont (2003). These work by using a blue LED to emit light, which is then filtered allowing light of around 460 nm to pass through. This light is of the correct wavelength to excite *chlorophyll a* that then fluoresces emitting infra red light in a broad band around a wavelength of about 685 nm (Hall and Rao, 1994). The instrument measures the levels of infra red light before and after the blue LED is switched on. A comparison between the two readings determines the amount of fluorescence occurring. However since other chemicals such as *chlorophyll b, pheophytin a* and *pheophytin b* have excitation and emission spectra that overlap with *chlorophyll a*'s (Dupont 2003, Jeffrey et al. 1997) it is difficult to distinguish how much of the fluorescence is due to *chlorophyll a.* Therefore the sensor gives a rough measure of some types of organic material. However since different types of organic material contain varying concentrations of *chlorophyll* and *pheophytin* the sensor's reading will change depending on the type of organic material present as well as the concentration.

For the algal growth sensor, the light from the blue LED illuminate, by means of optical fibres, a plate of glass upon which algae is grown (Figure 5.1 and 5.2). Optical fibres collect infra-red light that fluoresces from the algae to a photodetector. Algae growing on the front of the plate of glass then fluoresce emitting infra red light, which is detected by the photodetector.

The sensor was designed to allow algae to grow on the plate for several days after which the glass would be cleaned by an automatic wiper and then algae would be allowed to grow again. The purpose of this was to prevent the signal from the photodetector saturating when a thin layer of algae covered the glass. The wiper was spring mounted so a constant pressure could be applied and the wiping surface was fine sandpaper. Since the differences between scratched and unscratched glass might affect the signal the glass was scratched with the sandpaper before use.

The sensor was designed to be deployed facing directly upwards so that it would receive the maximum amount of ambient light available and not be effected by the orientation of the instrument. A cup-like shade covers the sensor every time a reading is taken to prevent the light from causing the sensor to go off scale. The cup was made of copper so that no algae will grow on it and affect the readings. When the instrument is not taking a reading the cup moves to the side, out of the way, to prevent it affecting the algal by either shading it or contaminating it with copper.

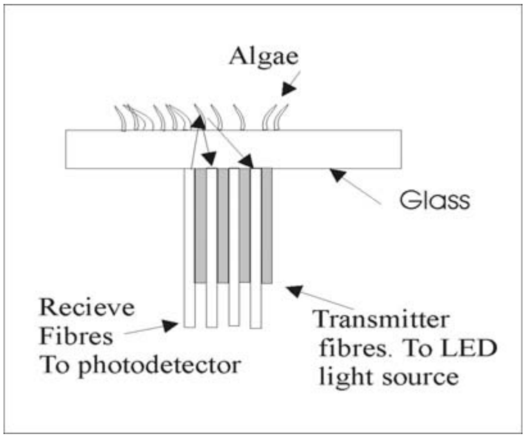

Figure 5.1: Principle of operation of sensor. Light from a bundle of optic fibres illuminates the algae on a glass plate. Fluorescent emissions from the algae are detected by a photodetector at the end of a second bundle of fibre.

Figure 5.2: Photographs of the Algal Growth Sensor. The circular glass plate, bottom left is the surface on which the algal growth is measured. Behind it is the wiper, bottom left corner of the same picture, and a hollow cylinder, top right corner, which moves over the glass plate to shade it from light during each measurement.

Instrument Testing

The instrument was deployed in the reef aquarium Reef HQ, Townsville (Australia), a 2.5 million litre coral aquarium. This was done to test the instrument in a safe and easily accessible environment where measurements on a range of nutrients and temperature were taken by aquarium staff. The number of hours of bright sunlight per day was taken from the Bureau of Meteorology's records as an indication of light levels. This would not take into account changes in light levels due to variations in SSC but it was assumed that these variations would but reasonably low in the aquarium. The range of nutrient values was modest (Nitrate concentrations were between 0 and 1 μM) but using the aquarium was a good way of getting some data in moderately controlled and monitored conditions. This allows the ability to test the consistency of the algal growth sensor. The sensor was deployed away from the edges of the aquarium facing directly towards the surface, which was directly exposed to the sun. The water depth was 4.5 m. The periods of deployment were 26/05/2005 to 01/09/2005 and 28/09/2005 to 18/01/2006 with the instrument set at different wiper periods to see how much time was required for the algae to grow.

As well as the tests at Reef HQ, the instrument was deployed in the ocean. The site chosen was Middle Reef, a reef half way between Townsville and Magnetic Island about 4 km from the mainland coast. This was to determine how well the sensor functioned in a real reef environment. The instrument was deployed between 22/11/2004 and 04/01/2005 at a water depth of approximately 3 m at low tide. For part of this period a conventional turbidity sensor using optical backscatter (Ridd and Larcombe 1994) was deployed at the same location so a comparison could be made between turbidity and algal growth.

Results

A time series for part of the data recorded at Reef HQ can be seen in Figure 5.3 (a). In this case the wiper was set to clean the glass every 4 days so a zig-zag pattern with the readings starting at a baseline and increasing until the point when the glass is cleaned can be seen (the tick marks on the x-axis mark the times when the glass was cleaned). The gradients of the slopes are reasonably consistent varying by about a factor of 3. The gradients tend to get steeper towards the end of each period, indicating an accelerated growth rate. A roughly sinusoidal diurnal pattern can also be seen in the data with a trough at about 7:50 and a peak at 19:50 (Figure 5.3 (b)). The gradient during each rise in the diurnal pattern is 3 to 4 times larger than the average gradient for each growth period, which indicates that a significant variation is occurring.

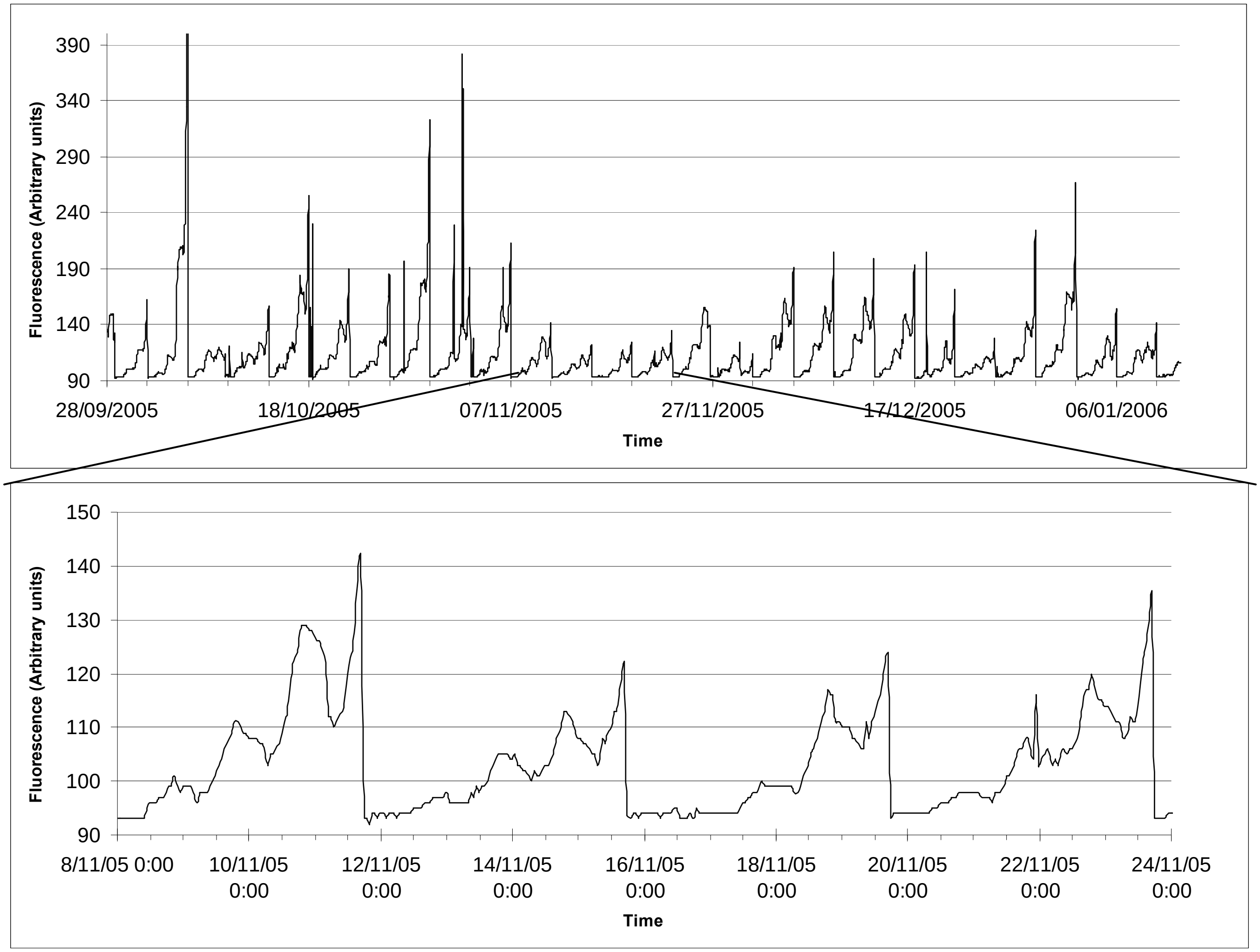

Figure 5.3: Fluorescence time series data at Reef HQ for: the whole of the second period (28/09/05 to 08/01/06), with each tick on the x-axis representing the time when the glass was cleaned (top, (a)), and an expanded graph showing 26 of the days during the period (bottom, (b)).

Figure 5.4 shows a comparison between the algal growth sensor's data, the nitrate concentration, temperature and light. The instrument's data is represented by the average of the slope for each of the intervals between wipes. For the first period, the instrument had a wiping interval of 6 days and the second period an interval of 4 days. The gradient of the sensor output does appear to have some of the same peaks as the nitrate concentration but the lag time between them varies. For example during the first period the nitrate concentration has 3 main peaks on the 09/07/05, 21/07/05 and 23/08/05 the algal growth rate also has peaks at similar times, from: 07/06/05 to 19/06/05, 13/07/05 to 19/07/05 and 18/08/05 to 30/08/05. Other nutrient concentrations, such as total organic nitrogen and total nitrogen, were also examined, but they showed less relationship to the algal growth than the nitrate concentration did. For the first period, the temperature time series (with temperatures recorded at about 9:30 and 16:30 everyday) also shows some of the same features as the algal growth rate, both having peaks around the 17/06/05 and the 23/08/05. The light time series also partially matches the peaks and troughs of the algal growth rate for the second period. For example both have troughs occurring around the 23/11/05, the 23/12/05 and the 12/01/06.

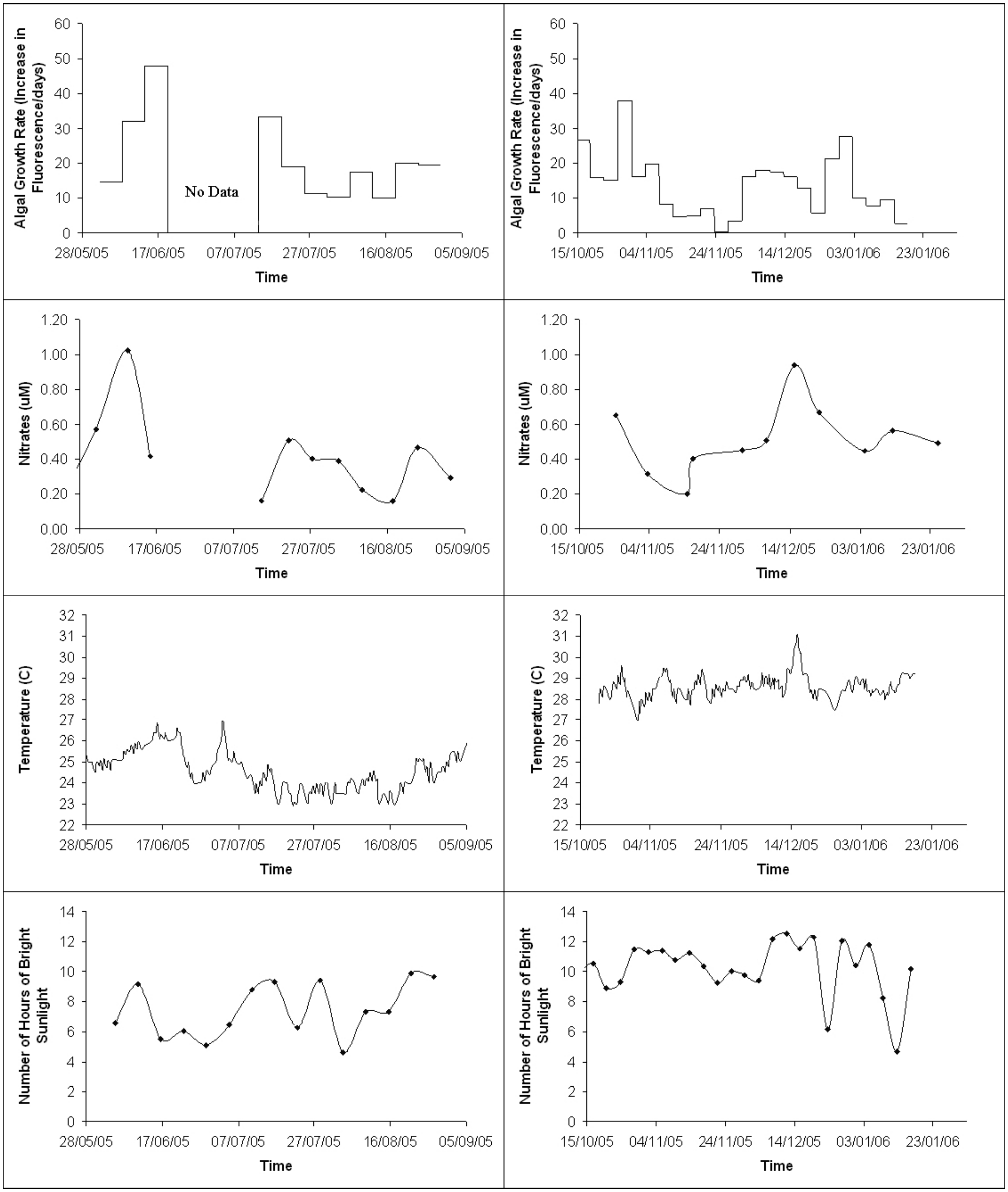

Figure 5.4: Comparison between algal growth rate, nitrate concentration, temperature and number of hours of bright sunlight at Reef HQ. The first period is on the left and the second period is on the right.

The scatter graphs in Figure 5.5(a) show the correlation between the rate of algal growth per day and the measured nitrate concentration for the two deployment periods. Both periods indicate little relationship between nitrate concentration and the growth rate;

R^2 values are less than 0.04 in both cases. Other nutrient concentrations, such as total nitrogen and total organic nitrogen, were also compared with the algal growth rate but these had R^2 values that were lower than those from the nitrate concentrations did. Figure 5.5(b) shows a stronger correlation between temperature and algal growth rate for the first period ($R^2 = 0.6$) but not for the second ($R^2 = 0.012$). While the correlation between light and algal growth rate is slightly higher for the second period than for the first, with $R^2 = 0.17$ compared to $R^2 = 0.0003$, however, in both cases the correlation is low (Figure 5.5(c)).

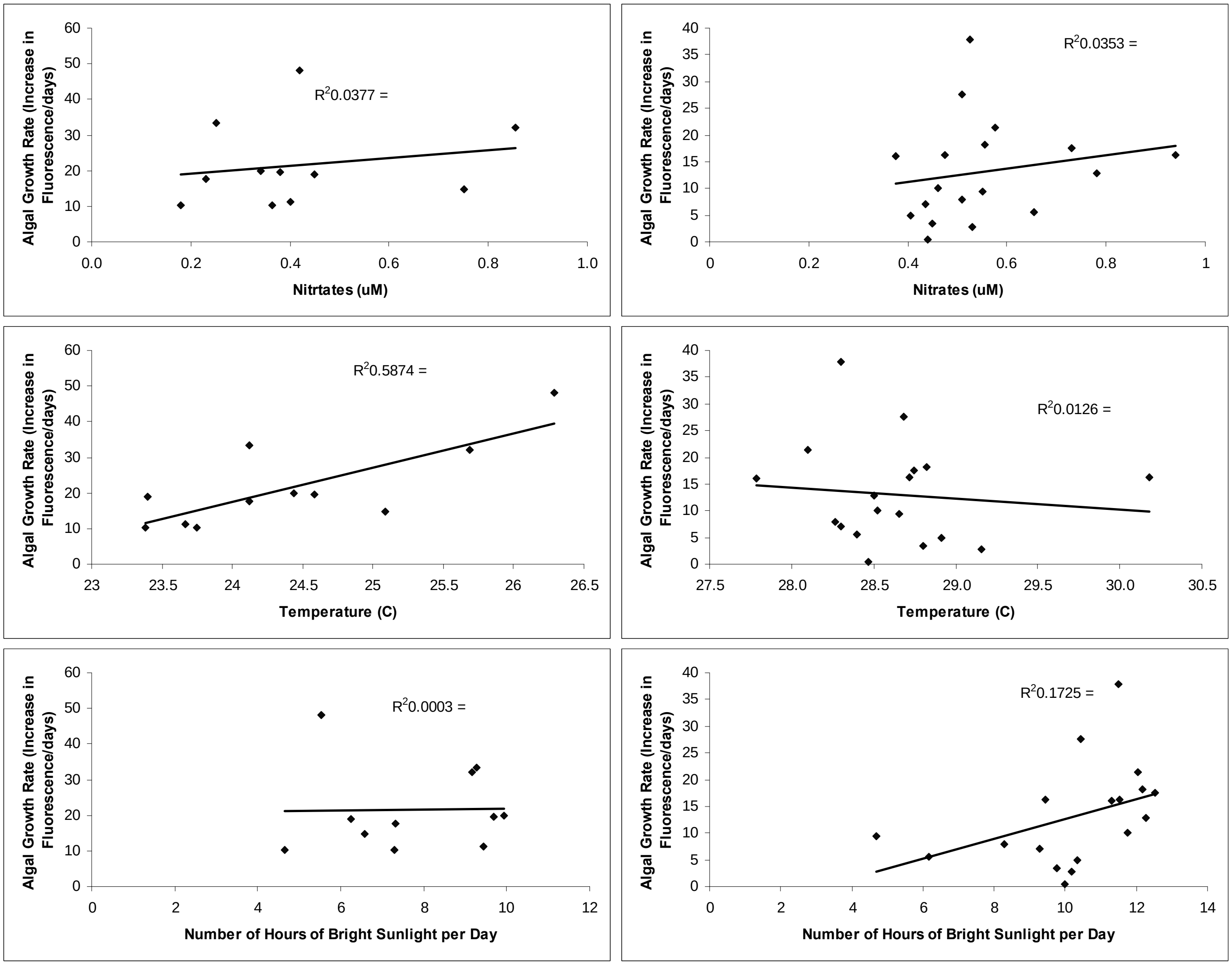

Figure 5.5: Correlations between algal growth rate and: nitrates (top (a)), T R² =0.0353 (middle (b)), and ı R² =0.0377 rs of bright sunlight (bottom (c)), for the first (left and second (right) periods.

Multiple regression analyses of the algal growth rates and the independent variables produced much better correlations than those produced when comparing algal growth to one variable alone. The regressions were made using the following quadratic equation:

$$G = p_1 L + p_2 T + p_3 N + p_4 L^2 + p_5 T^2 + p_6 N^2 + p_7 LTN$$

where G is the algal growth rate, L is the light level, T is the temperature, N the nitrate concentration and p_n are the coefficients. For the first period the model produced an R^2 of 0.76 and an adjusted R^2 of 0.20 (In cases where the number of independent variables are high compared to the sample size R^2 may be artificially high, adjusted R^2 compensates for this (Keller and Warrack 2003)). For the second period the R^2 value was 0.41 and an adjusted R^2 of 0.0004. The removal of the worst two data points for each period made a significant difference to the correlations. The first period then had an R^2 of 0.996 and an adjusted one of 0.970, while the second period had an R^2 of 0.87 and an adjusted value of 0.62. However, as the number of data points are small relative to the number of parameters a high value of R^2 is expected and even the adjusted R^2 value may not be able to compensate enough. Removing the three second order terms from the equation significantly reduced all the R^2 values.

Part of the data from the algal growth sensor and the turbidity sensor recorded at Middle Reef are shown in Figure 5.6, during this deployment the period between wipes was 2 days. The first 8 days, a period of relatively high turbidity, show little algal growth. During the remainder of the time series when algal growth does occur, the average gradient for this time is 11 arbitrary fluorescence units per day while for Reef HQ it was 14. However the variation in gradient is much higher with a factor of 10 between the smallest and largest slopes.

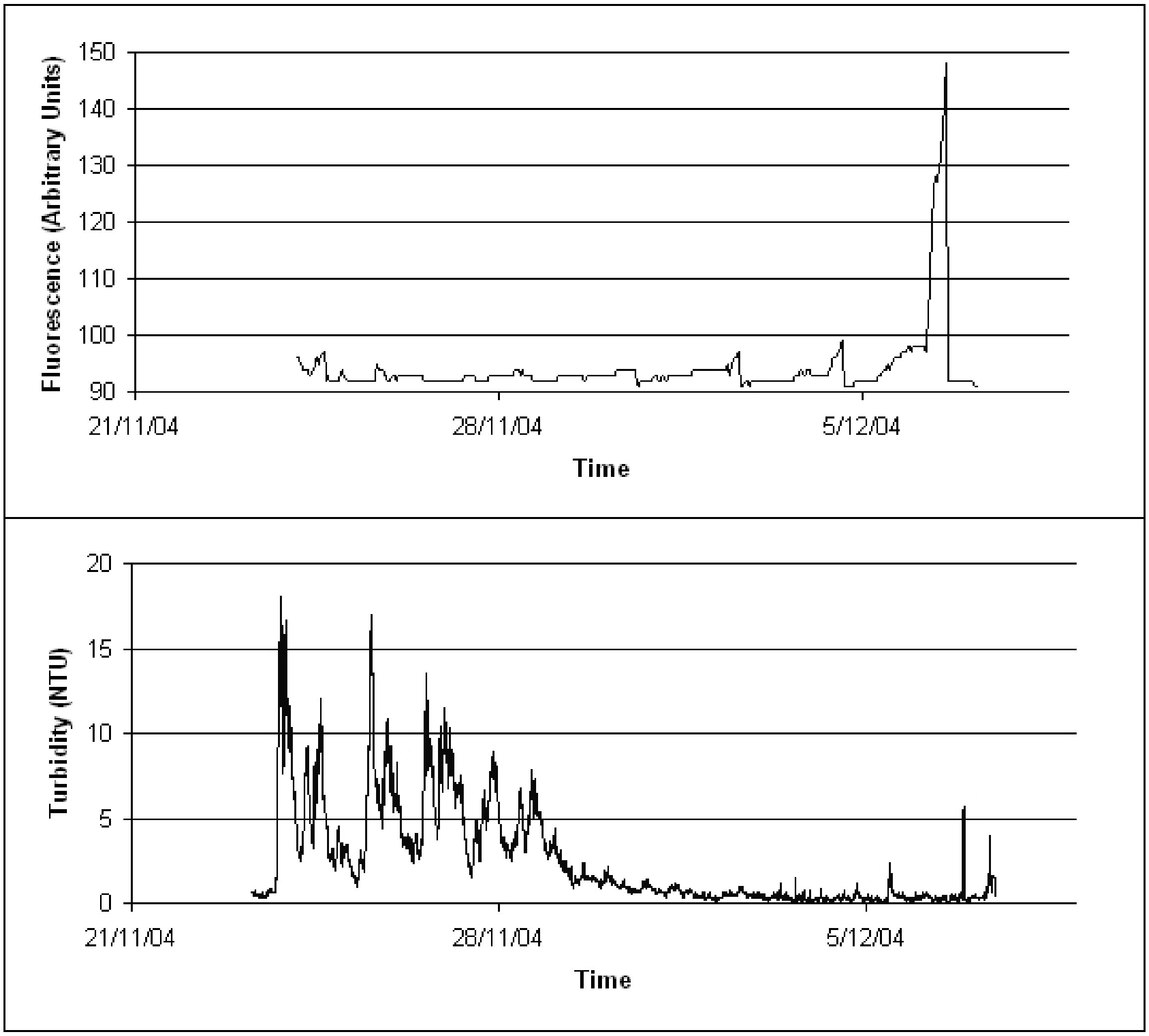

Figure 5.6: Algal growth (top (a)) and turbidity (bottom (b)) for Middle Reef.

Discussion

The data from the aquarium indicates a poor correlation between nutrient concentrations and algal growth; this could be due to a number of factors. Firstly the range of nutrient concentrations in the aquarium is small and the concentrations are low (nitrates varied from 0 to 1 μM where as a typical average nitrate concentration for a river supplying the Great Barrier Reef Lagoon is about 7 μM, but values can vary between 0 and about 25 μM). This could mean that the changes in nutrient concentration were too small for the sensor to pick up and that a greater range of concentrations could lead to a better correlation. Secondly measurements of nutrient concentrations were taken at irregular intervals with the period between each measurement varying from days to weeks. This meant that the measurements were not always taken often enough to pick up all the changes in nutrient concentrations over time or to see at exactly what time the changes occurred. This might lead to the sensor reacting to nutrient events that are not recorded, or to making it difficult to determine the lag between changes in nutrient concentrations and algal growth. Thirdly, as the light and temperature and multiple regression analyses show, the algal growth rate is not just dependent on nutrient concentrations. In fact growth correlated more strongly to temperature in the first period and to light in the second period than it did to nitrate concentrations. This indicates that nutrient concentration may not be the limiting factor for algal growth in the aquarium.

The relatively strong correlation between temperature and growth rate in the first period occurred during a time of relatively high temperature variation. Temperatures varied between 23 and 27 °C and it is possible that the lower range of recorded temperature limited algal growth, which would explain the strong correlation. During the second period the correlation between temperature and growth rate was very poor. The consistently high temperatures of around 28 °C during this period probably meant that temperature was not a controlling factor affecting growth rate change. Absence of major variations in this period also reduced the possibility for a good correlation. With temperature no longer a controlling factor in the second period changes in light levels seemed to have more effect on the algal growth rate.

The multiple regression analyses showed that a combination of nutrient concentrations, light levels, and temperature was needed to give a reasonable correlation with algal growth rate. Variations in R^2 values with the removal of the worst data points showed that with the small size of each data set any bad data could make a large difference to the result. Second order terms were required to model the diminishing effect of each variable as it reaches higher values. This corresponds with the idea that as the variable increases it is no longer the limiting factor for growth and so the other variables will become more significant. An improved model would use the concept of limiting factors further by preventing an increase in the growth rate while each variable remained below certain threshold values.

The diurnal pattern in the time series data is unlikely to be a result of chlorophyll saturation. Fluorescence yields are likely to be lower at higher light levels or low temperatures (Heinz Walz GmbH, 2002). However if the change in fluorescence was directly due to temperature or light variations it would be expected that the diurnal pattern would be centred on midday. Instead the troughs occur at 7:50 and the peaks at 19:50 neither of which are a peak or a trough for temperature or light levels. It is more likely that this variation in fluorescence is due to some kind of photo-chemical process occurring in the algae's chlorophyll. Other factors, like plankton migration are unlikely to be the cause since the layer of algae growing on the glass will dominate the fluorescence signal in comparison to more distant material.

The tests at Middle Reef showed that relatively high turbidity levels (more than about 10 NTU) reduced algal growth to almost zero. This is most likely due to the turbidity attenuating the light so that very little light reaches the seabed. So during this time series light appears to be the limiting factor for algal growth rather than nutrient concentrations.

The instrument's relationship with light levels at the seabed indicates that it would not be useful for measuring nutrient concentrations. Since growth of algae stops completely at low light levels, using a light sensor to adjust the results in an attempt to remove the effect of light levels from the data would not work. Therefore in order to measure nutrient concentration an algal growth sensor would require its own light source in a dark chamber so that light levels could be kept constant.

While the instrument is not useful for measuring nutrient concentrations it could be beneficial to use it to measure algal growth. As the tests indicate, the algae did not grow during times of high turbidity due to the limiting factor of light. Therefore while nutrient concentrations may have been high, little nutrient intake and growth took place. This indicated that nutrient concentrations alone may not be the best way of determining the risk to corals from algal growth. Periods of high turbidity were found to be detrimental to algal growth suggesting that a reef with high nutrient concentrations and high turbidity may not be the highest at risk from algal encroachment. Therefore the risk to corals from algal growth is probably better ascertained by directly measuring algal growth rather than nutrient concentrations.

Conclusions

Without control of light and other factors the instrument cannot be used to determine nutrient concentrations. Temperature and light were often more strongly correlated with algal growth than nitrate concentrations were. For example in the first deployment period temperature and growth had a linear correlation with an R^2 of 0.6 while nitrates and algal growth had an R^2 of 0.04.

Since variables like temperature and light can become limiting factors for growth it is not always possible to correct for their changes. For instance when turbidity exceeded 10 NTU at Middle Reef light levels became so low that almost no algal growth occurred. Therefore no measurement of nutrient levels would be possible during these low light level conditions with this method.

It may be useful to use this instrument to measure algal growth instead of nutrient concentration. Since algal growth is a more direct indicator of the threat of algal encroachment on corals than nutrient concentrations are.

High turbidity conditions lead to very low algal growth due to the reduction in light levels. This can be seen from the very small growth levels recorded when turbidity exceeded 10 NTU at Middle Reef.

Acknowledgements

We would like to thank the following people and organisations for their invaluable contribution to this paper: Severine Thomas, Reef HQ and the Australian Bureau of Meteorology.

References

Adey W. H., 1998. Coral reefs: Algal structured and mediated ecosystems in shallow, turbulent, alkaline waters. J Phycol 34, p393-406

Atkinson, M. J., 1988. Are coral reefs nutrient-limited? Proc 6th Int Coral Reef Symp 1 p157-166.

Bell, P.R. 1992. Eutrophication and coral reefs-some examples in the Great Barrier Reef lagoon. Water Research 26, p553-568.

Davison, W, Zhang, H., Grime, G.W., 1994. Performance characteristics of gel probes used for measuring pore waters. Environ Sci Tech 28, p1623–1632.

Dupont, L., 2003. Development of an In-Situ Fluorometer for the Study of Organic Materials on a Fringing Reef, Thesis, JCU.

Fabricius, K. E., Wolanski E., 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow, Est. Cos. Shelf Sci. 50, p115-120.

Ferrier-Pages, C., et al., 2000. Effect of Nutrient Enrichment on Growth and Photosynthesis of the Zooanthellate Coral Stylophora Pistillata, Coral Reefs 19, p103-113.

Hall. D. O., Rao, K. K., 1994. Photosynthesis Fifth Edition. Cambridge University Press: Cambridge.

Heinz Walz GmbH, 2002. PDA-100 PAM-Data Acquisition System for PAM-100 and E-PAM Fluorometer Instructions for Users. 2nd Edition, Heinz Walz GmbH.

Keller, G., Warrack, B., 2003 Statistics for Management and Economics. Thomson Brooks/Cole.

Krom, M .D., Davison, P., Zhang, H., Davison, W., 1994 High resolution pore water sampling with a gel sampler. Limnol Oceanogr 39, p1967–1973.

Lapointe, B.E., 1997. Nutrient thresholds for eutrophication and macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42, p1119-1131.

Larned, S.T., Atkinson, M.J. 1997. Effects of water velocity on NH4 and PO4 uptake and nutrient-limited growth in the macroalga Dictyosphaeria cavernosa. Mar Ecol Prog Ser 157 p295-302

Littler, M. M., Littler, D. S., 1984. Models of Tropical Reef Biogenesis: The Contribution of Algae, Prog. Phycol. Res. 3, p323-363.

McCook L.J., 1996. Effects of herbivores and water quality on the distribution of Sargassum on the central Great Barrier Reef: cross-shelf transplants. Mar Ecol Prog Ser 139, p179-192

McCook L.J., 1997. Effects of herbivory on zonation of Sargassum within fringing reefs of the central Great Barrier Reef. Mar Biol 129, p713-722.

Mortimer, R. J. G., Krom, M. D., Hall, P. O. J., Hulth, S., Stahl, H., 1998. Use of gel probes for the determination of high resolution solute distributions in marine and estuarine pore waters. Mar Chem 63, p119–129.

Ridd, P. V., Larcombe, P. 1994. Biofouling Control of Optical Backscatter Suspended Sediment sensors. Mar. Geol. 116, 255-258.

Russ, G.R. and McCook, L.J., 1999. Potential effects of a cyclone on benthic algal production and yield to grazers on coral reefs across the central Great Barrier Reef. J Exp Mar Biol Ecol 235, p237-254.

Schaffelke, B. & Klumpp, D. W., 1997b. Biomass and productivity of tropical macroalgae on nearshore fringing reefs in the Central Great Barrier Reef, Australia. Botanica Marina 40, p373-383.

Schaffelke, B. and Klumpp, D. W., 1998a. Nutrient-limited growth of the coral reef macroalga Sargassum baccularia and experimental growth enhancement by nutrient addition in continuous flow culture. Mar. Ecol. Prog. Ser. 164 p199-211.

Schaffelke, B. & Klumpp, D. W., 1998b. Short-term nutrient pulses enhance growth and photosynthesis of the coral reef macroalga Sargassum baccularia. Mar. Ecol. Prog. Ser. 170 p95-105.

Scott, F.J., Russ, G.R., 1987. Effects of grazing on species composition of the epilithic algal community on coral reefs of the central Great Barrier Reef. Mar Ecol Prog Ser 39, p293-304.

Turnewitsch, R., Graf, G. 2003. Variability of particulate seawater properties related to bottom mixed layer-associated internal waves in shallow water on a time scale of hours. Limnology and Oceanography, 48(3), 1254-1264.

6 - Conclusions

This thesis focused on the physical conditions experienced by nearshore, high turbid marginal reefs with a particular emphasis on the fringing reefs close to the mouth of the Tully River. It is possible that these reefs are amongst the most at-risks ecosystems of the Great Barrier Reef lagoon due to anthropogenic pollution derived from agriculture.

Measurements near the Tully River indicated that discharge from the Tully River did not have a major direct influence on turbidity and fluorescence on nearby fringing reefs. At Lugger Bay, resuspension of sediments produced SSC values that were elevated above 200 mg/l for 28% of the time and peak SSC values of over 1000 mg/l, which is significantly higher than the peak SSC measured by Furnas within the river (230 mg/l). SSC due to river plumes were very hard to detect due to the very large SSC values that naturally occur on this reef.

Fluorescence measurements at Lugger Bay also indicated that the direct influence of the Tully River was difficult to detect. High fluorescence values occurred during periods of wave resuspension, some of which occurred simultaneously with river discharge. A clear increase in fluorescence during river discharge, due to the effect of nutrients released in the river plume, was not detected. The ratio of fluorescence to SSC in Lugger Bay was similar during discharge and non-discharge events also indicating that the effect of nutrient discharge on fluorescence was small.

These results show that measurement of direct negative effects of the Tully River, over Lugger Bay Reef if any, remain elusive. Considering that the reefs adjacent to the Tully are very close to the river mouth, it is interesting to observe so little measurable impact of river plumes. This finding is contrary to the conventional wisdom that river discharge is causing serious and easily measurable damage to the GBR.

There is a common misconception that corals are clean water organisms that are very sensitive to suspended sediment. This work shows that corals can live under extreme conditions of water turbidity and low light levels. In the case of Lugger Bay, it was found that total light extinction occurred for periods of 1 to 2 weeks during rough weather events. Although Lugger Bay Reef is clearly a very marginal ecosystem dominated by only 1 species of coral, it appears healthy and has over 57% coral cover.

Sediment cores taken from Lugger Bay indicate that this reef formed very recently, 4,000 years ago. The recent formation of the reef highlights the changing form of reefs, some are being formed, and some presumably are being destroyed by changing conditions.

A semi-empirical model was developed to predict SSC for coral reefs. The primary use of the model was motivated by environmental monitoring work that is associated with dredging or harbour construction that is occasionally sited close to fringing coral reefs. Because the use of control sites for environmental monitoring is difficult due to very high spatial variability, an alternative approach is to compare potentially elevated SSC values due to marine work with the values of SSC that would have been expected in the absence of marine work.

To investigate a potentially better method for measuring an indication of nutrient concentrations a new instrument was developed. This instrument uses algal growth as a surrogate for nutrient concentrations. It was found that without control of such parameters as light and temperature the readings did not correlate well enough to nutrient concentrations to be useful. However, the instrument could be useful to help identify whether algal encroachment is a threat to a particular reef.

SSC and Fluorescence Throughout the Region

Discharges from the Tully River do not appear to have a major affect on the reef in Lugger Bay. This is indicated by the fact that SSC on Lugger Bay Reef are higher on average than those in the Tully River. Also the ratio between fluorescence and SSC does not change during river discharge events suggesting that the river is not introducing higher concentrations of nutrients to the reef.

There is a relationship between SSC and fluorescence that is site specific. The relationship tends to be linear for low SSC but at high SSC fluorescence saturates, which indicates that organic material become less abundant relative to SSC during high SSC events, suggesting that more inorganic than organic sediments are stirred up during resuspension events.

Changes in Tully River discharge did not significantly affect the relationship between fluorescence and SSC. This suggests that either high river discharge events such as river plumes did not carry an increased concentration of nutrients relative to SSC, or that such events did not reach Lugger Bay Reef 8 km to the north of the river.

SSC in the Tully River was low relative to that on Lugger Bay Reef. The Tully River has a wet season average of 23 mg/l and a maximum of 230 mg/l (Furnas 2003) while the average for Lugger Bay was 185 mg/l. This indicates that resuspension is more significant a cause of SSC for the reef than river discharge.

The combined sediment inputs of the Tully and Murray Rivers (170, 000 tonnes per year) is low compared with a potential of 630, 000 tonnes net transport through the region per year. It is therefore possible that there are sediment inputs from outside the region.

All these findings lead to the conclusion that the Tully River does not have a significant impact on the SSC and nutrient concentrations on Lugger Bay Reef and that wave resuspension is the dominant driving force behind SSC at this location

Lugger Bay Reef

SSC recorded on Lugger Bay Reef are high with the measurements exceeding 200 mg/l for 28% of the time. High SSC events can also last for several days and sometimes weeks. Light extinction events are also common, occurring on 49% of the days when light was recorded.

The reef itself has reasonable coral cover (about 57%). Algal encroachment is minimal with only 12% of the coral covered by algae. Coral species biodiversity is very low with less than 10 species recorded and 85% of all the area covered by coral was covered by just one species of *porites*. The reef is probably less than about 4000 years old.

SSC Prediction

The SSC prediction model achieved some degree of success, the level of which depended on what evaluation method was used. All but the model for Bedarra Island could predict the correct tercile over 50% of the time. The models for sites where the program generated unphysical parameters, like Nelly Bay and Thorpe Island, tended to perform poorly although not as badly as expected. The quality of the wind data used for each site did make some difference. Parameters at sites with relevant wind data tended to be more physically realistic, for example those at the Port Douglas sites, which in most tests performed well compared to the other sites, however this was not the case for all tests.

Considering the complexities involved in predicting SSC including the large temporal and spatial variations in SSC and the elaborate dynamics and topography, the model showed a useful degree of predictability. It is especially useful because it does not require the collection of any data other than wind to produce results. The fact that it was able to model a significant amount of the variation in SSC using just the wind data indicates that resuspension is a major factor in generating SSC.

Algal Growth Sensor

An algal growth sensor without control over factors such as light, temperature and algae type is not a good tool for measuring nutrient concentrations as too much of the variability in growth is due to these other factors. For example during one of the periods the instrument was deployed in the aquarium the correlation between growth and nitrates only had an R^2 value of 0.04 while the correlation with temperature gave an R^2 value of 0.6. Also tests at Middle Reef showed that when turbidity exceeded 10 NTU little growth was recorded, most likely due to an extinction of light on the seabed. The instrument does however have the potential to be useful for measuring algal growth and so be able to help determine the level of threat from algal encroachment. Raised turbidity conditions can lead to very low levels of algal growth, indicating that SSC has a detrimental effect on algae as well as other marine organisms.

Overview

The findings indicate that inshore reefs close to river mouths in the GBRL such as the one in Lugger Bay are exposed to high SSC, but generally from resuspension events rather than as a result of river discharge. Nutrient impacts from the river also appear to be minimal, suggesting that for rivers with relatively low nutrient concentrations and SSC, nutrient concentrations rapidly drop with distance from the river mouth. As expected biodiversity on these reefs will be low but the species inhabiting them are well adjusted to high sediment conditions. Even with the higher nutrient concentrations found on inshore reefs, algae does not appear to dominate. This could in part be due to high SSC and low light levels being detrimental to the algae as well as the corals, while some of the corals have the advantage of being able to use some of the suspended organic particles as a food source.

7 - Future Work

More study could be undertaken to develop a prediction model for SSC using wave height. This would be much more accurate than using wind data as all variations in wave generation by the wind would be removed. It would however require the development of SSC and wave loggers so that wave data could be gathered for each site.

A more thorough testing of the algal growth sensor including long deployments on reefs. The instrument would be deployed with SSC, fluorescence, light and temperature sensors to see how the growth rate related to all these factors. The instrument should also be tested in a laboratory to determine a calibration between the dry weight of algae growing on the glass plate and the fluorescence reading.

Further study of river plumes from the Tully River would be useful to discover more precisely the SSC in a typical plume, how far they spread and whether resuspension events during the same period are of similar magnitudes. This would be done by means of aerial photographs, water bottle sampling and with SSC measurements taken from a boat.

8 – Glossary

Fluorescence – the emission of radiation due to stimulation by the absorption of incident light.

GBRL – Great Barrier Reef Lagoon.

Marginal - used in a broad sense, to describe settings where coral communities or framework reefs occur either close to well-understood (or strongly perceived) environmental thresholds for coral survival (sensu Kleypas et al. 1999).

SSC – Suspended Sediment Concentration, measured in mg/l.

9 - References

Adey W. H., 1998. Coral reefs: Algal structured and mediated ecosystems in shallow, turbulent, alkaline waters. J Phycol 34, p393-406.

Atkinson, M. J., 1988. Are coral reefs nutrient-limited? Proc 6th Int Coral Reef Symp 1 p157-166.

Alcock, D., 1995. 1920s Research Sheds Light on a Potential Coral Reef Calamity. GEO Australia 17, p100-108.

Anthony, K. R. N., 2000. Enhanced Particle-Feeding Capacity of Corals on Turbid Reefs (Great Barrier Reef, Australia). Coral Reefs 19, p59-67.

Anthony, K. R. N., Fabricius, K. E., 2000. Shifting roles of Heterotrophy and Autorophy in Coral Energy Budgets at Varying Turbidity, J Exp. Mar. Biol. Ecol. 252, p221-253.

Anthony, K.R.N., Ridd, P.V., Orpin, A.R, Lough, J., Larcombe, P., 2004. Temporal Variation in Light Availability for Benthos in Coastal Marine Habitats: Effects of Cloud Cover, Turbidity and Tides. Limnology and Oceanography, p2201-2211.

Anthony, K. R. N., 2006. Enhanced Energy Status of Corals on Coastal, High-Turbidity Reefs. Mar Ecol Prog Ser 319, p111-116.

Bell, P.R. 1992. Eutrophication and coral reefs-some examples in the Great Barrier Reef lagoon. Water Research 26, p553-568.

Belperio, A. P., 1983. Terrigenous Sedimentation in the Great Barrier Reef Lagoon: A Model from the Burdekin Region, BMR Jour. Of Aust. Geol. And Geophysics 8, p179-190.

Birkeland, C., Lucas, J.S., 1990. Acanthaster planci: major management problem of coral reefs. CRC Press, Boca Raton LA, p257.

Brodie, J., 1996. River Flood Plumes in the Great Barrier Reef Lagoon, In Larcombe, P., Woolfe, K., Purdon, R. G. (eds), Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts, CRC Reef Research Centre, Research Symp. Proc., Townsville, p33-39.

Brodie, J., Furnas, M. J., 1996. Cyclones, River Flood Plumes and Natural Water Quality Extremes in the Central Great Barrier Reef., In: Hunter H. M., et al. (eds), Downstream Effects of Land Use, Department of Natural Resources, Brisbane..

Carpenter, R.C., 1988. Mass mortality of a Caribbean sea urchin: Immediate effects on community metabolism and other herbivores. Proc Natl Acad Sci 85, p511-514.

Davison, W, Zhang, H., Grime, G.W., 1994. Performance characteristics of gel probes used for measuring pore waters. Environ Sci Tech 28, p1623–1632.

Done, T., 1982. Patterns in Distribution of Corals Communities Across the Central Great Barrier Reef, Coral Reefs 1, p201-209.

Devlin, M. J. & Brodie, J., 2005. Terrestrial discharge into the Great Barrier Reef lagoon: nutrient behaviour in coastal waters. Marine Pollution Bulletin 51, 9-22.

Dupont, L., 2003. Development of an In-Situ Fluorometer for the Study of Organic Materials on a Fringing Reef, Thesis, JCU.

Fabricius, K. E., Wolanski E., 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow, Est. Cos. Shelf Sci. 50, p115-120.

Fabricius, K. E., Wild, C., Wolanski, E., Abele, D., 2003. Effects of Transparent Exopolymer Particles and Muddy Terrigenous Sediments on the Survival of Hard Coral Recruits. Estuarine, Coastal and Shelf Science, 57, Number 4, p613-621.

Ferrier-Pages, C., et al., 2000. Effect of Nutrient Enrichment on Growth and Photosynthesis of the Zooanthellate Coral Stylophora Pistillata, Coral Reefs 19, p103-113.

Furnas, M., 2003. Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef, AIMS and CRC Reef Research Centre.

Furnas, M., Mitchell, A. W., Skuza, M., 1996. Nitrogen and Phosphorus Budgets for the Central Great Barrier Reef Shelf, A Report to the Great Barrier Reef Marine Park Authority, Research Publication No. 36.

Gagan, M. K., Chivas, A. R., Herczeg, A. L., 1990. Shelf-Wide Erosion, Deposition, and Suspended Sediment Transport During Cyclone Winifred, Central Great Barrier Reef. Journal of Sedimentary Petrology 60, p456-470.

Grant, W. D., Madsen, O. S. 1979. Combined Wave and Current Interaction with a Rough Bottom. J. Geophys. Res. 84(C4), 1797-1808.

Gröen, P., Dorrestein, R. 1976. Zeegolven. KNMI Opstellen op Oceanografisch en Maritiem Meteorologisch Gebied, 11, 124.

Gilmour, J., 1999. Experimental Investigation into the Effects of Suspended Sediment on Fertilisation, Larval Survival and Settlement in a Scleractinian Coral, Mar. Bio. 135, p451-462.

Hall. D. O., Rao, K. K., 1994. Photosynthesis Fifth Edition. Cambridge University Press: Cambridge.

Hatcher, B.G., 1997. Organic production and decomposition. In: Birkeland C (Ed) Life and death of coral reefs. Chapman & Hall, New York, pp 140-174.

Heinz Walz GmbH, 2002. PDA-100 PAM-Data Acquisition System for PAM-100 and E-PAM Fluorometer Instructions for Users. 2nd Edition, Heinz Walz GmbH.

Hopley, D., 1982. Geomorphology of the Great Barrier Reef: Quaternary Development of Coral Reefs. New York: John Wiley-Interscience, 453p.

Hopley, D.; Slocombe, A.; Muir, F., and Grant, C., 1983. Nearshore fringing reefs in North Queensland. Coral Reefs, 1, 151–160.

Isdale, P., 1984. Fluorescent Bands in Massive Corals Record Centuries of Coastal Rainfall. Nature 310, p578-579.

Jeffrey, S. W., ET al., 1997. Phytoplankton Pigments in Oceanography, United Nations Educational: Paris.

Johnson, D.P., and Searle, D.E., 1984. Post-glacial seismic stratigraphy, central Great Barrier Reef, Australia. Sedimentology 31, p335-352.

Johnson, D. and Risk, M.J., 1987. Fringing reef growth on a terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia. Sedimentology, 34, 275–287.

Kleypas J.A., McManus J.W., Meñez .LA.B., 1999. Environmental limits to coral reef development: where do we draw the line? Am Zool 39, p146–159

Keller, G., Warrack, B., 2003 Statistics for Management and Economics. Thomson Brooks/Cole.

Krom, M.D., Davison, P., Zhang, H., Davison, W., 1994 High resolution pore water sampling with a gel sampler. Limnol Oceanogr 39, p1967–1973.

Lapointe, B.E., 1997. Nutrient thresholds for eutrophication and macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42, p1119-1131.

Larcombe, P., Ridd, P.V., Prytz, A., and Wilson, B., 1995. Factors controlling suspended sediment on the inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14, p163-171.

Larcombe, P., Woolfe, K. J., Purdon, R. G., (Eds), 1996. Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts. Second Edition. CRC Reef Research Centre, Research Symposium Proceedings: Townsville, Australia.

Larcombe, P., Woolfe, K. J., 1999. Increased Sediment Supply to the Great Barrier Reef will not Increase Sediment Accumulation at Most Coral Reefs, Coral Reefs 18, p163-169.

Larcombe, P., Woolfe, K. J., 1999a. Terrigenous Sediments as Influences upon Holocene Nearshore Coral Reefs, Central Great Barrier Reef, Australia. Australian Journal of Earth Sciences 46, p141-154.

Larcombe, P., Costen A., and Woolfe, K.J., 2001. The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48, p811-836.

Larcombe, P., Carter, R. M., 2004. Cyclone Pumping, Sediment Partitioning and the development of the Great Barrier Reef Shelf System: A Review. Quaternary Science Reviews 23, p107-135.

Lagarias, J.C., Reeds, J. A., Wright, M. H., Wright, P. E. 1998. Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions. SIAM Journal of Optimization, Vol. 9 Number 1, 112-147.

Larned, S.T., Atkinson, M.J. 1997. Effects of water velocity on NH4 and PO4 uptake and nutrient-limited growth in the macroalga Dictyosphaeria cavernosa. Mar Ecol Prog Ser 157 p295-302.

Littler, M. M., Littler, D. S., 1984. Models of Tropical Reef Biogenesis: The Contribution of Algae, Prog. Phycol. Res. 3, p323-363.

Lou, J., Ridd, P. V., 1996. Wave-Current Bottom Shear Stresses and Sediment Resuspension in Cleveland Bay, Australia. Coastal Eng. 29, 169-186.

Lou, J., Ridd, P. V., 1998. Reply to Comments by J. P. Xu regarding "Wave-Current Bottom Shear Stresses and Sediment Resuspension in Cleveland Bay, Australia". Coastal Eng. 33, 65-67.

Marshall, S. M., Orr, A. P., 1931. Scientific Report of the Great Barrier Reef Expedition 1, p94.

Maxwell, W. G. H., 1968. 'Atlas of the Great Barrier Reef.' (Elsevier: Amsterdam.).

McCook L.J., 1996. Effects of herbivores and water quality on the distribution of Sargassum on the central Great Barrier Reef: cross-shelf transplants. Mar Ecol Prog Ser 139, p179-192.

McCook L.J., 1997. Effects of herbivory on zonation of Sargassum within fringing reefs of the central Great Barrier Reef. Mar Biol 129, p713-722.

McCook, L. J., 1999. Macroalgae, Nutrients and Phase Shifts on Coral Reefs: Scientific Issues and Management Consequences for the Great Barrier Reef, Coral Reefs 18, p357-367.

Mortimer, R. J. G., Krom, M. D., Hall, P. O. J., Hulth, S., Stahl, H., 1998. Use of gel probes for the determination of high resolution solute distributions in marine and estuarine pore waters. Mar Chem 63, p119–129.

Moss, A. J., et al., 1992. A Preliminary Assessment of Sediment and Nutrient Exports from Queensland Coastal Catchments, Queensland Department of Environment and Heritage Technical Report No. 4, Brisbane.

Neil, D. T., Orpin, A. R., Ridd, P. V., Yu, B., 2002. Sediment Yield and Impacts from River Catchments to the Great Barrier Reef Lagoon. Marine and Freshwater Research 53, p733-752.

Orpin, A.R., Ridd, P.V. and Stewart, L.K., 1999. Assessment of the relative importance of major sediment transport mechanisms in the central Great Barrier Reef lagoon. Australian Journal of Earth Sciences 46, p883-896.

Orpin, A. R., Ridd, P. V., Thomas, S., Anthony, R. N., Marshall, P., Oliver, J. 2004. Natural Turbidity Variability and Weather Forecasts in risk Management of Anthropogenic Sediment Discharge Near Sensitive Environments. Marine Pollution Bulletin 49, 602-612.

Perry, A., Smithers, S. G., 2006. Taphonomic signatures of turbid-zone reef development: Examples from Paluma Shoals and Lugger Shoal, inshore central Great Barrier Reef, Australia. Palaeo 242, p1-20.

Pringle, A.W., 1986. Causes and Effects of Changes in Fluvial Sediment Yield to the North-East Queensland Coast, Australia: Townsville, James Cook University.

Ridd, P. V., Larcombe, P. 1994. Biofouling Control of Optical Backscatter Suspended Sediment sensors. Mar. Geol. 116, 255-258.

Riegl, B., 2003. Climate change and coral reefs: different effects in two high-latitude areas (Arabian Gulf, South Africa). Coral Reefs 22, p433–446.

Russ, G.R. and McCook, L.J., 1999. Potential effects of a cyclone on benthic algal production and yield to grazers on coral reefs across the central Great Barrier Reef. J Exp Mar Biol Ecol 235, p237-254.

Schaffelke, B. & Klumpp, D. W., 1997b. Biomass and productivity of tropical macroalgae on nearshore fringing reefs in the Central Great Barrier Reef, Australia. Botanica Marina 40, p373-383.

Schaffelke, B. and Klumpp, D. W., 1998a. Nutrient-limited growth of the coral reef macroalga Sargassum baccularia and experimental growth enhancement by nutrient addition in continuous flow culture. Mar. Ecol. Prog. Ser. 164 p199-211.

Schaffelke, B. & Klumpp, D. W., 1998b. Short-term nutrient pulses enhance growth and photosynthesis of the coral reef macroalga Sargassum baccularia. Mar. Ecol. Prog. Ser. 170 p95-105.

Scott, F.J., Russ, G.R., 1987. Effects of grazing on species composition of the epilithic algal community on coral reefs of the central Great Barrier Reef. Mar Ecol Prog Ser 39, p293-304.

Smith, S. V., et al., 1981. Kanhoe Bay Sewage Diversion Experiment: Perspectives on Ecosystem Responses to Nutritional Perturbation, Pac. Sci 35, p270-395.

Smithers, S. and Larcombe, P., 2003. Late Holocene initiation and growth of a nearshore turbid-zone coral reef: Paluma Shoals, Central Great Barrier Reef, Australia. Coral Reefs, 22, 499–505.

Stafford-Smith M. G., 1993. Sediment-Rejection Efficiency of 22 Species of Australian Scleractinian Corals, Mar. Bio 115, p229-243.

Taylor, J., 1996. Sediment Input to the Great Barrier Reef Lagoon via River Discharge: the Barron River, In Larcombe, P., Woolfe, K., Purdon, R. G. (eds), Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts, CRC Reef Research Centre, Research Symp. Proc., Townsville, p152-154.

Turnewitsch, R., Graf, G. 2003. Variability of particulate seawater properties related to bottom mixed layer-associated internal waves in shallow water on a time scale of hours. Limnology and Oceanography, 48(3), 1254-1264.

Wasson, R. J., 1997. Run-Off From the Land to the Rivers and the Sea. In 'The Great Barrier Reef, Science, Use and Management. Proceedings of a National

Conference'. P23-41 (Great Barrier Reef Marine Park Authority: Townsville, Australia).

Williams, D., 2001. Impacts of Terrestrial Run-off on the Great Barrier Reef World Heritage Area, AIMS.

Wolanski, E., van Senden, D., 1983. Mixing of Burdekin River Flood Waters in the Great Barrier Reef. Australian Journal of Marine and Freshwater Research 34, p49-64.

Wolanski, E., 1994. Physical Oceanographic Processes of the Great Barrier Reef, CRC Press, Boca Raton, p194.

Woolfe, K. J., Larcombe, P., 1998. Terrigenous Sediment Accumulation as a Regional Control on the Distribution of Reef Carbonates. Special Publications of the International Association of Sedimentologists 25, p295-310.

Woolfe, K. J., Larcombe, P., 1999. Terrigenous Sedimentation and Coral Reef Growth: a Conceptual Framework. Marine Geology 155, p331-345.

World Meteorological Organization. 1998. Guide to Wave Analysis and Forecasting, 2nd edition.

Wright, L. D., Boon, J. D., Kim, S.C., List, J. H. 1991. Modes of Cross-Shore Sediment Transport on the Shoreface of the Middle Atlantic Bight, Mar. Geol. 96, 19-51.

Zann, L. (Ed), 1995. Our Sea, Our Future: Major Findings of The State of the Marine Environment Report for Australia. Ocean Rescue 2000, Department of Environment, Sport and Territories: Canberra, Australia.