Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef

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Abstract

Fine sediment dynamics were recorded in February 2007 in coastal waters of the Great Barrier Reef during a moderate flood of the Tully River. An estuarine circulation prevailed on the inner continental shelf with a surface seaward velocity peaking at 0.1 m s^{-1} and a near-bottom landward flow peaking at 0.05 m s^{-1}. Much of the riverine mud originating from eroded soils was exported onto a 10 km wide coastal strip during the rising stage of the river flood in the first flush. In coastal waters, suspended sediment concentration peaked at 0.2 kg m^{-3} near the surface and 0.4 kg m^{-3} at 10 m depth in calm weather, and 0.5 kg m^{-3} near the surface and 2 kg m^{-3} at 10 m depth during strong winds when bottom sediment was resuspended. Diurnal irradiance at 4 m depth was almost zero for 10 days. The sedimentation rate averaged 254 (± 33) g m^{-2} d^{-1} over the 28-day study period, and concentrations of dissolved and particulate nutrients originating from the river were high. The observed low irradiance would have prevented coral photosynthesis, while the sedimentation rate would have been lethal to some juvenile corals. The mud may ultimately be minnowed out, however, this flushing occurs at time scales much longer than the flood event and is likely to affect coral physiology for significant periods after the flood has subsided. The data show the need to better control erosion on farmed land for the conservation of coral reefs on the inner shelf of the Great Barrier Reef.

Keywords: river plume, fine sediment, sedimentation, resuspension, coral, Australia

1. Introduction

Worldwide the health of coral reefs is declining due to a variety of human activities (Hughes and Connell, 1999; Wilkinson, 2004; Pandolfi et al., 2005). Runoff of sediments, nutrients and agrochemicals from adjacent catchments is a major threat to coastal coral reefs including those of the Great Barrier Reef (GBR) of Australia (Brodie et al., 2001; Wolanski and Dea'th, 2005). In small bays (length <2 km), river floods deposit terrigeneous mud directly onto coral reefs (Golbuu et al., 2003; Wolanski et al., 2003; Victor et al., 2006). This mud originates from river floods and storm-induced resuspension and degrades coral reefs by shading and smothering benthic organisms (Rogers, 1990; Wolanski et al., 2005). Algal mats further retain the mud and prevent the recruitment of coral larvae (Richmond et al., 2007). In systems where the reefs are located not directly at the river mouths but offshore on a continental margin, such as in the GBR, there remains much uncertainty about how much of the riverine mud reaches coral reefs. Parts of the GBR coast are becoming increasingly muddy due to human activities within the river catchments (Duke and Wolanski, 2001; Wolanski and Duke, 2002). Some of that mud is exported offshore by northward moving currents (e.g. Orpin et al., 1999; Francis et al., 2007) and as a bottom-tagging nepheloid layer (Wolanski and Spagnol, 2000; Brinkman et al., 2004). There have been no studies of the transport of mud to GBR coral reefs during river floods.

This paper reports the results of a field study of the fate of mud during a river flood in the GBR. The data show that in calm weather the bulk of the terrigenous mud is deposited inshore; nevertheless a large amount of mud reaches coral reefs up to 10 km offshore during the first flush of sediment during the rising stage of the river floods; the mud deposited inshore was later resuspended during storms and redistributed by oceanic currents up to 20 km offshore, extinguishing irradiance over coral reefs at 4 m depth for 10 days during this study.

2. Methods

The study was carried out offshore and north of the mouths of the perennial Tully and Murray rivers, North Queensland, Australia, in the Northern GBR (17° 59' S, 146° 08' E, Fig. 1). The Tully River is the larger of the two rivers, draining a wet tropical catchment of 10,130 km^2. The mean freshwater discharge is 14.2 m^3 s^{-1} with a marked seasonal fluctuation characterized by peak flows in the wet season (December – April) with a maximum recorded discharge of 697 m^3 s^{-1}, and smaller flows usually <5 m^3 s^{-1} during the rest of the year. The river exports annually about 10^5 tonnes of sediments, 1,000 tonnes of nitrogen and 100 tonnes of phosphorus (Furnas 2003). The smaller Murray River, located about 10 km south, further adds about 40% of the Tully freshwater, sediment and nutrient discharges into coastal waters of the GBR.

Moorings were deployed between January 20 and February 19, 2007 (Fig. 1). Upward looking, bottom-mounted RDI Acoustic Doppler Current Profilers (ADCP) and, at the inshore sites, Nortek single point current meters were deployed at sites along two cross-shore transects. SBE37 SeaBird salinometers, Analite nephelometers, and Nortek Awac wave gauges were also deployed at 4 m depth at these sites as well as on the seaward and the landward sides of Dunk and Bedarra Islands. Analite nephelometers, some with light sensors measuring photosynthetically active radiation (PAR) between 400 and 700 nm, and sediment traps (10.5 cm internal diameter, 38.5 cm high) were also deployed at the upper and lower reef slopes at the eastern and western sides of these islands 0.5 m above the substratum, and at 4 of the mooring sites. The wave gauges recorded data in bursts of 2048 samples at 0.5 sec intervals. All other instruments recorded data at 10 min intervals. The vertical bin size for the ADCP was 0.5 m. Twelve of the 20 sediment traps were replaced on February 3 2007. The others remained in place for 28 days.

Vertical profiles of temperature, salinity, dissolved oxygen concentration (DO), and suspended sediment concentration (SSC) were also obtained using a SeaBird SBE19plus CTD cum-OBS profiler at all mooring sites and along a cross-shelf transect on February 2, 4, 18 and 19, 2007 (sites 0-8, Fig. 1). At the same times, surface water samples were taken and processed for concentrations of dissolved and particulate nutrients, total suspended solids, chlorophyll and phaeopigments using standard laboratory procedures as outlined in Cooper et al. (2007). The sediments collected in the traps indicated mean sediment flux per day, and dried materials were analysed for percentages of carbonate, organics (loss after ignition), calcium, aluminum, iron and nutrients (total phosphorus and nitrogen, total organic and inorganic carbon).

Daily rainfall data at Tully, about 20 km inland along the Tully River, and twice daily wind data at Lucinda, a coastal town located about 70 km south of the study area, were obtained from the Australian Bureau of Meteorology.

3. Results

Between 20 and 26 January 2007, 132 mm of rainfall was recorded at Tully (Fig. 2). Intense rainfall started on January 30 and lasted until February 7; the total rainfall in that period was 1022 mm.

The Tully River flooded from January 31 for about 10 days (Fig. 2).

Meso-tidal, semi-diurnal tides prevailed with neap tides centered around January 26 and February 10 (Fig. 2). The wind was variable and moderate (wind speed <8 m s^{-1}) until January 29 when strong winds (speed ~15 m s^{-1}) with a northward longshore component occurred until February 9. Thereafter, light to moderate winds prevailed until February 18 when strong winds occurred again.

The significant wave height was similar at the windward sides of the two islands (not shown) and peaked at 0.8 – 1.4 m during each period of strong winds (Fig. 2), during which times the significant wave period was 5-7 s (not shown). The rest of the time, the significant wave height was less than 0.2 m.

The tidally-averaged longshore currents fluctuated with the wind, lagging the wind by about 16 hours (Fig. 2). The longshore southward currents peaked at 0.2 m s^{-1} and longshore northward currents peaked at 1 m s^{-1}, and were quite similar at all mooring sites (not shown). The tidal currents peaked at 0.1 m s^{-1} (not shown). The tidally-averaged longshore currents increased in magnitude with elevation above the bottom, being typically 50% smaller near the bottom than near the surface, and they did not reverse direction with depth (not shown). The tidally-averaged cross-shore currents reversed direction with depth during the river flood, with a seaward flow in the top layer on February 1 peaking at 0.1 m s^{-1} and a landward flow in the bottom layer peaking at 0.05 m s^{-1} (Fig. 3). This current vanished on February 2 and was re-established, but was 50% smaller, on February 3; it vanished again on February 5 (not shown).

The near-surface salinity at all the mooring sites was about 35 on January 22. It decreased markedly from January 31 onward and reached a minimum of 16 on February 8 (Fig. 2). It increased thereafter until February 15. The salinity of inshore waters (e.g. site D1 in Fig. 2) decreased by 0.3 between 26 and 29 January, thus before the peak flood event. There was considerable temporal variability of the salinity exemplified by several spikes of low salinity at most sites, indicating low salinity patches imbedded in the river plume (Fig. 2).

The suspended sediment concentration (SSC) in surface waters commonly peaked at all sites at ebb tides at about 0.3 kg m^{-3} with maximum values of 0.6 kg m^{-3} (Fig. 2) and at 2.9 kg m^{-3} at 10 m depth (not shown). As highlighted by the arrow in Fig. 2, the SSC values rose measurably in calm weather on January 28, a day before the peak of the river flood (i.e. the lowest salinity).

Sedimentation averaged 283 g m^{-2} d^{-1} (± 40.0 SE) near the bottom around reefs, and 123 (± 26.7) g m^{-2} d^{-1} in mid-water at the mooring sites over the 28 day period (Fig. 1). Sedimentation was highest at the western reef slope of Dunk Island, averaging 344 (± 61) g m^{-2} d^{-1} over all sites and over 28 days, peaking at 660 g m^{-2} d^{-1} at some sites. The concentration of organic matter, carbonate, aluminum and iron of the sediment in the traps averaged 7.16 %, 7.66 %, 5.95% and 3.23 %, respectively. Concentrations of dissolved inorganic nitrogen (NO_3, NO_2 and NH_4), phosphate and silicate in the water were high, peaking at 19.39 (± 0.85), 0.35 (± 0.08), and 54.0 (± 0.24) μmol L^{-1}, respectively during the rain period (4th February 2007) at outgoing tide near the river mouth. Ten of the 15 measures of nutrient concentration (namely, the dissolved inorganic forms of nitrogen, phosphate, dissolved organic carbon, and various forms of particulate nutrients) were significantly negatively related to salinity (Fig. 4) but unrelated to wave height, suggesting riverine origin (linear models, $p < 0.001$ for salinity, $p > 0.1$ for wave height in all cases; not shown). In contrast, chlorophyll, phaeopigments and total suspended solids were unrelated to both salinity and wave height ($p > 0.1$ in all cases; not shown).

Diurnal irradiance at 4 m depth declined to near-darkness during the period of rain and river flood between January 30 to February 9 (Fig. 2).

On February 2, the river plume was 5-7 m thick, it extended 20 km offshore, and the bulk of the suspended sediment settled out within the first 5 km (Fig. 3). The dissolved oxygen concentration decreased by no more than 0.5 ppm from the surface to near-bottom below the river plume (not shown).

4. Discussion

The dominant currents were longshore and phase-locked with the wind, a typical finding for coastal waters of the GBR (Wolanski, 1994). The net current was oriented at about 0^o when northward longshore and 150° when southward longshore (Fig. 2). Thus the longshore currents did not reverse 180° when they changed direction; this generated considerable cross-shore currents. Furthermore, the cross-shore currents reversed with depth during the river flood in the form of an estuarine circulation in coastal waters with seaward flow near the surface and landward flow near the bottom, as saltwater is pushed out of the estuaries during floods due to the shallow depth of the estuaries (depth <5 m; King et al., 2001). These processes enabled the river plumes to spread at least 20 km offshore, twice as much as that predicted by numerical models (King et al., 2001).

Low-salinity patches were imbedded within the river plume, an observation reported earlier by Wolanski (1994), and patch size was typically about 1 km. This patchiness implies that fine-scale temporal and spatial sampling is necessary to reliably map these river plumes and assess their impact on coral reefs.

In calm weather, the SSC events coincided with low salinity, indicating that these were low-salinity, turbid water patches. They were usually incoherent from site to site, suggesting that the size of these patches was less than 1 km. The low-salinity event of January 30; however, was an exception as SSC and salinity were coherent from site E3 to E5, indicating a patch size of about 2 km. During this event, the SSC also increased at 10 m depth, i.e. below the river plume (Fig. 2), indicating that the sediment was settling out of the river plume.

The surface SSC values on the coral reefs of the two islands first peaked at about 0.5 kg m^{-3}, two days before the peak of the flood (the minimum salinity), at a time when the salinity had only decreased by 0.3. This happened in calm weather when there was no resuspension of bottom sediment (see the arrow in Fig. 2). This suggests that the bulk of the fine sediment reached the coral reefs from the first flush of mud eroded from the river catchment during the rising stage of the river flood (Fig. 5; Wolanski, 1994). The first flush effect is also made apparent by the observation that two days later, on February 2, the river plume water had lower salinity but was much less turbid, with SSC values peaking at only 0.02 kg m^{-3}.

As the river plume was receding, bringing little new terrigenous sediment, corals continued to be exposed to high turbidity events due to resuspension of mud during storms that occurred during the remaining 2 weeks of the study. These SSC peaks all occurred during periods of high wave action, implying resuspension of both freshly deposited mud additionally to the older seafloor material. This explains the much higher SSC values at 10 m than at 4 m depth, and the higher SSC values at low tide than at high tide. Wave-induced resuspension minnowed the deposited sediment to a depth of about 12 m in exposed waters and about 3 m in the sheltered waters downwind of the islands (Fig 5; Wolanski et al., 2005).

Sedimentation rates were high throughout the period, with some of the western reef sites of Dunk and Bedarra Island experiencing >9.6 kg m^{-2} deposition within the 28- day long study period. Sedimentation rates of ~70 mg cm^{-2} d^{-1} are known to induce photophysiological stress, and when sustained over several days results in partial mortality in adult corals (Philipp and Fabricius, 2003). Such rates were recorded at several sites over the 28 days of the study. Sedimentation stress in corals increases with increasing concentrations of organic and nutrient related matter in sediments, and the values recorded here were similar to those sediments that caused high sedimentation stress in corals under experimental conditions (Weber et al., 2006). During the resuspension events, the high SSC values (0.5 kg m^{-3} in surface waters and 2 kg m^{-3} at 10 m depth) attenuated irradiance to almost zero at a few meters depth for 10 days during our study, adding to the physiological stress of corals. High rates of sedimentation of material rich in organic and terrigenous matter also coincided with high levels of nutrients in the water column, further adding stress to coral communities as spikes of some of these nutrients promote macroalgal productivity on reefs (Schaffelke 1999). The negative relationship between nutrient concentrations and salinity strongly suggested riverine origin of these nutrients. Chlorophyll was unrelated to salinity, which is expected since phytoplankton only grows at suitable levels of salinity and irradiance. Similarly, total suspended solids were unrelated to salinity due to turbidity being strongly influenced by resuspension. Specific tracers that decay over time will be needed to determine what proportion of the resuspended material was newly imported.

Therefore, as shown in Figure 5, river plumes deposited mud directly within the inner shelf of the GBR including nearshore coral reefs during the early rising stage of the river flood, as a result of the first flush of soil from the river catchment. This mud was later resuspended by wind-driven waves and redistributed by advection and diffusion due to strong longshore and cross-shore currents to a distance of at least 20 km offshore. The mud deposited below the resuspension depth (~12 m in open waters and 3 m in sheltered waters; Wolanski et al., 2005), may remain on the bottom except if shifted by cyclonic waves. Strong wind events resuspend the mud above this resuspension depth and maintain high turbidity over coral reefs until it is advected away or deposited in deeper waters. This sedimentation occurs during the wet season, which is also when juvenile corals have just settled on the substratum, and these juveniles are particularly susceptible to nutrient-rich sediments (Fabricius et al., 2003). The implication is that the GBR coral reef ecosystem extends into adjacent watersheds, and their conservation in Marine Protected Areas will fail without a decrease of soil and nutrient erosion in the adjoining river catchment coupled with the creation of terrestrial protection areas to act as buffer zones (Richmond et al., 2007).

A comparison of the results of this study at a scale of 20 km, as depicted in Figure 5, with that of Wolanski et al. (2003) of the fate of mud in small embayments at a scale of hundreds of metres, shows that the processes are similar in both systems and the impact on coral reefs is similar. In both systems, the riverine mud is initially deposited inshore by river plumes and then re-distributed by waves and currents.. Processes on the GBR inner shelf at a scale of 20 km appear to be similar to those in mangrove swamps at a scale of a few to tens of meters (Furukawa et al., 1997). In mangrove swamps, the mud is trapped in sheltered zones amongst the mangroves, while in the GBR the mud is initially trapped in sheltered zones behind islands and reefs (Fig. 5). In mangrove swamps, the freshly deposited sediment is reworked by bioturbation and redistributed by waves and currents (?)(tides?), while in the GBR it is reworked by waves and redistributed northward by longshore currents and nephloid layers (Orpin et al., 1999; Wolanksi and Spagnol, 2000; Francis et al., 2007). Thus ultimate result, that is the redistribution of terrigenous material through the ecosystem, is the same in both systems. Thus, this study has demonstrated that scale does not protect inshore coral reefs from exposure to riverine mud. As inshore corals are generally surrounded by a shallow seafloor, waves repeatedly resuspend the material and prolong the exposure of the benthos to suspended sediment until it is moved out of the GBR (Francis et al., 2007). The key question for inshore coral reefs of the GBR is whether the yearly gain of riverine mud exceeds the yearly export of mud by oceanographic processes (Richmond et al., 2007), and a net sediment budget for the inshore GBR is needed to answer this question.

5. Acknowledgments

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6. References

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Text for figures

Figure 1. Map of the study area showing the bathymetry and the location of the CTD casts (○) and of the oceanographic moorings on the inner shelf (▀) and on the slopes of the islands adjacent to the fringing coral reefs (●). Inserts: sedimentation rates over 28 days (± SE) with black and light grey representing organic and carbonate components, respectively.

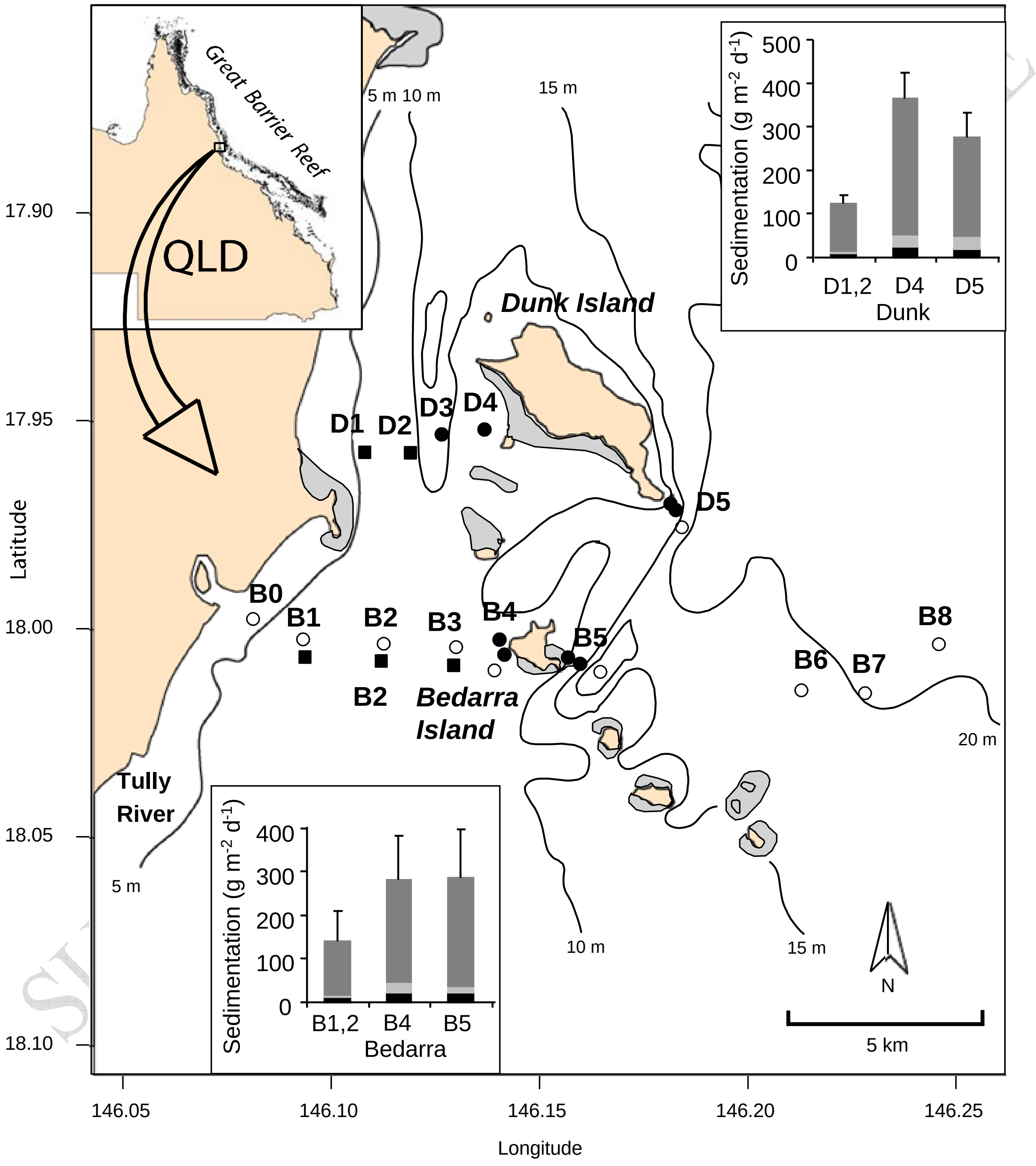
Figure 2. Time-series plots of daily rainfall R, Tully River freshwater discharge Q_f, sea level h, significant wave height h_s, wind vectors W (shown using oceanographic convention), tidally-averaged current vectors u at site D2, salinity S at sites D4 (- - -), B4 (━━━━) and B5 (—), suspended sediment concentration SSC at 4 m depth at sites B4 (━━━) and B5 (—) and at 10 m depth at site D5 (▬ ▬), and irradiance at 4 m depth at site D4. SSC values at 10 m depth at site D5 peaked at 2.9 kg m^{-3}; values greater than 0.5 kg m^{-3} were clipped.

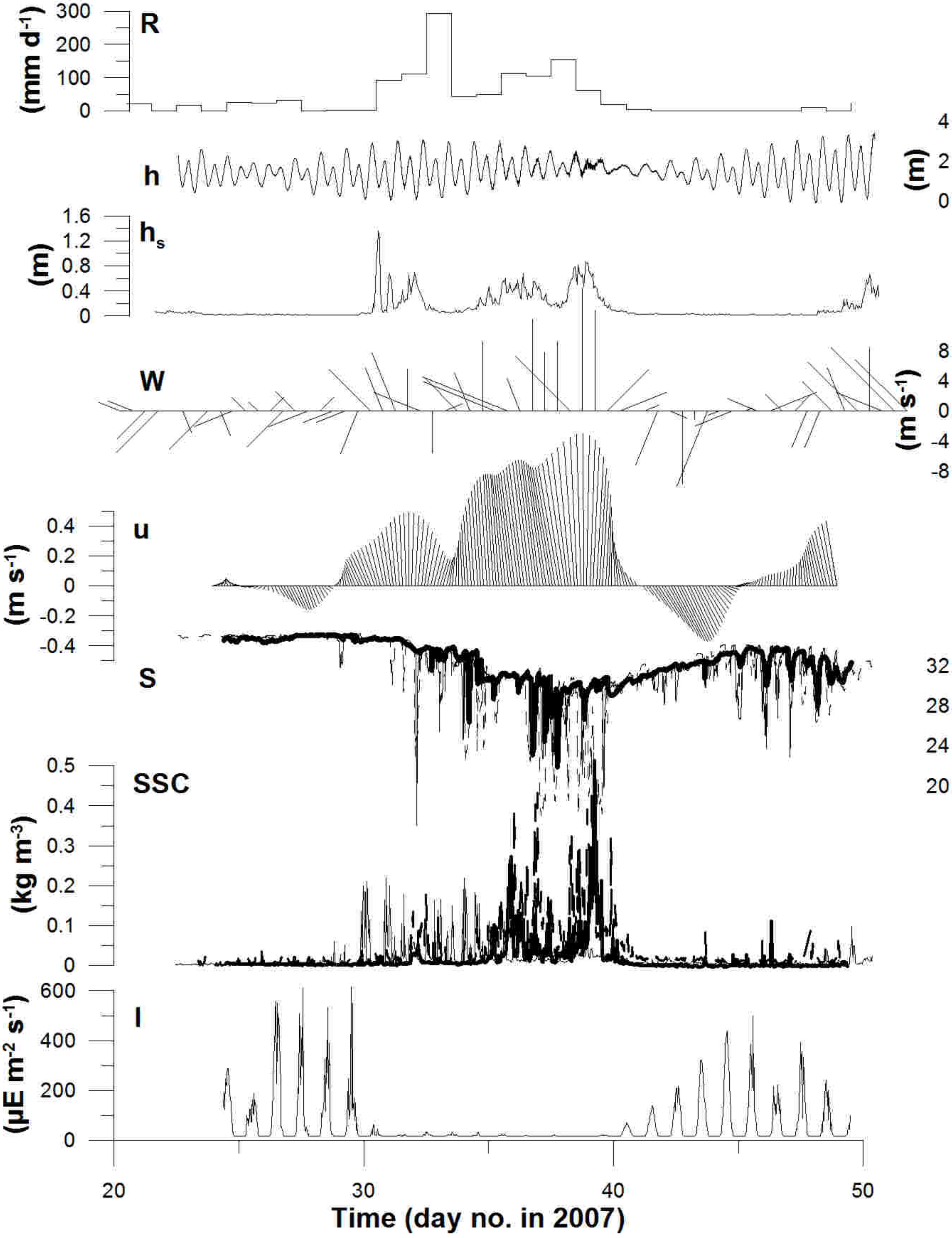
Figure 3. Cross-shore distribution on February 2, 2007, at sites 0-8 (Figure 1) of salinity and suspended sediment concentration SSC (kg m^{-3}), and vertical profile of the tidally-averaged cross-shore current v at site B2 on February 1, 2007.

Figure 4. Relationship of water nutrient concentrations and salinity, suggesting riverine origin and conservative dilution of these nutrients (DOC = dissolved organic carbon; PC, PN and PP = particulate carbon, nitrogen and phosphorus). Except for DOC (mg L^{-1}), all nutrients are presented as μmol L^{-1}.

Figure 5. Schematic of the dynamics of river and fine sediment in the transient river plume, highlighting mud deposition during the first flush Q_s of eroded soil from the catchment during the rise in the river flood Q_f during calm weather, the spread of river plumes, the resuspension and minnowing of that mud during storms and its spread in a wide

area of the inner shelf, the preferential settling of that sediment below the resuspended depth, and the accumulation of sediment higher up in the water column in the shelter zone in the lee of islands and reefs.

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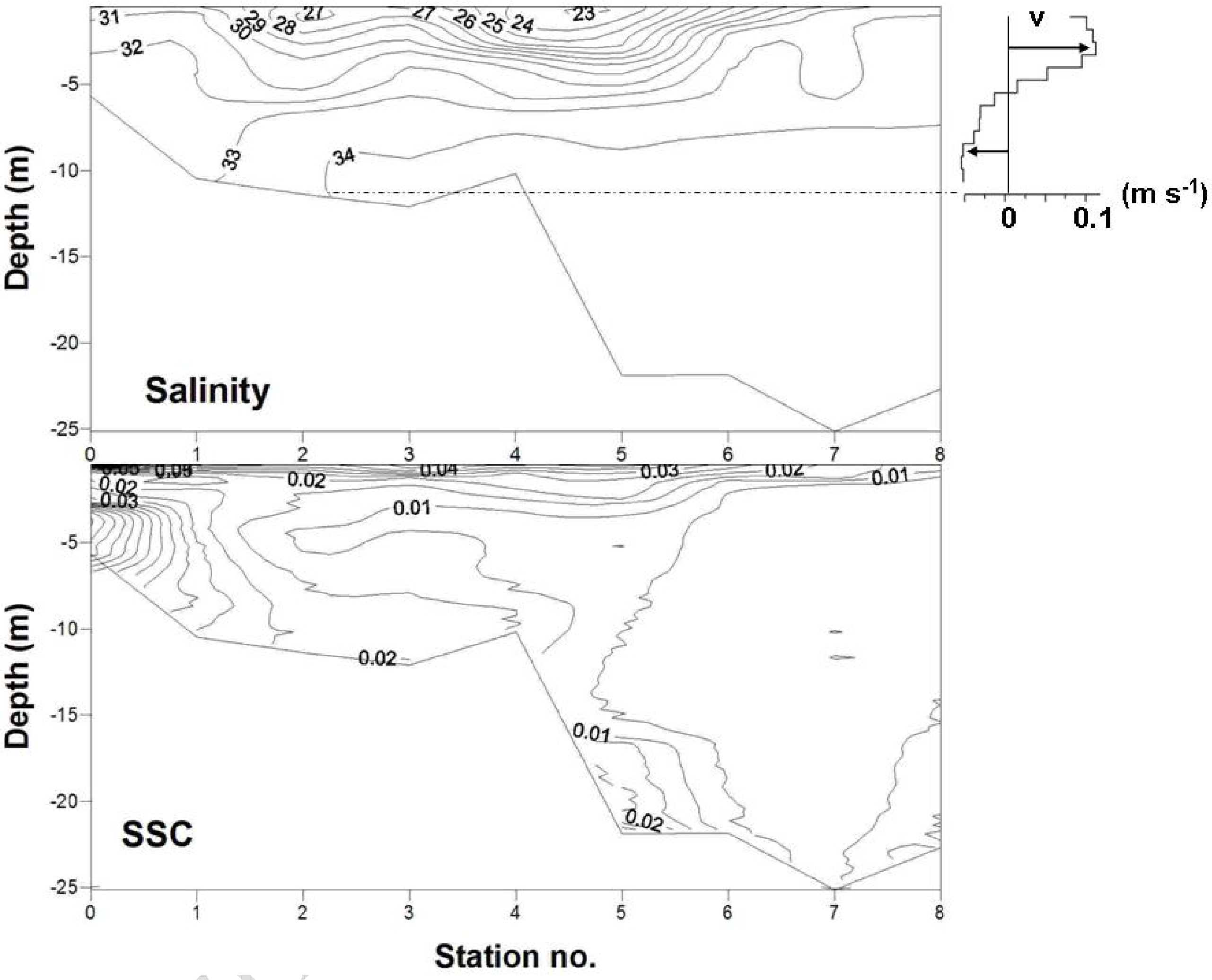
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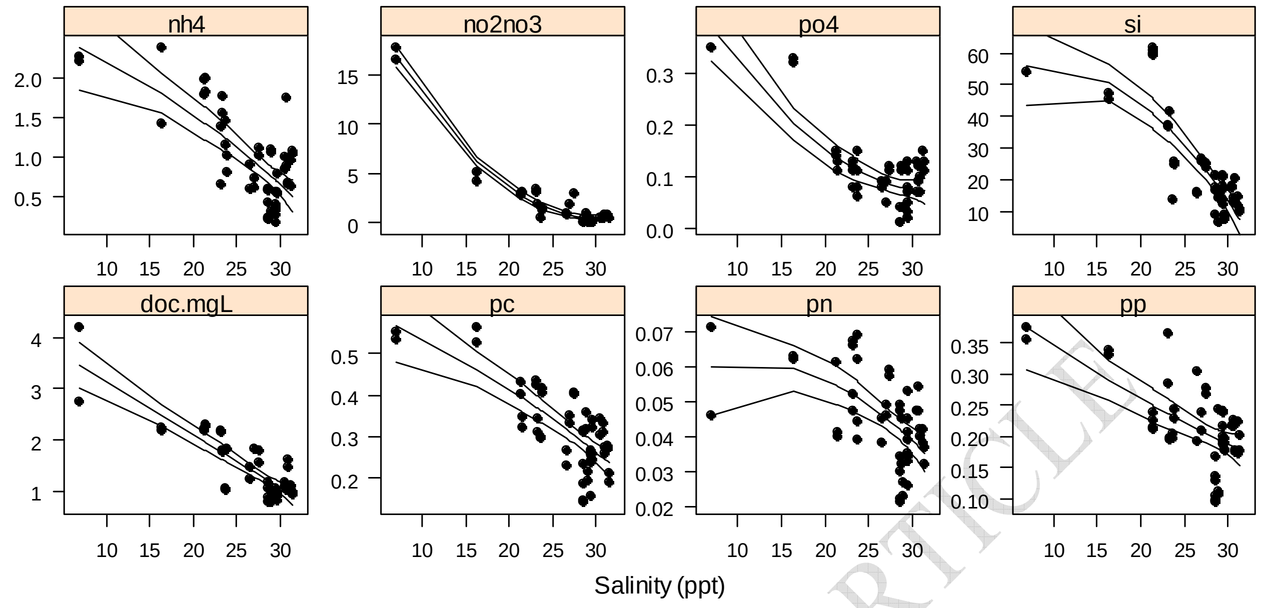
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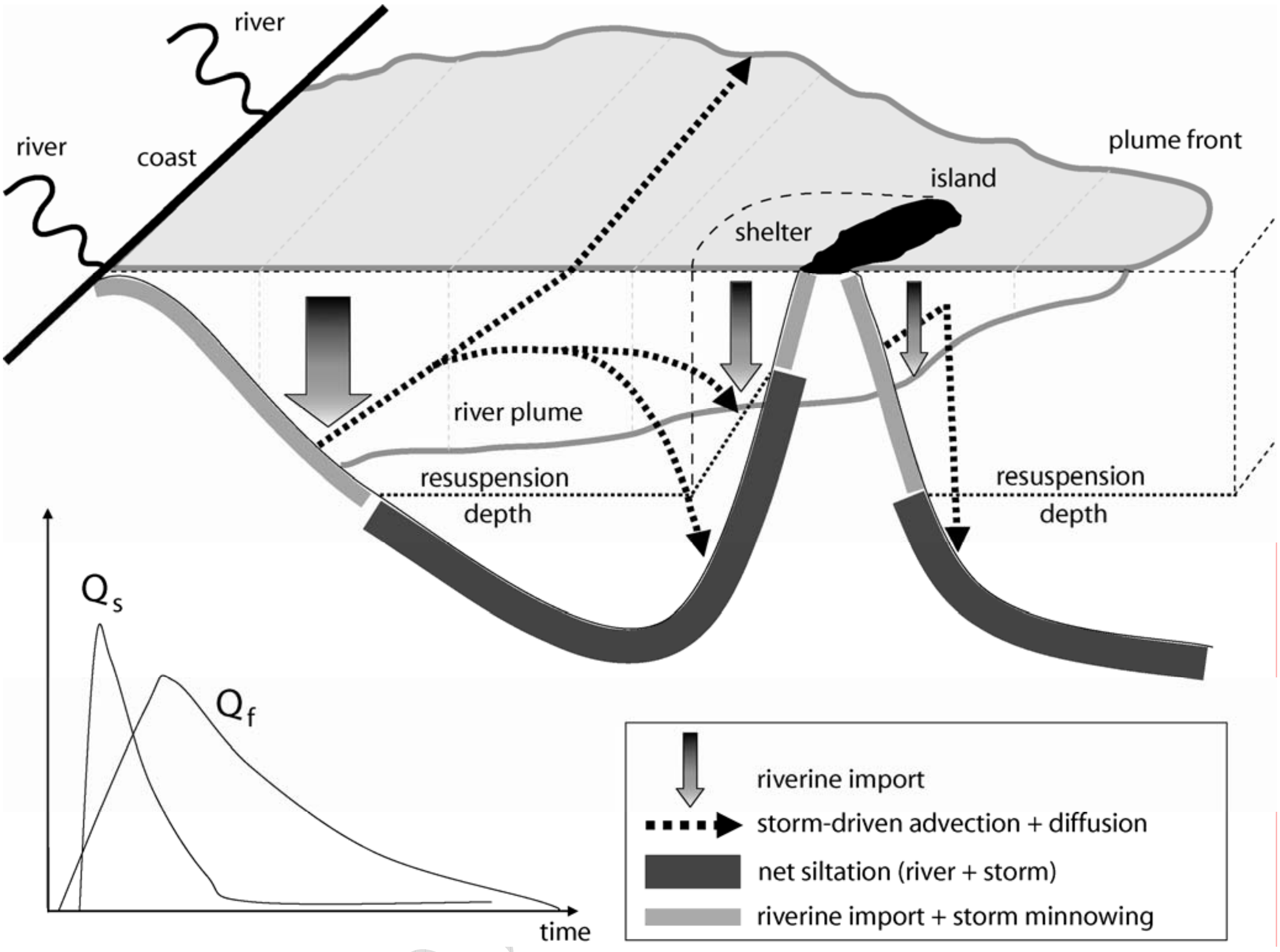
Salinity (ppt)


river
river
coast
plume front
island
shelter
river plume
resuspension depth
resuspension depth
Q_s
Q_f
time
riverine import
storm-driven advection + diffusion
net siltation (river + storm)
riverine import + storm minnowing