3.3. APPLICATION OF THE OCEAN COLOUR REMOTE SENSING TECHNIQUE TO A FLOOD EVENT IN THE HERBERT RIVER

3.3.1. Flood plumes

Coastal rivers collect freshwater runoff from the land and deliver it to the sea. The runoff also collects and carries sediment, nutrients and contaminants in quantities dependant on the catchment characteristics and land uses. Once the river flow reaches the sea, it drives a plume of freshwater and associated biogeophysical substances into coastal waters. The low-salinity content of the plume makes it buoyant and able to spread over the ambient seawater. As a result, strong density gradients at the base of the plume are established, inhibiting vertical mixing between the floodwater above and the underlying seawater. Being constrained by hydrodynamic forces, such density plumes are usually demarcated by sharp turbidity fronts and are therefore readily observed from remote sensing platforms (Devlin et al 2001; Burrage et al 2002).

Concentrations and forms of particulate matter and dissolved nutrients in flood plumes reflect the concentrations in the source waters, the extent of mixing with shelf waters and the biological processes occurring over time in river plumes. Thus plumes with different water properties have different fates in the coastal ocean due to a variety of physical, chemical and biological processes and interactions that act upon them. Sediment plumes are expected to diminish in size first, because heavy coarse sediments start settling as soon as the force keeping them in suspension (i.e. turbulence) is low enough. Fine-grained as well as low-density suspended particles have a longer lifetime in surface waters because of their lower settling velocity. These particles are usually more chemically reactive, being the major source of terrestrial phosphorus and other important nutrient elements as well as various contaminants in coastal waters (McCulloch et al 2003).

Without life in the oceans, dissolved matter would be characterised by conservative behaviour in its physical dispersal, that is, its concentration would change only as the result of mixing with water of different dissolved matter content or through evaporation. However, both dissolved and organic particular matters are subject to biological production, consumption and remineralisation, precluding the use of other, more easily measured parameters (e.g. temperature, salinity) for tracing the fate of these elements in the plume.

Finally, phytoplankton blooms and associated productivity fronts are expected to occur some time later (about a week) in coastal waters. With the rapid settling of suspended sediments and high nutrient levels in the surface layer, flood-affected waters translate into light and nutrient environments favourable for phytoplankton development. As a result, phytoplankton bloom can develop in coastal waters following a flood event in a nearby river. Since biological fronts are constrained by nutrient and light availability, they are tightly coupled with associated turbidity and density fronts.

Estuarine mangrove swamps covering the shoreline in the vicinity of Lucinda Point supply organic matter to underlying soils, which is subsequently washed into the nearby coastal ocean by tidal forces and deposited as organic-rich sediments prone to further resuspension (Wolanski et al 1990; Brunskill et al 2002). When stirred, these sediments move into suspension and therefore can be detected using remote sensing tools.

As shown in the previous section, optically significant water properties, such as TSS, CDOM (which is equivalent of dissolved matter in optical oceanography) and CHL (a proxy of phytoplankton), can be studied using ocean colour remote sensing. The method of retrieving these substances from SeaWiFS water-leaving radiances developed in the present work was applied to a flood event in February 1999 in the Herbert River region, and the evolution of the river plume was modelled and monitored.

3.3.2. 1999 flood event

Heavy rain commenced on the northern side of the upper Herbert River on the morning of 11 February 1999 and fell almost continuously until late on the night of 12 February. In the middle reaches of the Herbert River, the heavy rain fell for about 12 hours from the afternoon of 11 February to about 9 am the next day, while in the lower part of the Herbert River rainfall was only intermittently heavy during this period. Precipitation totals over the period of 4 flood days (11-14 February 1999) ranged from just under 100 mm in the lower catchment to over 550 mm in the upper catchment areas (BOM 2000).

The rainfall produced a flood in the Herbert River 2 days after the maximum precipitation, due to the time required for floodwaters from the upper Herbert River to arrive at the coast. The flood was classified as major by the Bureau of Meteorology and was the third largest flood event in the previous 50 years, with the maximum discharge of just under 600,000 ML/day on 13 February (Figure 3.19a).

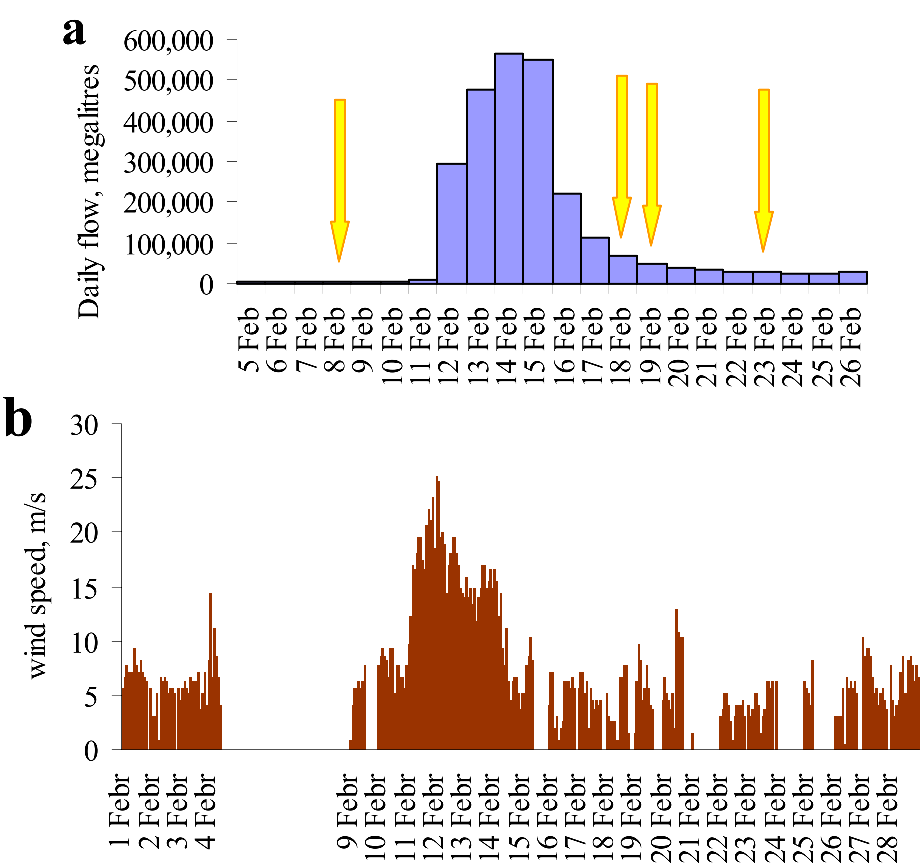

Figure 3.19. (a) Herbert River daily discharge in megalitres, and (b) wind speed covering the February 1999 flood. Arrows show dates of available SeaWiFS imagery.

SeaWiFS data

Four SeaWiFS images were obtained for the period of 2 weeks covering the flood: 3 days before the start of the event (8 February), 5 days (18 February), 6 days (19 February) and 10 days (23 February) after the peak discharge (Figure 3.19a). The images were processed using the modified atmospheric correction described in the previous section. Unfortunately, the SeaWiFS correction algorithm masked some pixels adjacent to the coast as being stray light contaminated. As a result, strips of unprocessed pixels about 5 km wide (equivalent to 4 SeaWiFS high resolution pixels) were observed along the coast in all images studied.

Following the modified atmospheric correction, resultant water-leaving radiances were processed by the inverse modelling procedure developed in the present work using the previously digitised bathymetry of the area. The process is time-consuming, as it requires about 4 minutes to process a pixel using Compaq Visual FORTRAN 6 and a 126 Mb RAM

900 Hz computer. Consequently the average of about 1000 pixels in each image translate into 11 days of machine time required for complete processing of four chosen images.

Figures 3.21-3.24 show distributions of suspended sediments, coloured dissolved organic matter and chlorophyll in the coastal ocean adjacent to the Herbert River as derived from the SeaWiFS data using the inverse bio-optical model. As was mentioned earlier, retrieval blanks in the near coast region observed in all images correspond to contaminated (by stray light) pixels and therefore were not processed by the SeaWiFS atmospheric correction algorithm. Colour gradations are associated with typical levels of the water properties observed in the Lucinda region (section 3.1 and Appendix 4) and correspond to open ocean (TSS, CDOM and CHL are < 2 g/m^3, < 0.05 m^{-1} and < 0.5 mg/m^3, respectively), coastal ocean during dry season (2 colour gradations, TSS, CDOM and CHL are 2-4 g/m^3, 0.05-0.2 m^{-1} and 0.5-2 mg/m^3, respectively) and coastal ocean during wet season (2 colour gradations, TSS, CDOM and CHL are > 4 g/m^3, > 0.2 m^{-1} and > 2 mg/m^3, respectively). Hereafter, a eutrophic plume is defined if concentrations of a water property are above dry season coastal levels, while a high-concentration plume is described as TSS concentrations above 8 g/m^3, CDOM absorption above 0.4 m^{-1} and CHL levels above 5 mg/m^3.

8 February

Two days before the start of the flood in the Herbert River, low concentrations of all biogeophysical constituents were observed in the adjacent coastal area, with small patches of elevated concentrations close to the river mouth (Figure 3.21). The latter are most probably related to a tide-induced plume (the SeaWiFS-hosting satellite overpass was at the time of the low tide) and reflect the extent of the flow of estuarine waters into the coastal ocean under no-flood conditions. The distribution of water properties in the coastal ocean as observed on 8 February can be considered as representative background distributions of components, with the average image concentrations of 2.46 g/m^3, 0.06 m^{-1} and 0.39 mg/m^3 for TSS, CDOM and CHL, respectively (Figure 3.20).

An interesting feature observed on maps of satellite-derived water properties (Figure 3.21) is elevated concentrations of TSS and CDOM in the shallow zone along the coast south of the Herbert River mouth, with TSS above 5 g/m^3 and CDOM around 0.1 m^{-1}. These higher than image average concentrations, as well as the absence of a similar response in CHL distribution, are probably the result of resuspension of inorganic and organic (hence CDOM) sediments due to wind waves. Unfortunately, no wind data were available on that day (Figure

3.19b). However, a recent study showed that wave-induced bed stress is the most significant mechanism of sediment resuspension in the GBR (Orpin et al 1999).

18 February

On 18 February the Herbert River discharge was 69,000 ML/day, which is about one order smaller than the peak discharge on 13 February and about an order larger than the pre-flood values (Figure 3.19a). The plumes of the three water-colouring constituents produced by the flooding are clearly visible on satellite-derived distributions, with the average concentrations in high-concentration plumes of 15.8 g/m^3, 0.78 m^{-1} and 6.9 mg/m^3 for TSS, CDOM and CHL, respectively (Figure 3.22).

As the fraction of inorganic matter in total suspended sediments tends to increase with the discharge rate in the Herbert River (see Chapter 4), more inorganic particulates in the flood-affected coastal waters are expected. As a result, mostly hydrodynamic forces such as advection, diffusion, settling and resuspension drive the dynamics of the TSS plume. The distribution of suspended sediments in Lucinda coastal waters 5 days after the Herbert River peak discharge support the above conclusion, as strong gradients of this substance are well defined in the direction away from the river mouth (Figure 3.22a). The high-concentration sediment plume, with estimated dimensions of 20 km width and 30 km length, would contain about 9500 t of sediment. Using a dry sediment density of 10^6 g/m^3 for a clay-rich mud of circa 60 % porosity (Orpin et al 1999), such a plume would deposit a thin layer of sediments of approximately 16 μm thickness on the sea floor.

High concentrations of TSS observed in the coastal ocean south of the Herbert River mouth are most likely attributable to the neighbouring Burdekin River flood. The Burdekin River is the largest river system that drains into the GBR, and its plumes have been documented to stretch northward along the coast and reach Palm Isles and Hinchinbrook Island during major flood events (King et al 2001; Burrage et al 2002).

Phytoplankton abundance, on the other hand, is constrained by biological processes, such as production and consumption by organisms, as well as by physical dispersal by moving waters. The optimal combination of nutrient and light levels coupled with advective forces acting upon this biogeophysical property led to a complex pattern of CHL distribution 5 days after the peak in the Herbert River flood (Figure 3.22c). The general trend can be described as decreasing concentrations towards the sea, with concentrations above 2 mg/m^3 found predominantly within the first 20 km offshore.

CDOM is the least scientifically understood component of the three water properties of interest as it is defined in optical terms while its chemical composition and production-consumption pathways are complex and quite variable (Hansell et al 2002). The CDOM distribution on 18 February reflects the dispersion of the river outflow, while patches of elevated absorption values in the northern and southern parts of the area studied are observed (Figure 3.22b). The latter are possibly related to flood events and associated plumes in adjacent river systems, i.e. the Burdekin River to the south and the Tully River to the north.

19 February

In the afternoon of 18 February and the morning of 19 February the wind was predominantly from the west, circa 6 m/s on average (Figure 3.19b). Such a wind direction is expected to produce a shallow offshore current. As a result, plumes of all studied water properties were advected in the across-shelf direction. This is not a typical scenario as SE winds are predominant in the area during the wet season. From the research point of view, however, it provides an opportunity to observe the fate of riverine water and associated biogeophysical substances pushed towards the mid-shelf reefs, and therefore directly address the question set in Chapter 1: *"What is the fate of biogeochemical substances from Herbert River plumes in the coastal ocean?"*

On 19 February both eutrophic and high-concentration plumes of suspended sediments off the Herbert River mouth had decreased in size compared to the previous day (Figure 3.23a). The TSS concentrations above 8 g/m^3 were confined to an area extending 15 km east from Lucinda Point as well as along the shore west of the Palm Isles. TSS concentrations in the waters adjacent to mid-shelf coral reefs did not exceed 3 g/m^3 on either 18 or 19 February. These are the average background levels of suspended sediments typical for coastal waters of the GBR (Furnas 2003).

The dramatic reduction in the sediment plume size must be the result of weakening of the river discharge and consequent precipitation of heavy as well as large flocculated particles to the sea floor as suspended matter flocculates intensively where river water meets with sea water (Eisma 1993). From the observed dynamics of the satellite-derived TSS plume it can be concluded then that due to rapid settling, highly turbid sediment-rich riverine influxes are generally confined close inshore, thus providing little chance for detrimental amounts of sediments to reach mid-shelf and offshore coral reefs. This conclusion is in agreement with other sediment-related studies in the area, which show that terrestrial sediment deposition in the coastal waters off Lucinda is largely restricted by a 20-m isobath (Woolfe et al 2000). Therefore, significant quantities of modern riverine sediments are unlikely to be deposited on mid- and outer reefs in the central GBR lagoon (Larcombe et al 1996; Orpin et al 1999; Woolfe et al 2000).

The CHL plume off the Herbert River mouth, on the other hand, had intensified on 19 February in comparison with the previous day, with the average CHL concentration above 2 mg/m^3 of 9 mg/m^3 as opposed to 6.9 mg/m^3 on 18 February (Figure 3.23b). Levels of CDOM absorption in the coastal ocean followed the corresponding CHL distribution, with a noticeable cross-shelf excursion of absorption values above 0.1 m^{-1} north of Pelorus Island (Figure 3.23c). The observed coherence between satellite-derived CHL and CDOM distributions confirms the tight association between these optically significant substances discovered when analysing in situ data (section 3.1.3).

Dr Shigeru Tabeta kindly ran the hydrodynamic model developed earlier for the region (Tabeta et al 2002) for the February 1999 flood event. His calculations showed that north of Pelorus Island and at the latitude of the Hinchinbrook Channel water salinity increased from 30 to 34 ‰ during 18-19 February, indicating that the low-salinity waters were diluted by 11 % during that period. The observed twofold decrease in CDOM absorption at the same location over that period is therefore due to a combination of mixing with ambient seawater as well as biological consumption of dissolved organic matter.

The elevated CDOM and CHL levels on 19 February extended further offshore than on other flood-affected days. At 40 km east of the Herbert River mouth (the longitude of Bramble Reef, the closest mid-shelf reef to the Herbert River), CDOM and CHL concentrations were around 0.14 m^{-1} and 1.2 mg/m^3, respectively. Using the CDOM-DOC (dissolved organic carbon concentration) relationship established for the coastal waters in the nearby Townsville area (DOC [g/m3] = 3.31 x CDOM [m-1] + 0.92, Oubelkheir et al 2003), it is possible to convert CDOM absorption to, DOC concentration. Assuming all phytoplankton is remineralised to inorganic nutrients following the Redfield ratio (Falkowski et al 1992), the above concentrations of CHL and CDOM translate into approximately 1 µM of inorganic phosphorus, or equivalently, 16 µM of inorganic nitrogen (these are conservative estimates as dilution was not considered). Similar levels of inorganic nutrients were used in the low-loading phase of a nutrient enrichment experiment conducted on coral reefs on One Tree Island in the GBR (Koop et al 2001). The results of that experiment indicated that such amounts of nutrients did not significantly affect the biotic processes studied within coral reef communities, such as coral growth, reproduction, calcification rate and mortality, while the impacts on the treated reefs were subtle. Therefore, it can be concluded that following the 1999 Herbert River flooding, no potentially harmful amounts of nutrients reached the adjacent mid-shelf reefs. Considering that the 1999 Herbert River flood was the third largest flood event in 50 years, the above conclusion can be generalised to any flood with the probability of occurrence of 15 years.

23 February

Hydrodynamic forces and biological activity ultimately led to disappearance of the Herbert River runoff plume and associated elevated levels of sediments and nutrients carried within the plume. As a result, a week after the event the distributions of water properties returned to background concentrations similar to those observed prior to the flood (Figure 3.24), with eutrophic and high-concentration plumes confined to the first 10 km offshore from the river mouth. These are most likely tide-induced phenomena, as the satellite overpass over the area was approximately at the time of the low tide.

3.3.3. Conclusion

Average image concentrations of the examined biogeophysical substances (Figure 3.20) show background distributions of components before the flood, a large increase in the levels of all constituents in the flood aftermath followed by immediate decrease in the TSS pool, and a return to pre-flood values of the water properties 10 days after the peak flood.

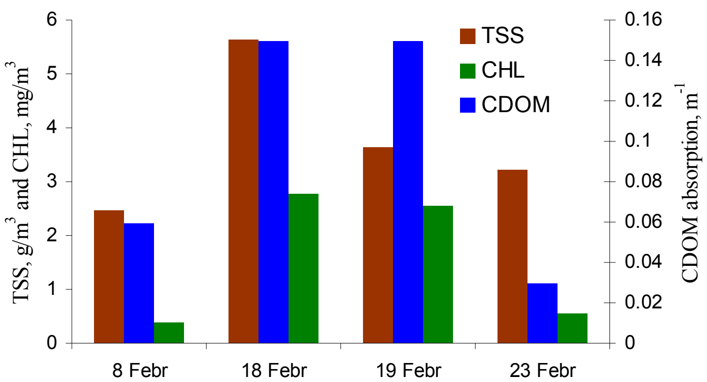

Figure 3.20. Average SeaWiFS-derived concentrations of water properties in the coastal ocean adjacent to the Herbert River for the 1999 flood. 8 February is before the flood, 23 February is after the flood.

The ocean colour remote sensing technique for monitoring coastal waters developed in the present work was successfully applied to study fluxes of particulate and dissolved organic and inorganic matter following a flood event in the vicinity of the Herbert River during austral summer of 1999. The approach allowed monitoring of the evolution of the plumes produced by each of the satellite-derived geophysical substances, namely TSS, CHL and CDOM. The observed distributions of substances in the coastal waters adjacent to the Herbert River reveal that under favourable conditions for across-shelf plume dispersal, none of the plumes managed to carry harmfully significant amounts of nutrients and sediments to mid-shelf reefs. Therefore, it can be concluded that a 15-year flood in the Herbert River and the resultant plumes of terrestrial substances in the adjacent coastal ocean do not affect mid-shelf and outer reefs in this section of the GBR.

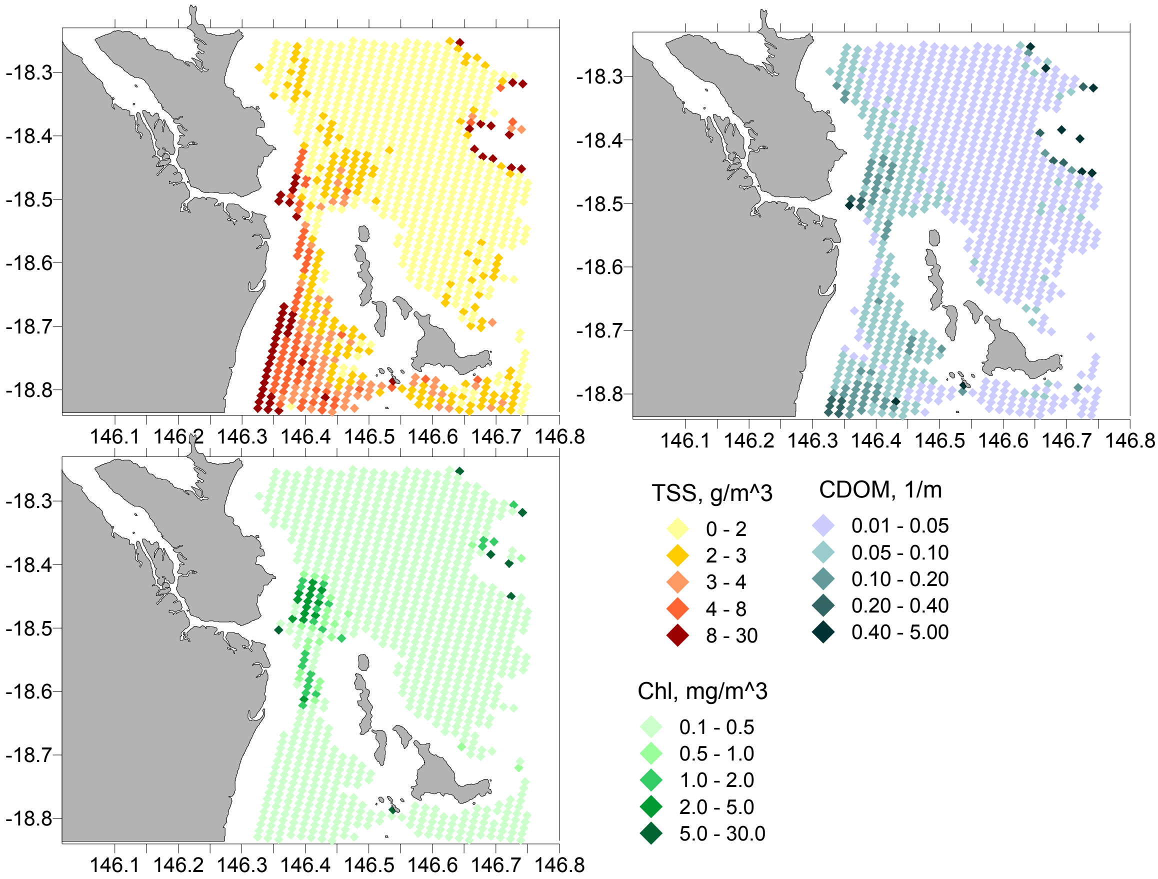

Figure 3.21. Distributions of SeaWiFS-derived TSS (a), CDOM (b) and CHL (c) on 8 February 1999 (3 days before the flood) in the coastal ocean adjacent to the Herbert River.

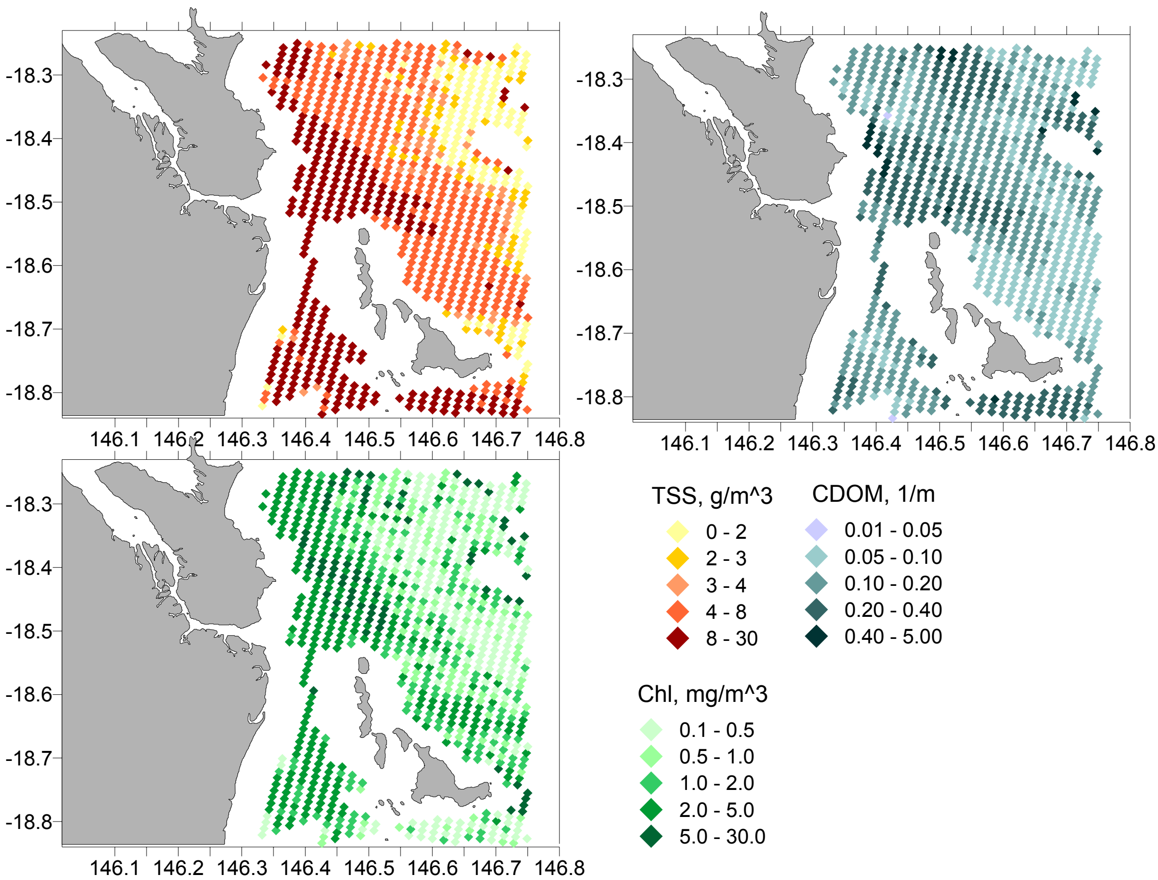

Figure 3.22. Distributions of SeaWiFS-derived TSS (a), CDOM (b) and CHL (c) on 18 February 1999 (5 days after the peak discharge) in the coastal ocean adjacent to the Herbert River.

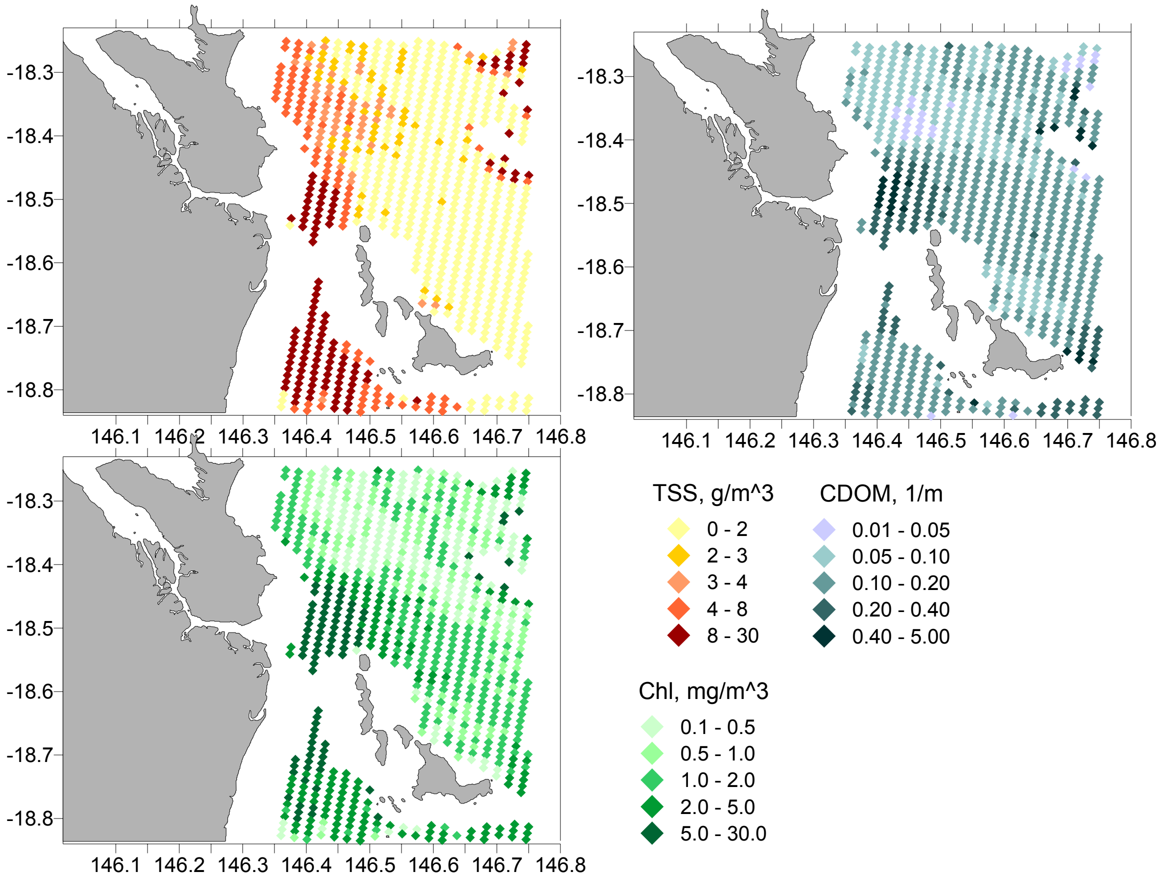

Figure 3.23. Distributions of SeaWiFS-derived TSS (a), CDOM (b) and CHL (c) on 19 February 1999 (6 days after the peak discharge) in the coastal ocean adjacent to the Herbert River.

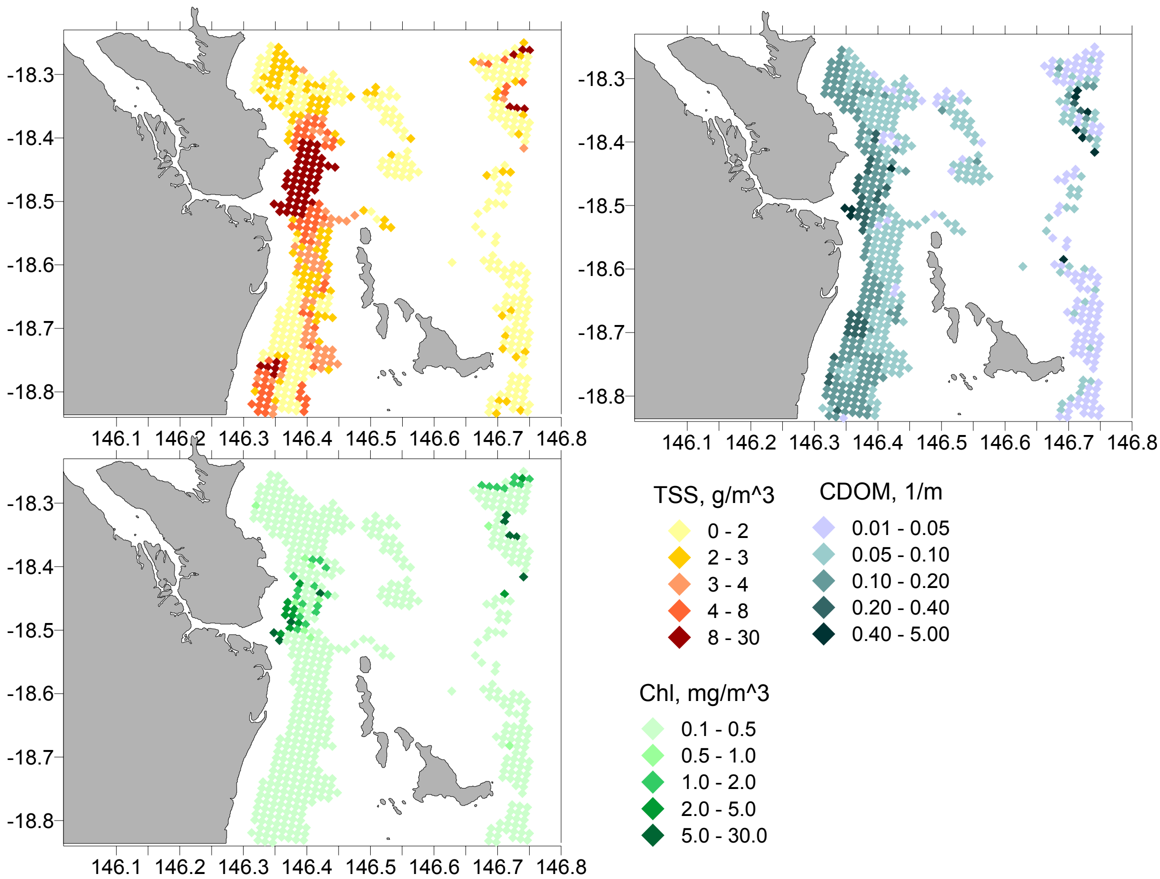

Figure 3.24. Distributions of SeaWiFS-derived TSS (a), CDOM (b) and CHL (c) on 23 February 1999 (10 days after the peak discharge) in the coastal ocean adjacent to the Herbert River.