CHAPTER 5

CONCLUSIONS

5.1. MAJOR FINDINGS OF THE PRESENT STUDY

5.1.1. Research question 1: Is satellite remote sensing suitable for studying flood plumes?

The immediate answer to this question would probably be negative, because of the intensified cloud formation associated with flood-generating weather systems (e.g. tropical cyclones) on the one hand, and the inability of ocean colour sensors to "see" through clouds on the other. For the seven wet seasons covered by the SeaWiFS data, only 15 images of Lucinda coastal waters had reasonably cloud-free coverage within fortnights centred on flood events in the Herbert River. Of those, a single series of four good-quality images in February 1999 allowed monitoring of the dynamics of a flood-induced plume in the coastal ocean using SeaWiFS data (section 3.3). Within that series the first available image after the flood peak was 5 days after the maximum discharge. Therefore during the initial phases of a flood, cloud-free satellite images are lucky exceptions rather than expected phenomena.

On the other hand, the maximum spread of a flood-generated river plume in coastal waters is expected several days after the event, due to the hydrodynamic constraints of mixing between floodwaters and seawater. According to the results of the regional hydrodynamic model for February 1999 (Shigeru Tabeta, unpublished data), approximately 5 days is required for a low-salinity plume created by a flood in the Herbert River to reach its maximal spatial expanse. Similar time scales were observed for a turbidity plume during the February 2004 field trip (section 3.1.3). Since flood-generating mechanisms are highly dynamic weather formations and hence are unlikely to stay over a region for a considerable period of time, cloud-free satellite images are expected 4-5 days after the initiation of a flood, which is also the expected time for the furthest dispersal of elevated concentrations of terrigenous substances carried by flood-affected coastal waters. Indeed, for the available SeaWiFS dataset, six images of the Lucinda region with some cloud-free areas and within 5 days after the peak discharge were available for 6 out of 7 years.

Overall, *ocean colour remote sensing is not a reliable tool for studying the dynamics of flood-induced plumes in the coastal ocean during the initial phases of floods due to cloud cover over the area associated with cyclones. However, this technology is suitable for such studies in the aftermath of a cyclone*.

5.1.2. Research question 2: Can SeaWiFS be used in coastal waters?

SeaWiFS algorithms were originally designed for clear open ocean waters. When SeaWiFs is applied to significantly more optically complex coastal waters, the two main issues of ocean colour remote sensing needed to be addressed, namely (i) relationships between water leaving radiance and water properties and (ii) atmospheric correction.

To address the first issue, an inverse bio-optical model of the Lucinda region was constructed. The model determines concentrations of water-colouring substances such as chlorophyll (CHL), total suspended sediments (TSS), and coloured dissolved organic matter (CDOM) as well as the values of optical parameters from SeaWiFS-derived water leaving radiances. The model was validated using the in situ dataset of water-colouring constituents collected in the area in 2002-2004. To the author's knowledge, this is the first application of the SeaWiFS data to simultaneous retrieval with successful in situ validation of the three optically significant substances in case II waters. At the same time, due to the optical dominance of CDOM and non-chlorophyllous sediments in the surface waters of the region, better CHL retrievals were achieved by expressing its concentration as a function of dissolved matter absorption (section 3.2.4).

To deal with the atmospheric issue, the SeaWiFS algorithms were modified in the present study to allow for relaxation of the black pixel assumption. This was achieved by adopting the nearest neighbour method of Hu, Carder et al. (2000), which transfers the aerosol type over clear waters to adjacent turbid water pixels. As a result, both aerosol and water signals in the near infrared spectral region are derived, which are then extrapolated in the visible spectrum using SeaWiFS default algorithms. The application of the modified atmospheric correction procedure to validation data resulted in substantially more accurate retrieval of water-colouring constituents from the SeaWiFS data than under the "black pixel" assumption (section 3.2.4).

Overall, *SeaWiFS can be used in coastal waters with appropriate considerations for atmospheric correction and water complexity.*

5.1.3. Research question 3: What is the fate of biogeochemical substances of Herbert River plumes in the coastal ocean?

Biogeochemical substances such as CHL, suspended sediments and CDOM exhibit distributions created by a variety of chemical, biological and geophysical processes and interactions. Once discharged into the coastal ocean by a river, a plume of freshwater and associated terrestrial matter is subject to mixing with ambient waters. Were hydrodynamics the only driving force, this process would result in conservative behaviour of substances, similar to that observed for temperature and salinity. However, because of the contribution of other independent and interdependent processes, the dynamic patterns of the water-colouring constituents studied are strongly non-conservative.

Individual pathways that characterise each of the substances include settling by gravity and resuspension of suspended sediments, and photodegradation and salinity-induced chemical transformations of CDOM. These processes act independently on targeted properties and can become prevailing driving forces behind observed distributions under favourable conditions. Study of the flood-mediated sediment transport in the Herbert River and coastal ocean in February 2004 showed that the bulk of suspended sediments exported from the river were quickly deposited upon entering the coastal ocean (section 4.1). A plume of high TSS that developed in the aftermath of the major Herbert River flood in 1999 rapidly reduced in concentration as soon as the rate of the river flow decreased, most probably due to gravitational settling of particles (section 3.3). These examples demonstrate the significance of the settling process for the dynamics of suspended sediment in flood-affected environments. The low association of TSS with other optically significant constituents in shallow waters of the region (section 3.1.3) further supports the notion of the independence of suspended sediment dynamic pathways in Lucinda waters.

Yet another type of process affecting biogeochemical substances in natural aquatic environments is interactions between them. Phytoplankton starts to proliferate with a concurrent rapid increase in CHL concentration and decrease in inorganic nutrient stocks as soon as optimal conditions for its growth (i.e. adequate nutrient and light levels) are achieved. However, upon depletion of available nutrients the growth is halted and the phytoplankton bloom gradually dies off. Therefore, the extent and the very existence of phytoplankton are constrained by the presence of nutrients (in dissolved or nutrient-rich particulate form) brought by river plumes or resuspended from the bottom. This assertion is supported by the highly correlated behaviour of CHL, CDOM and TSS in Lucinda offshore waters, away from shallow areas prone to resuspension (section 3.1.3). At the same time, the tight association between CHL and CDOM suggests that phytoplankton acts as a significant immediate source of CDOM in Lucinda waters.

Overall, *the major factors controlling the distribution of biogeochemical substances in Herbert River plumes in the coastal ocean are gravitational settling of suspended sediments,* *remineralisation and production of dissolved organic matter by marine organisms, and availability of adequate nutrient levels for phytoplankton development*.

5.1.4. Research question 4: Do riverine sediments and nutrients reach coral reefs?

In the present study two flood events in the Herbert River (February 1999 and February 2004) were monitored, while the resultant plumes in the adjacent coastal ocean were mapped using satellite ocean colour, aerial photography and in situ measurements. These efforts facilitated assessment of the spatial extent of flood-induced plumes relative to the location of adjacent mid-shelf coral reefs.

The ocean colour remote sensing technique developed in the present work allowed study of the remotely sensed fluxes of particulate and dissolved organic and inorganic matter following a major flood event in the vicinity of the Herbert River during the austral summer of 1999. The observed evolution of the plumes produced by each of the geophysical substances suggests that even under favourable conditions for across-shelf plume dispersal, none of the plumes managed to carry harmful amounts of nutrient or sediment to mid-shelf reefs (section 3.3).

The comprehensive field expedition in February 2004 captured a moderate flood in the Herbert River, which was caused by a tropical cyclone. In situ measurements and aerial mapping techniques were employed to monitor the resultant plumes in Lucinda coastal waters. The maximal extent of the flood-affected waters was observed 5 days after the peak river discharge as a visible plume with a frontline located halfway between the mainland and the closest mid-shelf reef. At the same time, the plume was defined by small gradients across its edge of all studied water properties and thus was prone to disappearance under appropriate conditions such as wind mixing. Such a scenario must have occurred, as aerial photographic images taken 3 days later did not record any visible plumes at similar or further offshore locations.

Overall, *river-borne sediments and nutrients released by a typical flood in the Herbert River are precipitated and/or consumed within the first 20 km from the coast and therefore are unlikely to reach and possibly affect the mid-shelf coral reefs of this section of the GBR lagoon.* However, the same conclusion cannot be extrapolated to low-probability (> 15 years) significant flood events, and further research is required in this direction.

5.2. ISSUES RAISED BY THE PRESENT STUDY

Satellite remote sensing can contribute to environmental monitoring by allowing managers to obtain repetitive, non-intrusive and low-cost data for water properties and related environmental quality parameters across broad spatial and temporal domains. The tools of remote sensing can provide many useful products for a coastal manager, but, as a relatively new field of science, have their limitations and unresolved issues. Issues raised by the present study in association with the use of ocean colour remote sensing to study flood-induced plumes in coastal waters are briefly outlined here.

Determination of *nutrient levels in river plumes* is one of the primary objectives put to the research community by water quality managers (GBRMPA 2003). CDOM, which is an optically active part of dissolved organic matter (DOM) and a satellite-derived product, is the best available remotely sensed proxy for dissolved organic nutrients levels. As pointed out in Chapter 2 (section 2.2.5), CDOM is not an exact equivalent of DOM, since (i) some DOM can be non-absorbing and thus colourless, and (ii) photooxidative degradation of organic matter by light ultimately leads to destruction of CDOM. Therefore, the extent and content of DOM distributions can be underestimated by using CDOM as a proxy. Clearly, region-specific DOM-CDOM relationships are required to elucidate the nutrient situation in the ocean surface layer using remote sensing techniques.

There is a general understanding among coral biologists and geochemists that excess *sediments and nutrients are detrimental to coral reef ecosystems*. At the same time, a gap exists in the scientific knowledge regarding (i) how much in excess is detrimental, (ii) what types of sediments and nutrients are bad for corals, and (iii) what "detrimental" really means. These are not trivial questions, because (i) various species respond differently to similar levels of sediment and nutrient input, (ii) adequate levels of sediments and nutrients are crucial for maintaining biological stability and diversity of coral reefs, and (iii) detrimental effects might not be identified until an irreversible shift has occurred in the ecosystem. Therefore, distinguishing between the adequate and threshold levels of sediments and nutrients, which trigger ecosystem degradation, is of primary interest to those concerned with corals, and future research directed towards the assessment of the physiological effects of sediments and nutrients on corals should address these aspects in more detail.

In order to monitor the highly dynamic biogeophysical processes in coastal regions, better *spatial and temporal resolutions* of remote sensors are desired. This, however, entails an intrinsic trade-off problem for polar-orbiting satellite systems, as better spatial resolution automatically translates into less frequent temporal coverage, and vice versa. The issue of infrequent revisit time of a particular satellite can be improved by using several satellite systems that sequentially pass the same area. Such a strategy would permit the derivation of snapshots of distributions of water properties on time scales more appropriate for coastal regions. This approach, however, requires intercalibration efforts and consistency checks between the remote sensing platforms employed. An example of current activity in this direction is a Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Program (http://simbios.gsfc.nasa.gov/).

Owing in part to the relatively small range of measured concentrations of optically significant substances in Lucinda waters during the field expeditions of 2002-2004, *further satellite validation work* is recommended for the area. Larger ranges of water-colouring constituents will additionally validate and, as such, improve the model. If the high degree of correlation found between CHL and CDOM at low and medium levels is valid for higher concentrations of these constituents, the current treatment of CHL in the model should be altered by expressing it as a function of CDOM. As a result, the model would describe the water-leaving radiance in terms of two independent water-colouring constituents, namely TSS and DOM. At the same time, due to (i) current temporal resolutions of operational ocean colour satellites, (ii) limited and strongly defined validation sampling time, and (iii) unpredictability of cloud-free atmosphere conditions over the validation area, a comprehensive validation program is a heavily time- and resource-consuming process.

As mentioned in section 3.2.4, *variations of a water property within a satellite pixel* are among the reasons behind deviations between satellite-derived and in situ-measured values. Unfortunately, this issue was not addressed in the present study and further work to assess the sub-pixel patchiness of the employed sensors is considered beneficial.

The main disadvantage of the present inversion approach is the substantial *computational time* required to process satellite data, which currently prohibits application of the method in operational SeaWiFS processing. The immediate alternative to the current iterative inversion procedure would be one of the standard optimisation methods widely employed by the oceanographic scientific community (Roesler et al 1995; Garver et al 1997; Pierson et al 2001; Maritorena et al 2002). A different way to address the time issue is to identify bio-optical provinces, where different seasons, proximity to the river and other local conditions are represented by appropriate sets of corresponding bio-optical parameters. However, defining bio-optical provinces requires extensive fieldwork, and available data for the Lucinda region are insufficient to classify optical parameters according to this scheme. Yet another alternative to deal with the computational time issue is to run the model initially at coarse spatial and concentration resolutions in order to determine general distribution patterns of water properties as well as to identify the presence of objects of interest (e.g. plumes). More targeted model runs with higher resolutions for the objects of interest would then follow this initial stage of analysis.

There is always room for improvement, and the present bio-optical model is no exception. Potential *amendments to the model* would involve (i) inclusion of optical contribution of bacteria in backscatter estimates; (ii) a better estimate of the CHL-TSS conversion factor; (iii) accounting for ancillary pigments in the phytoplankton absorption term and thus potentially differentiating algal functional groups; (iv) inclusion of inelastic optical processes in the model, such as Raman scattering and fluorescence of both CHL and CDOM; (v) refinement of bottom reflectance spectrum estimates; and (vi) relaxation of water homogeneity assumption. These amendments, however, require additional degrees of freedom in the model to accommodate the new variables, which is not feasible for SeaWiFS applications considering the eight spectral bands of the sensor. At the same time, other satellite systems and associated ocean colour sensors continue to evolve and will decrease the gap between their technical capabilities and user needs (for an overview of current and scheduled ocean colour sensors see http://www.ioccg.org/sensors_ioccg.html).

While the present bio-optical model was being developed, a contemporary question was *how general or local should a model be*. At one extreme, there is an option of an all-inclusive global model applicable to any coastal environment around the world. However, in recent years there has been a shift in the ocean colour community's understanding of the issue, based on building evidence that such an approach is not suitable for the study of region-specific coastal processes (Doerffer et al 1994; Sathyendranath 2000; Pozdnyakov et al 2003). At the other end of the scale there is a very detailed model accounting for pixel-scale variability of optical water properties. This option would require a comprehensive pixel-by-pixel approach to model parameterisations derived from detailed in situ measurements. The latter, however, provokes a general query about the need for a model if measurements at each point are to be carried out anyway. The answer to the question posed at the beginning of this paragraph would be that a regional model should be suitable for the task that it is addressing. For the objectives of the present study, a bio-optical model should be able to provide reasonably accurate distributions of the water properties of interest in the studied region. The validation of the model developed in the present work using SeaWiFS data confirms the achievement of this requirement (section 3.2).

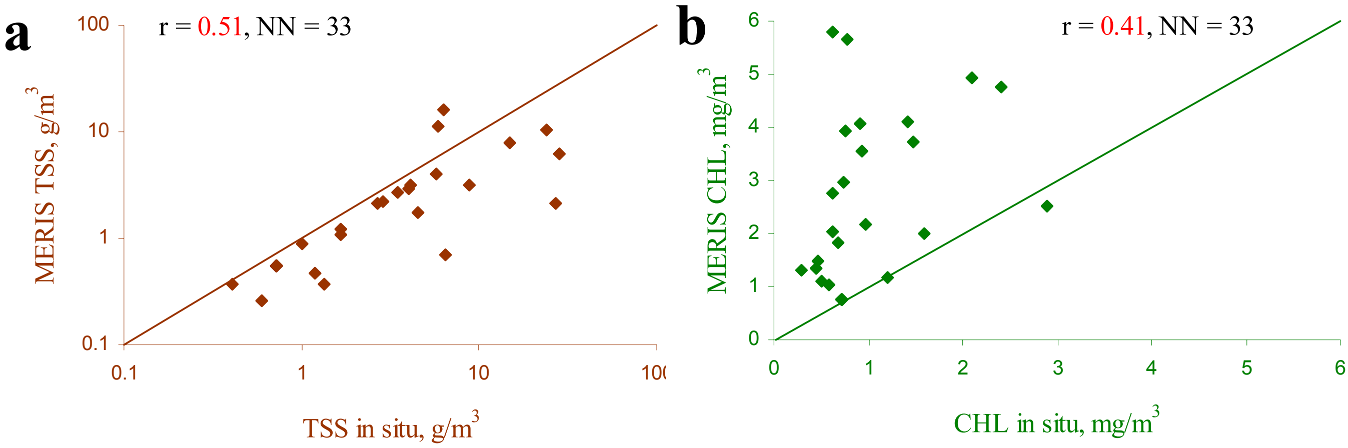
5.3. WHERE TO GO NEXT

5.3.1. MERIS potential

With a spatial resolution of 250 m and 15 spectral bands in the visible and near infrared regions, the recently launched European ocean colour sensor MERIS is better designed for coastal waters than its predecessor SeaWiFS. Its potential is substantiated by a recent study in which inversion results from ocean colour retrievals carried out for different wavelength combinations indicate that 15 channels that cover the 400-800 nm range are adequate for most coastal and oceanic applications (Lee et al 2002).

In order to assess the feasibility of MERIS data for ocean colour studies in the Lucinda area, an effort was made to include in situ measurements coinciding with overpasses of MERIS while planning and organising field trips. As a result, three cloud-free days with corresponding in situ measurements in October 2003 and February 2004 permitted comparison of satellite-derived and in situ measured values of water properties. The concentrations of water-colouring constituents obtained by MERIS were averaged for pixels within a 0.5 km radius of a validation station and were subsequently compared to corresponding in situ data (Figure 5.1). The best correspondence between measured and satellite-derived values was found for TSS concentration. CHL concentration was consistently overestimated by MERIS, while CDOM was scattered randomly, with absorption values mostly underestimated by the sensor. The latter effect was even more pronounced considering that the MERIS yellow substance absorption term includes contributions from detritus as well as dissolved organic matter (ESA 2002). Poor associations between measured and satellite-derived concentrations of optically significant substances can probably be explained by the fact that the MERIS algorithms (i.e. the training dataset for the neural network) were calibrated in north European waters (i.e. North Sea, Schiller et al 1999).

The above validation results suggest that the present ocean products generated by MERIS are not suitable for operational remote sensing studies in the Lucinda area. However, the potential of this sensor should not be ignored, as it continuously provides high quality water-leaving radiance data over the area. The MERIS algorithm scheme includes an option of user-defined training datasets for various coastal regions (Doerffer et al 1997), an alternative that should be explored and possibly employed for Australian waters. Moreover, MERIS is just one of 10 multidisciplinary instruments on board the Envisat satellite providing comprehensive measurements of the atmosphere, ocean, land and ice (http://www.esa.int/envisat/instruments.html). Analysis of these multidisciplinary data, however, is a task suitable only for collaborative teams of researchers from various fields.



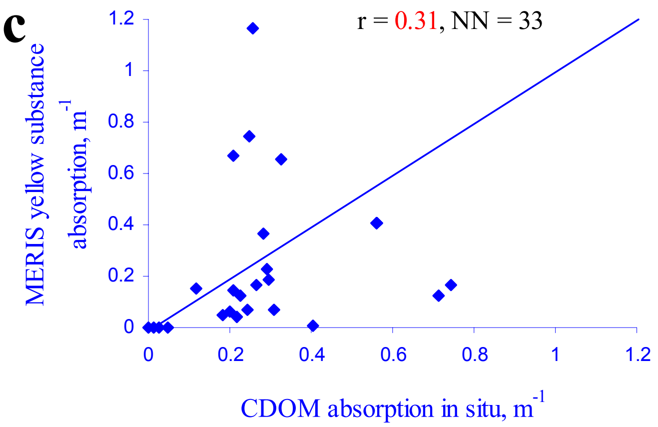


Figure 5.1. Comparison between MERIS and in situ concentrations of TSS (a), CHL (b) and CDOM (c) in Lucinda waters. TSS correlation is significant at < 0.01, CHL correlation is significant at < 0.05.

<u>5.3.2. Numerical modelling</u>

A regional biogeophysical numerical model is an excellent tool to (i) understand suspended particulate matter transport, (ii) derive biomass production patterns in coastal waters, (iii) attempt short-term forecasts of algal blooms, and (iv) predict the extent of river plumes in adjacent coastal seawaters. Model simulations enable users to scientifically estimate dilutions and time frames for the transfer of sediment, nutrients, and possibly contaminants from terrestrial runoff to offshore ecosystems such as mid-shelf reefs.

Numerical modelling permits the calculation of synoptic three-dimensional distributions of variables, but it requires thorough knowledge of the relevant processes, boundary conditions and parameters involved in the process formulations. Such information is conventionally built through comprehensive and expensive field expeditions. Alternatively, satellite data in conjunction with field measurements can be used to calibrate and repeatedly validate the model (Ametistova et al 2004; Ouillon et al 2004). A combined ocean colour remote sensing and modelling approach applied to the Lucinda area would allow continuous monitoring of discharge properties, composition and spatial dynamics of river plumes entering this section of the GBR lagoon. The work is currently underway in this direction (Tabeta et al 2002; Ametistova et al 2004).

5.3.3. Linking science and management

Satellite remote sensing has a strong potential for employment as a significant component in the operational monitoring of the water quality in the GBR region. Advantages of this technology include both the qualitative benefits derived from a visual overview, and, more importantly, the quantitative potential for systematic assessment and monitoring of natural environments. Once in service, satellites are a continuous source of information for many years, providing decade-scale monitoring of natural and man-made changes in ecosystems. Advances in instrument capabilities and analysis methods continue to increase the accuracy and level of effectiveness of the resulting data products and their usefulness for regional planning and management.

Despite these advances, environmental managers have been reluctant to adopt remote sensing tools for routine monitoring of water quality, in part because of prevailing perceptions of poor algorithm resolution and also because it is considered costly and technically complex (Steven et al 2004). As mentioned by the 2004 recipient of the Ocean Sciences Award 2004, Bilal U. Haq, *"I have been a bit worried about our complacency as research scientists. We may not be paying enough attention to the immediate relevance of our work to society, remaining quite content if only a handful of our colleagues understand or care about what we accomplish. I believe that we have to change this mind-set if we want to claim greater impact in solving pressing societal problems of resource exploitation and conservation, environmental degradation and remediation, and the overall quality of human existence, problems that loom big in this century. As stewards of the oceanic milieu, we will be called upon to provide lasting solutions and must prepare ourselves to face these issues."* (Haq 2004). Therefore, the current challenge for the remote sensing community is to advance the understanding that the non-invasive, synoptic, repetitive data of water quality parameters across broad spatial and temporal domains provided by satellite imagery can improve decision making in coastal management in a cost-effective manner.

5.4. SUMMARY

The tropical rivers on the littoral of the Great Barrier Reef lagoon deliver most of their sediment and nutrient discharge in the course of high intensity episodic events during monsoonal wet seasons. Due to logistical constraints, it has been difficult to develop an understanding of the advection and mixing of the turbid plumes from these rivers under flood conditions. With the advent of ocean colour sensing satellites, a new tool became available to provide synoptic images of the near surface expression of flood plumes. However, neither suspended sediment and nutrient levels nor reliable chlorophyll estimates could be obtained from satellite-derived data using the existing algorithms. Therefore, an optical model of the water-leaving radiance in terms of water properties was required. Moreover, as the signal received by the satellite is strongly influenced by the atmospheric path and current operational atmospheric correction schemes were inadequate for application in turbid waters typical of flood plumes, an alternative atmospheric correction had to be developed.

To address the above issues, an inverse bio-optical model was developed in the present work, based on analytical and empirical relationships between optically significant substances and remote sensing water-leaving radiance. It determines concentrations of water-colouring constituents such as chlorophyll (CHL), total suspended sediments (TSS), and coloured dissolved organic matter (CDOM), using water-leaving radiances derived from SeaWiFS. To deal with the atmospheric correction problem, the SeaWiFS algorithms were modified to allow for relaxation of the black pixel assumption. This was exercised by transferring the aerosol type over clear waters to adjacent turbid water pixels. As a result, both aerosol and water signals in the near infrared spectral region are derived and are then extrapolated in the visible spectrum using SeaWiFS default algorithms.

The vicinity of the Herbert River, central GBR zone, Australia, was used as a case study for the application of the newly developed algorithm. Here the presence of optically significant particulate and dissolved matter in coastal waters suggests that the standard SeaWiFS atmospheric and ocean algorithms are inapplicable. The new satellite ocean colour technique, which accounts for water-leaving radiance in the near infrared and retrieves three optically significant substances, was successfully validated using sea-truth measurements of water-colouring constituents acquired in the area during various seasons throughout 2002-2004. For low CHL values and turbid waters, the model predicted a weak dependence of the water-leaving radiance spectra on CHL concentration, making inversion of the satellite signal to obtain this geophysical property uncertain. A high correlation between CHL and CDOM was noticed in the coastal waters of the region, and when the bio-optical model was constrained to make CHL a function of CDOM the relationship between in situ and satellite-derived data was substantially improved.

With reliable retrievals of the major water-colouring constituents, the technique was subsequently applied to study fluxes of particulate and dissolved organic and inorganic matter following a flood event in the Herbert River during the austral summer of 1999, which was the third biggest flood in the previous 50 years. It was found that a plume of high TSS, which developed in the aftermath of the flood in the coastal ocean, rapidly reduced in concentration once the river flow rate started to decrease. A CHL bloom was observed in the coastal waters 5 days after the peak discharge, and a fortnight after the initiation of the flood the coastal ocean had returned to its pre-flood conditions. No evidence of significant enrichment of the waters over the offshore reefs was observed. The modelled distributions of substances revealed that under conditions favourable for across-shelf plume dispersal, none of the plumes managed to carry harmful amounts of nutrients and sediments to mid-shelf reefs. This study showed that following a once-in-15-year flood in the Herbert River, resultant plumes of terrestrial substances in the adjacent coastal ocean did not affect mid-shelf and outer reefs in this section of the GBR.

Extensive field observations covering a seasonal flood in the Herbert River in February 2004 suggested high sediment and nutrient exports from the river to the adjacent coastal waters. However, due to rapid settling, the bulk of the sediment-rich influx was deposited close inshore. The phytoplankton levels in the coastal ocean in the flood aftermath were sufficient to have consumed all the macronutrients exported to the coastal ocean during the flood. The clearly visible offshore plume observed 5 days after the peak discharge was thin and bounded by extremely small gradients across its edge of all the water properties studied, and thus was prone to immediate disappearance under favourable conditions such as wind mixing.

With the help of ocean colour remote sensing, the present study was able to demonstrate that river-borne sediments and nutrients discharged by a typical flood in the Herbert River are mostly precipitated or consumed within the first 20 km from the coast and therefore do not have the potential to reach and possibly affect the mid-shelf coral reefs of this section of the GBR lagoon. With the technique developed in this thesis, the routine monitoring of sediment and nutrient fluxes entering the GBR with river runoff is not a desirable future but rather a present-day reality. Such monitoring, along with integrated coastal management and appropriate technologies for pollution prevention, would ensure the environmental protection of a natural wonder we have inherited, the Great Barrier Reef.