CHAPTER 4

BEYOND SEAWIFS

4.1. FLOOD-MEDIATED TRANSPORT FROM THE HERBERT RIVER TO THE COASTAL OCEAN

4.1.1. Introduction

The flux of suspended sediments from a river into nearby coastal ocean depends on the size of the river, its discharge pattern, suspended matter supply and the circulation in the river mouth. In most rivers that drain into the GBR, estuarine mixing is confined to a predominantly inshore area and the export of suspended matter is limited, with much river-transported material trapped inside estuaries and freshwater tidal areas (Larcombe et al 1996). However, episodic events such as floods, which are a prominent feature of the GBR river systems, can enhance the transfer of river-derived material to the adjacent coastal ocean and can affect biogeochemical and sedimentation processes in these waters.

Suspended sediment runoff contains not only inorganic particulates but also the end products of the destruction and decomposition of the vegetation cover, as well as organic matter produced within the boundaries of the fluvial aquatic systems. As a result, sediment export from rivers introduces nutrients into coastal waters, which stimulate biological production, consumption and remineralisation in these waters.

Due to gravity, all suspended material with a density greater than the surrounding water will eventually sink to the bottom unless there is a force that keeps it suspended. Normally this force is the drag provided by the turbulent motion in the water. Whether the material remains in suspension or not is closely related to the intensity of the turbulence, as well as to the density, size, shape of the particles involved. The upper size limit of particular matter in suspension is not fixed. Relatively large and heavy particles like sand grains and gravel sink rapidly to the bottom, but very large low-density structures can remain in suspension for quite a long time.

To illustrate the importance of river discharge for the above processes in the area studied, this chapter details results from a comprehensive 2-week experiment covering the Herbert River flood in February 2004. Detailed information was collected during the experiment with the aim of providing insights into suspended sediment pathways in the Herbert River – coastal ocean system and elucidating the major factors controlling particle transfer processes in this highly dynamic environment.

4.1.2. Data overview

During the 7-20 February 2004 field trip a number of sediment-related measurements were undertaken to study flood-induced suspended sediment transport in the Herbert River mouth and adjacent coastal waters (Figure 4.1). The data collected included total suspended sediment concentration (TSS), fraction of organic matter in TSS, particulate and dissolved phosphorus concentrations (PP and DP), and turbidity profiles (for measurement procedures see section 3.1). The first three parameters were measured in the Herbert River mouth during daytime high and low tides for a total of 14 days, while turbidity vertical profiles were recorded daily during 9-16 February along the jetty (Figure 4.1).

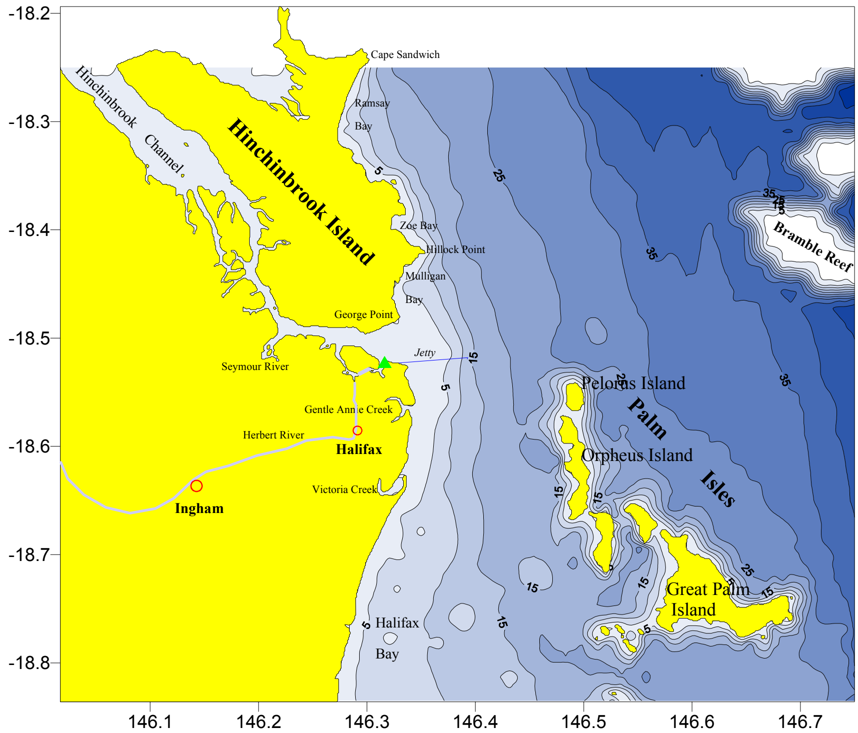

Figure 4.1. Herbert River and adjacent coastal ocean with bathymetry. Green triangle shows the sampling site at the river mouth.

Tropical cyclone Fritz first formed into a tropical cyclone on 10 February 2004 in the Coral Sea east of Queensland, Australia. The storm came ashore on the morning of the 11 February as a minimal cyclone along the northeast coastline of Queensland. The system weakened into a tropical depression over land and continued moving westward, cutting across the Cape York Peninsula before re-emerging over the waters of the Gulf of Carpentaria. It then re-intensified back into a Category 1 cyclone on 12 February and made a final landfall on the far northwest coast of Queensland (BOM 2004; NASA 2004).

The cyclone-induced rainfall event produced some very high hourly totals in the Herbert River area, but was of relatively brief duration (Figure 4.2). The associated wind rose during the second week of February and peaked at 13.9 m/s on 11 February at 8 pm, the evening before the maximum rainfall, weakening in the following 3 days, and from 15 February levelled up at around 4 m/s for the rest of the observational period (Figure 4.3).

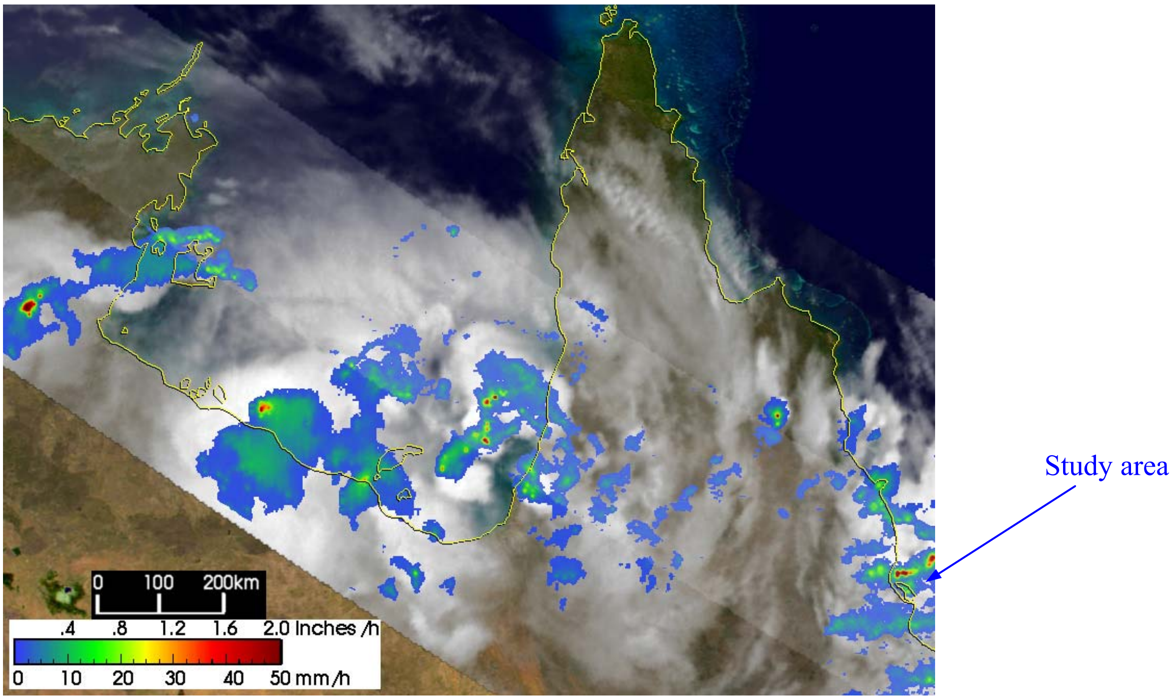

Figure 4.2. Rainfall rate as recorded by the Tropical Rainfall Measuring Mission (TRMM) at 12:18 am Australian EST, 12 February 2004.

The Herbert River flood occurred in the tropical cyclone aftermath and was classified as medium by the Bureau of Meteorology, with a maximum discharge of 237,000 ML/day on 12 February 2004 (Figure 4.4). The lowest discharge during the observational period was around 16,000 ML/day on 20 February. This value is about one order higher than background Herbert River flow levels, as the river experiences discharge rates between 200 and 2,500 ML/day throughout the dry period of the year (DNRM 2002).

On 7-10 February 2004 river heights at the Ingham station (30 km up from the river mouth) had a mean level of 1.5 m and exhibited about 40-50 cm tidal amplitudes (Figure 4.5). Following heavy rains associated with tropical cyclone Fritz, river levels in the Herbert River began rising on 11 February. During the subsequent flood period (11-15 February), the river heights followed the Herbert River flow rates with indistinct tidal oscillations, peaking at 5 m above the local reference zero (the station gauge zero is 0.98 meters above Australian Height Datum) on 12-13 February. Starting from 16 February, a tidal cycle reappeared on the river height record with relatively large tidal amplitudes of the first semidiurnal tides, reaching a maximum of 1.4 m on 18 February.

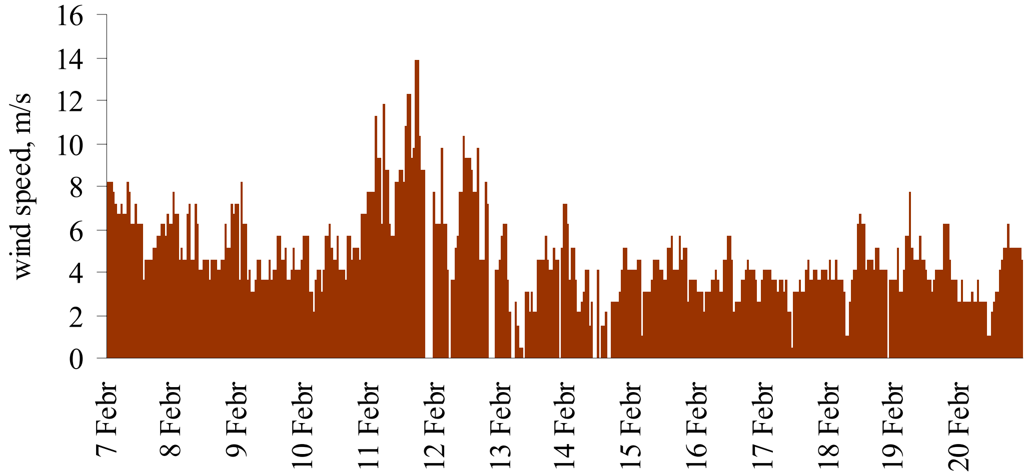

Figure 4.3. Wind speed at the end of the Lucinda jetty in February 2004.

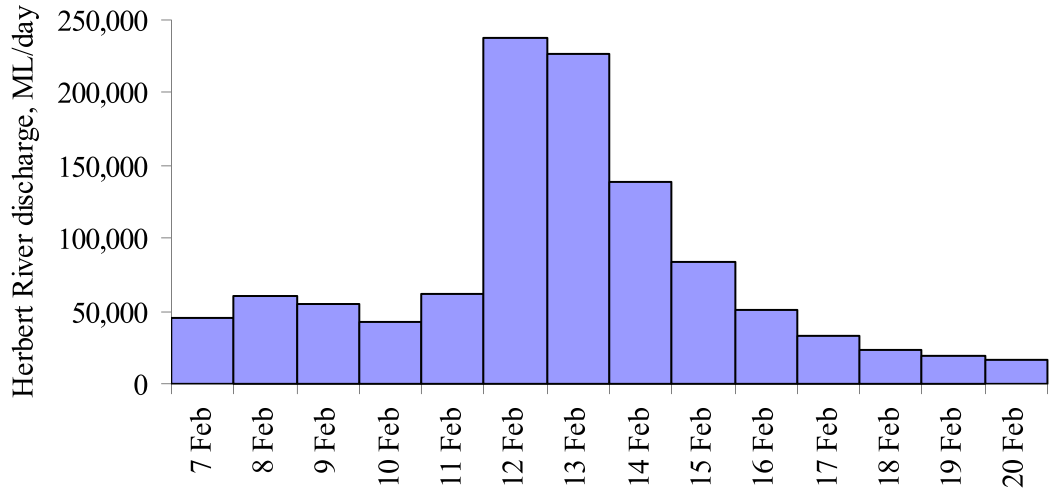

Figure 4.4. Herbert River daily discharge at Ingham station in February 2004.

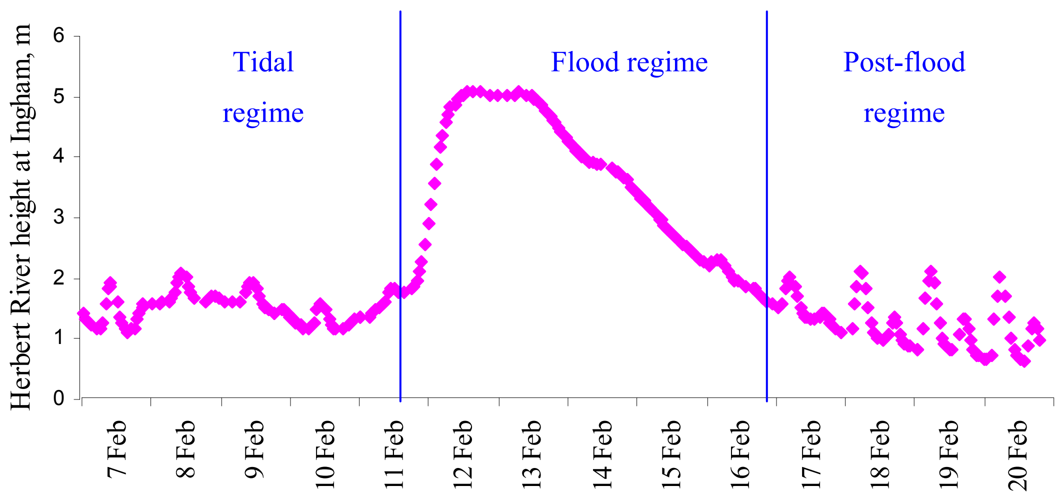

Figure 4.5. Herbert River height at Ingham station in February 2004.

Around the Herbert River flood peak (12 February), the maximum concentration of suspended sediments measured in the river was about 190 g/m^3, falling afterwards to the pre-flood values of between 10 and 70 g/m^3, depending on the tidal phase and local conditions (Figure 4.6). TSS oscillations at high/low tides before and after the flood were in opposite phases. Prior to the flood event, higher TSS concentrations were observed at low tides and lower values at high tides (35-45 and 10-15 g/m^3, respectively). The reverse situation occurred after the flood: consistently higher TSS concentrations were recorded at high tides in comparison to low tide values (62-88 and 16-25 g/m^3 at high and low tides, respectively).

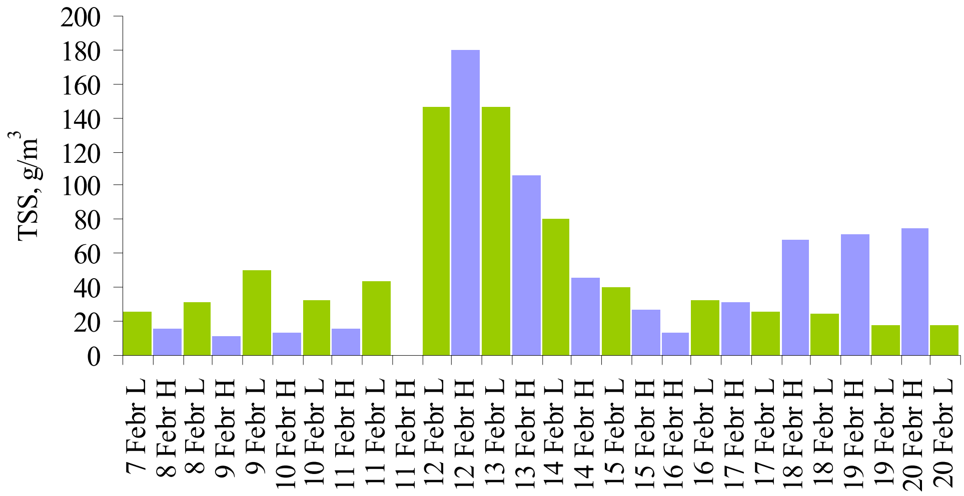

Figure 4.6. TSS concentration in February 2004 at the Herbert river mouth. TSS at high tide is shown in blue, and TSS at low tide is shown in green.

Similar patterns were observed in particulate phosphorus concentrations, with the maximum concentration of 114 µgP/L on 12 February (Figure 4.7). Dissolved nutrients, on the other hand, did not exhibit the same variations with discharge but were dominated by the tidal cycle for the whole observational period.

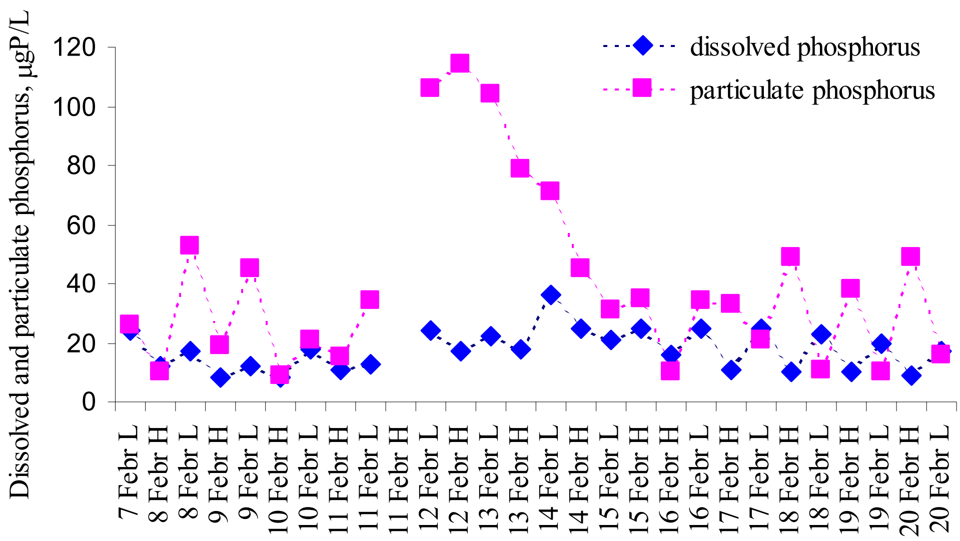

Figure 4.7. Dissolved and particulate phosphorus concentrations in February 2004 at the Herbert river mouth.

During the experiment the average organic matter fraction in TSS was 0.31, with distinctive daily fluctuations before and after the flood and consistently lower values during the flood event (Figure 4.8).

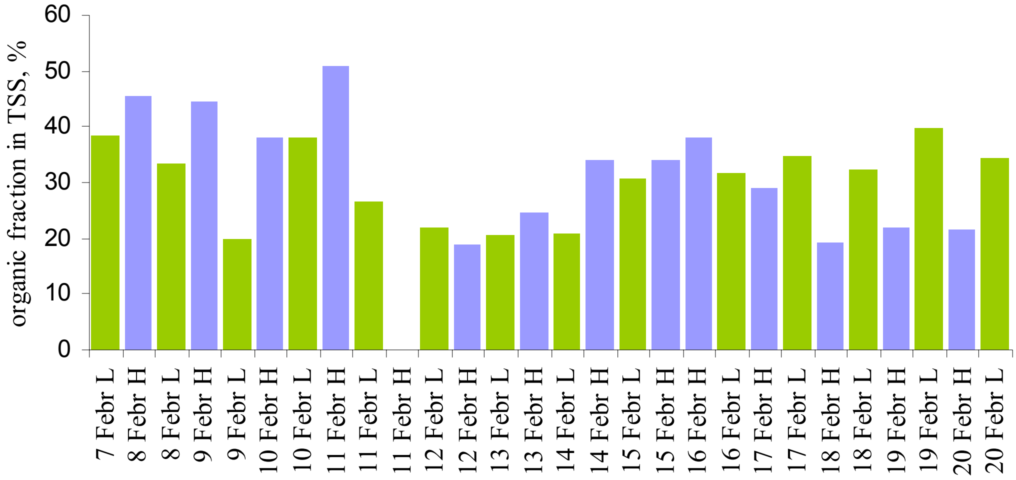

Figure 4.8. Organic matter fraction in TSS in February 2004 at the Herbert river mouth. Values at high tides are shown in blue, and at low tides in green.

4.1.3. Herbert River hydraulic regimes

Three distinctive hydrodynamic and geochemical regimes were detected over the observational period in February 2004 in the Herbert River mouth and correspond to *tidal, flood and post-flood* regimes (Figure 4.5).

Under no-flood conditions, the tidal elevation in the Herbert River estuary causes the river flow to slow down and reverse direction. As a result, clearer coastal seawater is expected in the river mouth at high tides and more turbid riverine water at low tides. Such tidal forcing determined the observed sediment and nutrient concentrations during the *tidal* regime, with low concentrations of TSS and particulate nutrients at high tides and high concentrations at low tides (Figures 4.6-4.7).

During the second, or *flood regime*, turbid waters laden with sediments and nutrients are carried out into the Hinchinbrook Channel and subsequently dispersed in the coastal ocean by mixing with ambient seawaters. As a result, both TSS and particulate phosphorus exhibited peaked responses to elevated river flow rates, with masked tidal oscillations (Figures 4.6-4.7). The latter must be result of the strong unidirectional advection of flooded river waters, which continuously resuspend bottom sediments and associated particulate nutrients.

Finally, during the *post-flood* regime, TSS and nutrient distributions exhibited “antitidal” cycles, with anomalously high concentrations during high tides and relatively low levels at low tides (Figures 4.6-4.7). At the same time, larger fractions of organic matter in TSS were observed at low tides, the trend being opposite to the tidal regime (Figure 4.8). It is not immediately clear what processes were responsible for such counterintuitive patterns in the inventories of the parameters during the last 4 days of measurement. After a number of discussions with other participants in the field trip (Prof Mal Heron and Dr Charles Lemckert), the following explanation of the observed phenomena emerged and is introduced below.

After a flood, the river advects relatively clear waters with little sediment, as all washable material has been transported down the river during the flood period. When the tide reverses the flow, it resuspends the sediments recently deposited on the sea floor and carries them up the river. As a result, less turbid water is advected to the sampling site during ebb tides (hence low concentrations of TSS and nutrients) while more turbid water arrives from the coastal side during flood tides (hence high concentrations of TSS and nutrients). Over the course of time the situation is expected gradually to revert to the normal tidal cycle mode (i.e. tidal regime).

For the above scenario to occur, river flow rates during the falling stage of the flood must be below critical levels for suspension, so that sediments would precipitate over the sea floor. At the same time, the post-flood tidal currents are expected to be above the threshold for resuspension in order to lift the sediments from the sea floor. Large tidal amplitudes and hence high tidal current velocities during the last 4 days of measurement, as well as a general tidal asymmetry at Lucinda (stronger flood than ebb tides), support the above assumptions.

In the context of the above explanation of the observed phenomena in the Herbert River during the February 2004 flood, it is worth mentioning that a similar scenario has been found in the Amazon and Parana Rivers. These river systems exhibit peculiar behaviour in connection with yearly floods, where mean slopes of the water surface in both rivers become smaller with increasing river discharges. Lower slopes mean decreasing water velocities and possibly sedimentation, whereas steeper slopes denote higher water velocities and likely resuspension. As a result, the Amazon and Parana Rivers store sediments in their lower reaches during the rising stages of floods and resuspend the previously stored sediments during the falling stages (Ittekkot et al 1996).

4.1.4. Discharge rate versus water properties relationships

It is generally agreed that concentrations of suspended sediments in a river are not closely correlated with water discharge, because for most rivers the suspended sediment discharge is determined more by the sediment supply than by the capacity of the river flow to transport it (Eisma 1993; Furnas 2003). However, for the data collected during the February 2004 flood in the Herbert River, a strong relationship between TSS and river discharge was observed (Figure 4.9). The TSS concentration at zero river flow is circa 10 g/m^3, which is close to the background no-flood values in the river. The good agreement of the relationship with that of a previous study in the Herbert River (Mitchell et al 1997) indicates that it can be safely adopted for the Herbert River sediment export estimates for river flow values above 500 ML/day.

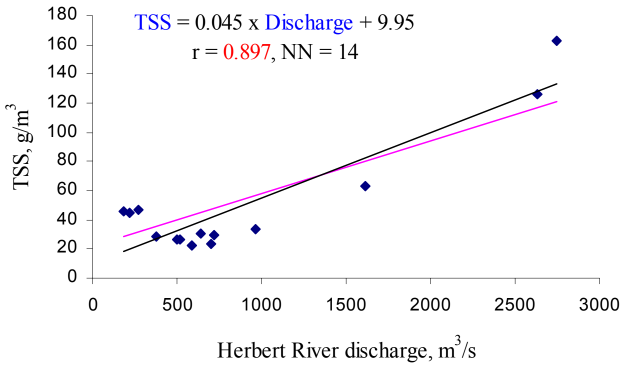

Figure 4.9. Relationship between Herbert River discharge rate and TSS concentration. The pink line shows the same relationship for 1994 flood (Mitchell et al 1997).

Not surprisingly, concentrations of particulate phosphorus were well correlated with the TSS concentrations during the observational period (Figure 4.10). Although it had been found earlier that particulate phosphorus was not well correlated with the discharge in the Herbert River (Furnas 2003), the data collected during the February 2004 flood revealed statistically significant correlations at 99 % confidence level (r = 0.95, NN = 14). Dissolved phosphorus, on the other hand, exhibited no response to elevated values of either Herbert River flow or TSS, and the resultant relationships were weak (Figure 4.10). The relative constancy of dissolved phosphorus throughout the year in the Herbert River is possibly related to chemical solubility constraints of this nutrient in the river waters (Furnas 2003).

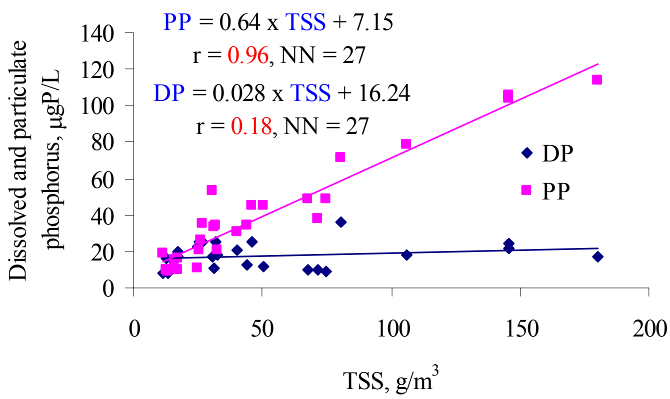

Figure 4.10. Relationship between TSS concentration and particulate and dissolved phosphorus concentrations.

The fraction of organic matter in TSS, on the other hand, is inversely correlated with the discharge (Figure 4.11). The negative relationship between the two can be explained by the fact that both organic suspended sediment (OSS) and inorganic suspended sediment (ISS) concentrations rise with the river flow, but ISS rises more quickly and in a non-linear fashion (Figure 4.12). The latter is probably due to enhanced resuspension of bottom sediments (which have higher inorganic content in the Herbert River area) at higher flow velocities. On the other hand, at lower discharge values and below critical turbulence levels, relatively more OSS is expected to be in suspension as generally heavier inorganic minerals settle more quickly than often lighter organic particles. A similar non-linear response in predominantly inorganic TSS to increasing river discharge has also been noted in the Rhine River estuary (Jonge et al 2002).

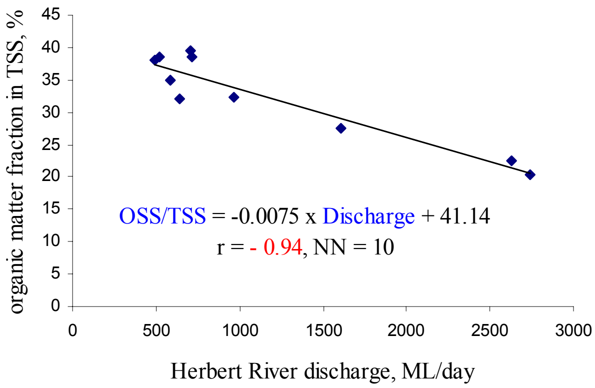

Figure 4.11. Relationship between Herbert River discharge and organic matter fraction in TSS.

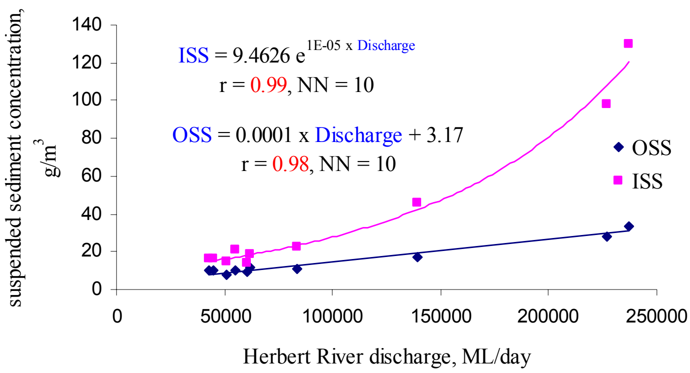

Figure 4.12. Relationship between Herbert River discharge and organic and inorganic suspended sediment concentrations.

<u>4.1.5. Sediment dynamics in the coastal ocean</u>

Using the TSS-turbidity relationship (section 3.1, Figure 3.6), vertical profiles of TSS along the jetty were reconstructed from the nephelometer data. The large range of measured TSS as well as excellent correlation between suspended sediment concentrations and nephelometer readings indicated that the derived relationship was robust and could be employed for practical applications. TSS vertical profiles for 8 measurement days along the jetty are presented in Figure 4.13a-h.

During the first two days of measurements and 3 days before the flood, a simple two-layer vertical structure of suspended sediment distribution was observed in the inshore part of the jetty bounded by the sand bank, with an upper layer of moderately turbid waters (TSS concentrations between 5 and 10 g/m^3) and a lower layer of sediment-rich waters (TSS values above 10 g/m^3) (Figure 4.13a-b). The two most offshore stations were occupied by seawater with low TSS values (< 5 g/m^3) throughout the water column. On 11 February wind-induced resuspension (wind speed 9.4 m/s during the time of sampling) was most likely responsible for the observed increase in turbidity throughout the water column in the first 5 km offshore, with variations in TSS concentrations between 10 and 100 g/m^3 (Figure 4.13c). On the following day the highest Herbert River discharge was recorded for the measurement period. The flood pushed fresh water over the coastal ocean where it gradually mixed with the coastal waters of salinity 35 ‰. As a result, sediment-rich estuarine waters reached the jetty and, being more buoyant than the ambient coastal waters, occupied the surface layer of the water column (Figure 4.13d). A three-layered system developed along the jetty, with relatively high suspended matter concentrations in the surface and bottom layers (6-30 and 10-33 g/m^3, respectively) and less turbid water at intermediate depths (5-10 g/m^3, Figure 4.13d-f). The turbid bottom layer, where present, was caused by (i) remobilisation of bottom sediments by wind waves, (ii) advection of riverine suspended material along the seafloor, and (iii) a combination of the above. At the most offshore station a two-layered structure was present, with a 1-m thick high turbidity layer on top, separated by a sharp licnocline from the relatively clear waters below (Figure 4.13f). The vertical three-layered pattern prevailed in the waters below jetty until 15 February when clear seawater occupied the surface waters of the two most offshore stations, most plausibly due to the weakening of the Herbert River discharge (Figure 4.13g). The following day the seawater intrusion spread to the mid-jetty, although residual floodwaters were still evident in the surface layer of the four coastal stations (Figure 4.13h).

An interesting situation occurred on 13 February in the jetty waters (Figure 4.13e): turbidity in the bottom layer rose in the absence of wind-induced waves and hence resuspension (wind virtually zero at the time of sampling). The immediate explanation for the increased bottom turbidity would be bottom sediment transport of riverine suspended material. However, this is an unlikely scenario since the bottom turbid layer was thicker further offshore – a trend opposite to what is expected in the case of river water advection. A more plausible explanation for the observed phenomenon is the downward settling of suspended sediments from the surface water with the subsequent development of a fresh top layer of turbid estuarine water during the next tidal pulse. Therefore, nephelometer data suggest that precipitation of riverine sediments from the surface waters rather than resuspension was responsible for the observed three-layered stratification of suspended sediments on 13 February.

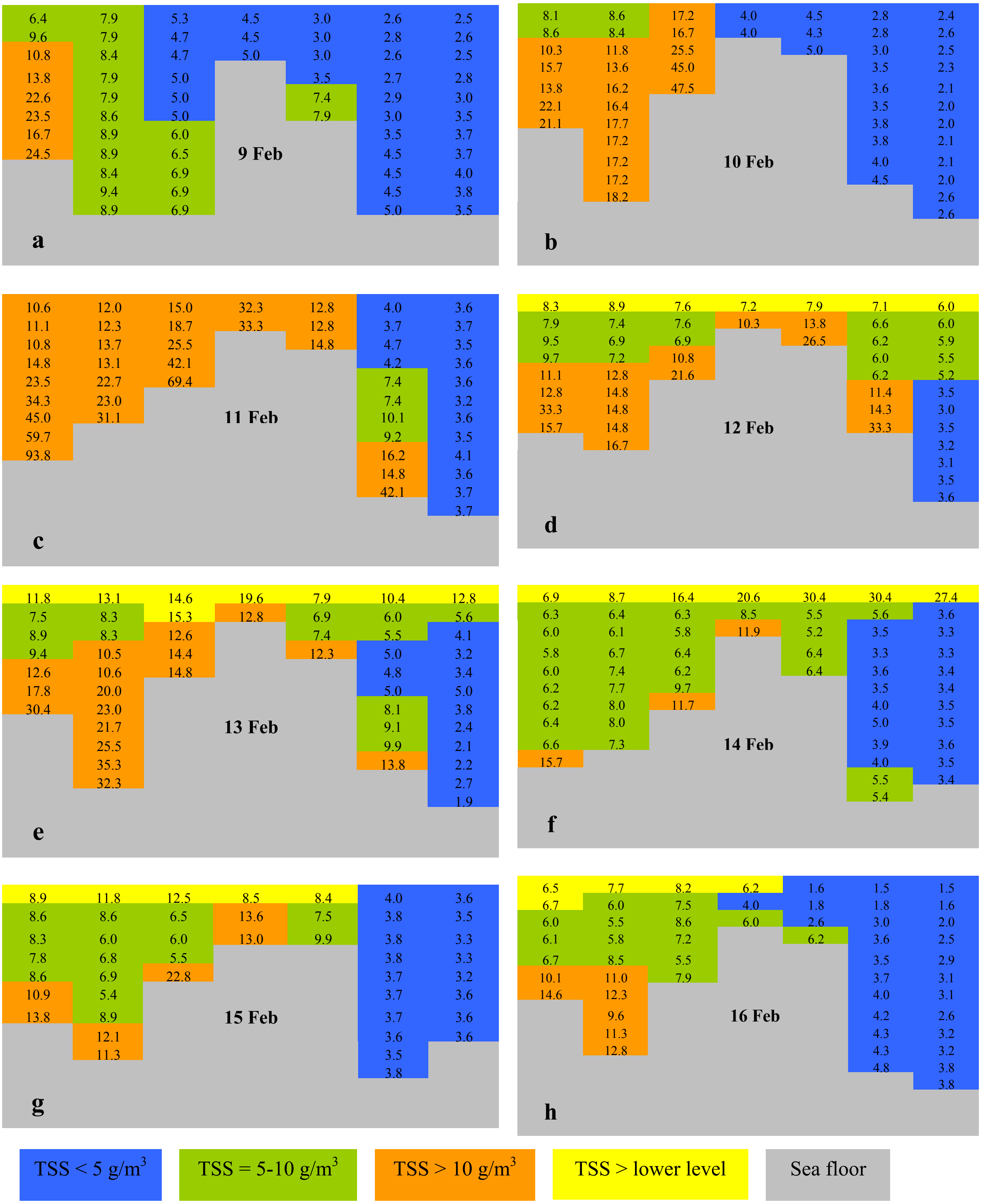

Figure 4.13. TSS vertical profiles along the jetty, 9-16 February. The most offshore station is on the right.

4.1.6. Sediment and nutrient export

Sediment transport takes place between two moments: the initiation of particle motion by scour or erosion, and the settling of particles where the turbulence is below a critical level for suspension. Export of sediments can take place through the water column (suspended sediments) and as bottom transport. Sand may partly move in an intermediate mode by jumping over the bottom, which is called saltation. As the proportion of suspended sediments in total sediment load in lowland rivers varies from 70 to 95 % (Lenzi et al 2000), the Herbert River sediment transport can be approximated by suspended sediment export estimates.

The average TSS concentration during the flood period multiplied by the total discharge for the duration of the flood provides the first approximation of suspended sediment export from the river. Assuming an average suspended particulate matter concentration in the Herbert River mouth of 83 g/m^3 during the 2004 flood (11-15 February) and integrating the river discharge over the same period, the above procedure results in an export flux of about 62,000 t of suspended sediments from the river mouth. Similar calculations for phosphorus produce estimates of 47 tP of particulate and 14 tP of dissolved phosphorus having been transported through the river mouth during the Herbert River flood. These estimates are consistent with a previous study of the flood-mediated sediment and nutrient exports from the Herbert River following Cyclone Sadie in January 1994 (Mitchell et al 1997). Those export figures, for a larger flood event in the Herbert River (maximum discharge for the 1994 flood was around 380,000 ML/day), were 84,000-100,000 t, 52-54 tP and 11-13 tP for TSS, PP and DP export fluxes, respectively.

Considering the average annual sediment, particulate and dissolved phosphorus exports in the Herbert River of circa 0.2×10^6 t, 150 tP and 50 tP, respectively (Horn 1998; Neil et al 2002; Furnas 2003), the above estimates indicate that about 30 % of the annual total suspended sediment and nutrient loads were exported from the Herbert River catchment during 5 flood days in February 2004. This example demonstrates the significance of such brief high-discharge events in annual exports of sediment and nutrients from the studied fluvial system.

Estimates of the residence time of sediments in an estuary are complicated by the deposition of sediment in the estuary: some sediment will be moved again shortly after deposition, e.g. at the next tide or the next flood, whereas other sediment may remain deposited for a considerable period of time (Eisma 1993). However, under the rather crude assumption that all the material that was transported through the river mouth reached the coastal ocean, a general idea of the amount of sediment washed out into the coastal ocean and the amount deposited in the estuary can be derived. Under these considerations and assuming that the average suspended particulate matter concentration in the coastal ocean during the 2004 flood had decreased to 12 g/m^3 (average surface TSS along the jetty for 11-15 February), the estimate of the suspended sediment flux in the coastal ocean results in an export flux of about 9,000 t of suspended sediments, or about 15 % of the export flux at the river mouth. The fraction of the Herbert River sediments in suspension being deposited in the estuary versus that carried out into the coastal ocean is consistent with a similar study in the Gironde estuary, where it was found that on average circa 70 % of the supply is trapped in the estuary and only 30 % is moved outwards into the coastal sea (Eisma 1993).

Assuming that (i) particulate phosphorus follows the suspended sediment dynamics, (ii) all dissolved material is transported into the coastal ocean, and (iii) all phosphorus is consumed by phytoplankton, the above export fluxes of particular and dissolved phosphorus translate into about 900 t of carbon by the Redfield ratio. It can be further estimated, adopting the carbon–chlorophyll conversion factor of Falkowski and Woodhead (1992), that 18 t of chlorophyll were produced in the coastal ocean in the 2004 flood aftermath. For plume dimensions similar to that observed in the area on 20 February 2004 (section 3.1.3), the above estimate gives an average chlorophyll concentration of 3 mg/m^3 in the flood-affected coastal waters (assuming phytoplankton is spread in the upper 10 m of the surface ocean). Such levels of biological production are similar to those measured in situ in the coastal ocean following the Herbert River flood in 2004 (Figure A6, Appendix 4). It can be concluded, then, that the bulk of nutrients exported during the February 2004 flood event from the Herbert River was consumed by phytoplankton in a 20x30 km area of the adjacent coastal ocean.

4.1.7. Conclusion

(1) The delivery, flux and fate of suspended sediments and nutrients in the Herbert River and adjacent coastal ocean were studied extensively during the moderate flood in February 2004. The relationships observed between river discharge, organic and inorganic suspended sediments, and particulate and dissolved phosphorus allowed the major factors controlling particle transfer processes in the Herbert River – coastal ocean environment to be established.

(2) Three sediment and nutrient regimes were observed in the Herbert River mouth during the February 2004 flood, resulting in distinctive patterns in all water properties studied. These regimes highlight the significant and often complex interplay of hydrodynamic and geomorphologic forces (i.e. river flow, tidal dynamics, river-bed

shape and types of sediment) that determine the observed distributions of sediments and nutrients.

(3) Bottom resuspension, advection of floodwaters and precipitation of riverine sediments were the major processes responsible for the observed multi-layered stratification of suspended sediments in the coastal ocean.

(4) This study illustrates the potential for high sediment and nutrient export from the Herbert River during brief flood events. Most of the suspended sediment export was immediately deposited in the estuary, while the remaining part was pushed into the coastal ocean, forming a buoyant surface layer of turbid waters. The majority of nutrients exported during the flood event from the Herbert River were consumed by phytoplankton in a relatively small area of the adjacent coastal ocean.