GREAT BARRIER REEF
MARINE PARK AUTHORITY

RESEARCH PUBLICATION NO. 68

Flood Plumes in the Great Barrier Reef: Spatial and Temporal Patterns in Composition and Distribution

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SUMMARY

Protecting water quality in the Great Barrier Reef World Heritage Area is recognised as one of the major challenges facing management of the area. One of the most important processes directly impacting the Great Barrier Reef (GBR) is the input of terrestrially derived nutrients and sediments to nearshore regions. This mainly occurs via river run-off, especially during periods of intense rainfall typically associated with tropical cyclones. Flood plumes occur at a time when the majority of inputs into the GBR lagoon are at peak concentrations and reefs and other inshore marine ecosystems then experience the highest concentrations of pollutants. The principal threat to the water quality of the reef arises from changes to the composition of the riverine discharge due to changed land use on coastal catchments. The characteristics of the plume water, including salinity, nutrients, sediment and toxicants pose a range of potential threats to the health of inshore ecosystems.

One of the key research areas of the Great Barrier Reef Marine Park Authority (GBRMPA) is the assessment of riverine input into the GBR lagoon, the importance of flood plumes as a source of nutrients and sediments and the impact of flood plumes on nearshore reef and seagrass communities. The Great Barrier Reef Marine Park Authority, in conjunction with other agencies, runs a multi-institutional research and monitoring program on the discharge properties, composition and spatial dynamics of river plumes entering the GBR. This work forms a component of a larger research and monitoring program to understand the sources, transport and effects of terrestrial pollution on the GBR. This study has monitored and measured flood plumes associated with cyclones from 1991 to 1999. The sampling events were cyclones Joy (1991), Sadie (1994), Violet (1995), Ethel (1996), Justin (1997), Sid (1998) and Rona (1999).

Plume distributions presented in this report establish that the main driving influence on plume dispersal is the direction and strength of wind and discharge volume of the river. Wind conditions are dominated by south-easterly winds which drive the plume north and towards the coast. The greatest number of plumes mapped over this study (Violet, Ethel, Justin, Sid and Rona) were restricted to a shallow nearshore northward band by stronger south-easterly winds following the cyclone. However, under relatively calm conditions such as those following Sadie, light offshore winds allowed the plume to disperse seaward and north over much of the shelf and there was a short period of direct impingement upon mid- and outer-shelf reefs. The flood plume associated with cyclone Joy in the Fitzroy River also moved offshore, following light northerly winds, eventually impinging on reefs of the Capricorn-Bunker group.

The amount of rainfall that falls over a particular catchment can have a marked effect on the distribution of the plume. Another factor in the distribution of flood plumes is the influence of headlands on the movement of the plumes ('steering'). This can be observed most clearly in the vicinity of Cape Grafton (slightly south-east of Cairns) in extent of the Sadie, Violet and Ethel plumes where northward moving plumes are steered across Green Island Reef. Green Island Reef appears to be the one mid-shelf reef of the GBR south of the Daintree, which is regularly covered by river plume water. Therefore the assessment of plumes impacting on mid-shelf reefs adjacent to the Barron River (Green Island) are expected to be underestimates due to effects from other river systems to the south 'steering' past Cape Grafton.

Modelling of the plumes associated with specific weather conditions has demonstrated that inshore reefal areas adjacent to the Wet Tropics Catchment (between Townsville and Cooktown) regularly experience extreme conditions associated with plumes. Inshore areas

(north of the Burdekin and Fitzroy Rivers) receive riverine waters on a less frequent basis. Spatial distribution of the frequency of plume coverage delineates the inshore area of the GBR, which is annually inundated by flood plume waters. This report presents a summary of the frequency and distribution of all flood plumes mapped in the GBR over the last 10 years. From this information, an assessment of the area of risk from river run-off has been developed. Inshore reefs and seagrass beds within this high frequency area and adjacent to agricultural catchments, are seen to be the highest risk from catchment activities.

As part of the assessment of the impact of flood plumes on GBR ecosystems, an estimate is required of the areal and volumetric extent of plumes emanating from the rivers draining to the GBR. The observed distribution of flood plumes between 1994 and 1999 serves as a baseline for evaluating plume distribution with respect to variables controlling plume extent. Based on these observations, a summary of plume distribution for waters discharging in the vicinity of the Russell-Mulgrave and Barron rivers, has been developed with six qualitative fields of plume distribution (inner1, inner2, inner-mid, mid, mid-outer, and outer).

A model has been developed to estimate the expected distribution of a plume using variables which include wind speed and direction coupled with river flow data. Formulation of expected plume distributions over a longer time period than individual observations allows for the identification of reefs that are subject to plumes and an estimate as to the frequency of impact. Based on the model an estimate of spatial extents of plumes has been made using the Barron River as a case study.

Flood plumes from the Barron River are visually apparent from aerial observations with discharges in the order of 30 000 to 40 000 MLd^{-1} (data for Myola gauging station). Based on this information a figure of 30 000 MLd^{-1} was assigned to historical flow data as a primary variable that needed to be exceeded for a plume to develop. Relationships between the discharge criteria and wind conditions experienced between the 1994 and 1999 period were documented to ascertain the extent of the plumes with respect to these two variables. Integrating the wind and discharge data with the mapped plume extents produced a matrix for prediction of plume distribution based on similar historical conditions. The hindcasted plumes provide a preliminary estimate of how frequently plumes extend to a particular area of the GBR. Based on the data for the Barron River it is estimated that in the past 58 years a plume may have reached the mid-shelf reefs (outer category) on 18 occasions.

Plume mapping and use of the model indicates that some reefs in the GBR experience river waters annually, some episodically, some rarely and some never at all. 'Hot spots' can be assigned to the reefs that are inundated by river plumes each year. Inshore reefs, north of the Palm Island group, see river plumes most years. These inshore reefs include Gould Island, King Reef, Brooks Family Group, Frankland Islands, Fitzroy Island, Double Island, Low Isles and Snapper Island. Reefs south of the Palm Islands, including Pandora, Acheron, Rattlesnake, Herald and Phillip Reefs, Magnetic Island reefs and the Whitsundays reefs experience river plumes from coastal and Burdekin River catchment run-off less frequently; perhaps every two to three years. Reefs in the Keppels and Cumberland groups experience river water even less frequently perhaps every four to six years. However, these latest predictions are based on a very limited observational record. Offshore reefs in the southern GBR experience river waters infrequently; only once in the 10 years of this monitoring study. However, a few mid-shelf reefs in the northern GBR do experience river water quite frequently, particularly Green Island.

Data from flood plumes clearly indicate that the composition of plumes is strongly dependent on particular events, between days and through a single event, depths and catchment. Timing of sampling is critical in obtaining reliable estimates of material exported in the flood plumes. There is a hysteresis in the development of a flood plume, which is related to catchment characteristics (size, vegetation cover and gradient) rainfall intensity, duration and distribution and flow volume and duration. The time lag difference is significant in the smaller Wet Tropic rivers (Herbert to Daintree) compared to the larger Dry Tropic rivers of the Burdekin and Fitzroy.

Dissolved inorganic nitrogen (DIN) concentrations measured in the plume are generally high compared to ambient (non-flood) conditions. The number of sites with elevated nutrients suggests that the high nutrient concentrations in the flood plumes extend over a significant area and over a number of days. DIN concentrations are in the range of 1–10 μM, compared to ambient concentrations, typically 0.1 μM.

Dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) concentrations were relatively constant throughout individual plumes, with DOP ranging between 0.1–1.0 μM and DON concentrations typically found between 5 and 15 μM. There seems to be no relationship between increasing salinity and organic nutrient concentrations as organic nutrient concentrations in river waters and lagoon waters in the lagoon have approximately similar concentrations. Organic nutrients, particularly DON, are relatively stable and not known to be rapidly used in any biological process.

Particulate nutrients and suspended matter were higher than ambient conditions with peak concentrations measured adjacent and north of the flooding rivers. Concentrations of particulate nitrogen (PN) reached a maximum of 24 μM and generally were higher than 15 μM at low salinity levels. Concentrations of particulate phosphorus (PP) reached a maximum of 1.0 μM and concentrations of PP were generally higher than 0.5 μM at low salinity levels. Particulate matter settles out over relatively short distances, though concentrations are significantly higher than ambient concentrations for all samples taken within the surface waters associated with flood plumes. PN and PP can be a source of continually desorbing nutrients over long periods. The resulting dissolved nutrients can serve as a nutrient source for phytoplankton growth.

Chlorophyll *a* concentrations had an inverse pattern of increasing concentrations at some distance from the river mouth. This was likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated nutrients and the increasing light as the suspended matter settled out. Chlorophyll *a* concentrations were higher than phaeophytin concentrations in all samples, confirming that most of the chlorophyll detected was associated with new algal biomass stimulated by flood water discharge. Chlorophyll *a* levels were highest in the Fitzroy surface plume, generally 20 times ambient (non-flood) inshore values, indicating an extensive phytoplankton bloom within the plume.

Measurements of all parameters taken further away from the river are influenced by the physical and biological processes occurring over time as the elevated concentrations in the river water mixed with the lagoonal waters of the GBR. Concentrations of NO_x and DIP ranged from 10–15 μM and 0.2–0.5 μM at sites close to the river mouth and declining to levels between 0–2 μM (NO_x) and 0–0.2 μM (DIP) at higher salinity concentrations. Though these later concentrations are still high in comparison to baseline concentrations they do reflect influences by other processes. The distribution of nutrients within the plume is a function of riverine inputs, mixing and biological activity which adds or removes nutrients.

Mixing profiles demonstrate initial high concentrations of all water quality parameters in low salinity waters, with decreasing concentrations over the mixing zone. Mixing patterns for each water quality parameter are variable over catchment and cyclonic event, though there are similar mixing profiles for specific nutrient species. Processes occurring in addition to mixing can include the biological uptake by phytoplankton and bacteria, sedimentation of particulate matter and mineralisation or desorption from particulate matter. These processes can occur at the same time and make it difficult to determine which processes dominate. Nutrients carried into coastal waters by river plumes have a marked effect on productivity in coastal waters.

NO_x and DIP demonstrate a gradual decrease of concentration in the plume away from the river mouth, with a rapid decline in the nutrient concentrations at salinities between 26 and 30. This salinity range is in the area of highest productivity where there is greatest uptake of nutrients by phytoplankton. Ammonia (NH_4) concentrations are far more scattered reflecting both variations in supply, uptake and production from biological processes in the plume. Concentrations of NH_4 remain elevated in the higher salinities suggesting sources of ammonia in the plume, for example, excretion by zooplankton. Values for the river end member were lower than some concentrations at intermediate salinities. This may be related to variability in riverine concentrations over time, combined with multiple discharge points and differing mixing dynamics in various regions of the plume, or higher values occurred at the frontal convergence where biomass levels were concentrated and perhaps regeneration of nutrients was enhanced.

In the initial mixing zone, water velocity is reduced and changes in salinity, pH and eH promote flocculation of particulate matter. Most of the river-derived particulate matter settles from the plume in this zone. This is most clearly shown in the results from the Burdekin for cyclone Sid where suspended solid and particulate phosphorus concentrations drop to very low levels only a few kilometres from the river mouth at salinity of approximately 10. However benthic sediment distribution information shows that the area off the mouth of the Burdekin River has a low proportion of fine sediments. This apparent inconsistency is best explained by the resuspension and northward transport and deposition in northerly facing bays of fine sediments which occurs throughout the year under the influence of the south-east wind regime on the inner shelf. Reductions in suspended sediment with increasing salinity in the plume are less clear in some of the other plumes but this is complicated by resuspension during the plume event in stronger wind conditions on these occasions.

The high spatial variance of nutrient concentrations in the plumes is related to plumes constrained and broken up by islands and reefs, with the complexity directed by the multiple rivers and streams acting as source water for the plume. Outlying scatter points in the mixing graphs could also be due to resuspension processes resulting from rough weather conditions. Samples in plumes are taken on one day (more or less) whereas concentrations of dissolved components vary greatly during flooding in the river, e.g. first flush.

Nutrients such as nitrogen associated with the discharge travel much further offshore than sediment. Concentrations of nitrate and orthophosphate measured in flood plumes reached 50 times the concentrations measured in non-flood conditions. These elevated concentrations are maintained at inshore sites adjacent to the Wet Tropics catchment for periods of approximately one week. Plumes associated with the larger Dry Tropics catchments, the Fitzroy and Burdekin rivers experience elevated concentrations for periods of up to three weeks, but on a less frequent basis.

Concentrations of dissolved nutrients experienced at inshore reefs are considerably above those known to produce adverse affects on coral reef ecosystems, particularly in respect to enhancement of algal growth, reductions in coral reproductive success and increase in mortality.

Changing land practices associated with loss from grazing lands and fertilised cropping has resulted in increases in inorganic nutrients in north Queensland rivers. This has resulted in inshore coral reefs experiencing higher concentrations of nutrients than in past years. Reefs offshore of the Wet Tropics catchment are at a higher risk, specifically those closest to the shore, with annual inundation from high nutrient riverine waters.