Marine and Tropical Sciences Research Facility

Wetlands and floodplains: connectivity and hydro-ecological function

Part I - The role of overbank floods in transporting sediments and nutrients to the Great Barrier Reef lagoon

Jim Wallace, Aaron Hawdon, Rex Keen, Fazlul Karim, Lachlan Stewart and Joseph Kemei

Australian Government
Department of the Environment, Water, Heritage and the Arts

Reef & Rainforest RESEARCH CENTRE

Wetlands and floodplains: connectivity and hydro-ecological function

Part I – The role of overbank floods in transporting sediments and nutrients to the Great Barrier Reef lagoon

Jim Wallace, Aaron Hawdon, Rex Keen, Fazlul Karim, Lachlan Stewart and Joseph Kemei

CSIRO Land and Water, Davies Laboratory, University Road, Townsville, QLD 4814

CSIRO

Australian Government

Department of Sustainability, Environment, Water, Population and Communities

Supported by the Australian Government's
Marine and Tropical Sciences Research Facility
Project 3.7.4 Wetlands and floodplains: connectivity and hydro-ecological function

ISBN 978-1-921359-59-0

This report should be cited as:
Wallace, J., Hawdon, A., Keen, R., Karim, F., Stewart, L. and Kemei, J. (2010) *Wetlands and floodplains: connectivity and hydro-ecological function. Part I – The role of overbank floods in transporting sediments and nutrients to the Great Barrier Reef lagoon*. Final Project Report prepared for the Marine and Tropical Sciences Research Facility (MTSRF). Published by the Reef & Rainforest Research Centre Ltd, Cairns (27pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's Marine and Tropical Sciences Research Facility.

The Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) supports world-class, public good research. The MTSRF is a major initiative of the Australian Government, designed to ensure that Australia's environmental challenges are addressed in an innovative, collaborative and sustainable way. The MTSRF investment is managed by the Department of Sustainability, Environment, Water, Population and Communities, and is supplemented by substantial cash and in-kind investments from research providers and interested third parties. The Reef and Rainforest Research Centre Limited (RRRC) is contracted by the Department to provide program management and communications services for the MTSRF.

Cover photograph: Burdekin River in flood, 2007 (GBRMPA).

This report is available for download from the
Reef and Rainforest Research Centre Limited website:
http://www.rrrc.org.au/publications/research_reports.html

Report first completed June 2010
Published by RRRC February 2011

Contents

List of Figures

List of Tables

Acronyms and Abbrevations

ACTFR .... Australian Centre for Tropical Freshwater Research

BOM .... Australian Bureau of Meterology

CSIRO .... Commonwealth Scientific and Industrial Research Organisation

DEWHA .... Commonwealth Department of the Environment, Water, Heritage and the Arts (now Sustainability, Environment, Water, Population and Communities)

DIN .... Dissolved Inorganic Nitrogen

DON .... Dissolved Organic Nitrogen

DOP .... Dissolved Organic Phosphorus

DNRW .... Queensland Department of Natural Resources and Water (now Environment and Resource Management)

FRP .... Filterable Reactive Phosphorus

GBR .... Great Barrier Reef

MTSRF .... Marine and Tropical Sciences Research Facility

NRM .... Natural Resource Management

PN .... Particulate Nitrogen

PP .... Particulate Phosphorus

TN .... Total Nitrogen

TP .... Total Phosphorus

TSS .... Total Suspended Sediment

WQIP .... Water Quality Improvement Plan

Acknowledgements

We would like to thank the Marine and Tropical Sciences Research Facility (MTSRF), funded by the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA), as well as Terrain NRM Ltd., and the CSIRO Water for a Healthy Country Flagship for co-funding this study. We are also grateful for the assistance of the Australian Centre for Tropical Freshwater Research (ACTFR) for processing our water quality samples. We would also like to acknowledge the supply of rainfall data from the Australian Bureau of Meteorology (BOM) and river flow data from the Queensland Department of Natural Resources and Water (DNRW). We are grateful to CSIRO colleagues and the external reviewers for their very helpful comments on this manuscript.

Executive Summary

The potential for agricultural practices to enhance the loads of sediment and nutrients entering the Great Barrier Reef (GBR) lagoon has led to the development of a number of catchment based 'Water Quality Improvement Plans' (WQIPs). These plans identify the current constituent loads along with a set of management practices to reduce them. The current sources and annual average loads of sediment and nutrient are estimated using gauged river flow and concentration data and runoff water quality modelling. However, in catchments that are subject to frequent flooding, standard river gauges may significantly underestimate overbank flood flows. This is the case in the Tully and Murray catchments where the river gauges do not record the total catchment discharge during floods very well. For example, during the thirteen flood events between 2006 and 2008 investigated in this study, the Tully river gauge at Euramo recorded only 36-88% of the flood discharge, while the Upper Murray gauge recorded only 11-27% of the flood discharge. Furthermore, current ocean sediment and nutrient loads are based on concentrations measured within the rivers, yet it is not known what the sediment and nutrient concentrations are in overbank flood waters.

This report addresses these issues by updating current estimates of sediment and nutrient loads from the Tully-Murray floodplain to the GBR lagoon, taking explicit account of flood events. New estimates of flood discharge that include overbank flows are combined with direct measurements of sediment and nutrient concentrations in flood waters to calculate the loads of sediment and nutrient delivered to the ocean during the above mentioned flood events between 2006 and 2008. Although absolute concentrations of sediment and nutrient were quite low, the large volume of water discharged during floods means that they make a large contribution (30-50%) to the marine load. By not accounting for flood flows correctly, previous estimates of the annual average discharge are 15% too low, and annual loads of nitrogen and phosphorus are 47% and 32% too low respectively. However, as sediments may be source limited, accounting for flood flows simply dilutes their concentration and the resulting annual average load is similar to that previously estimated.

A second important feature emerges from the flood water quality data, which show that flood waters carry more dissolved organic nitrogen (DON) than dissolved inorganic nitrogen (DIN) and this is the opposite of their concentrations in river water. Consequently, DON loads to the ocean may be around twice those previously estimated from riverine data. Whereas the main source of DIN is from agricultural land, the main source of DON is likely to be from upper catchment rainforest. If runoff to the GBR lagoon has increased due to land drainage, there may therefore be an enhanced and biologically available DON load to the ocean arising from the upper catchment rainforest.

The implications of the flood water quality studies in the Tully and Murray catchments, and potentially for other GBR catchment WQIPs, are as follows:

1. Overbank floods can make a large contribution to the marine load of sediment and nutrients and much of this load may not be recorded by standard river gauges.
2. In GBR catchments where floods are a significant proportion of the annual flow, current marine load estimates of sediment and nutrients (based on gauged flows, measured river concentrations and modelling) are probably too low, by significant amounts, depending on estimation method and constituent.
3. The size of this underestimate in any year will depend on the number and size of overbank flood events in that year. This will make the monitoring of any underlying trends in ocean loads difficult unless it is possible to remove inter-annual variability.

4. Monitoring of marine loads will take a significant number of samples of both river and flood flows (in time and space) – otherwise the large uncertainties in mean loads may be misleading and it may be difficult to detect any load reduction trends.
5. The cause of the above underestimate in loads is mainly due to the poor recording of flood (overbank) discharges by river gauges, but also to differences in flood water and river water quality concentrations.
6. Flood waters can carry more DON than DIN, and this is the opposite of their concentrations in river water. Consequently DON loads to the ocean may be much higher than those previously estimated from riverine data.
7. WQIP actions that focus on farm interventions in agriculture will potentially reduce DIN loads.
8. Reductions in DON (and sediment) loads that arise outside the floodplain require different interventions to those used in agriculture to reduce DIN, e.g. measures that slow and reduce drainage and the introduction and/or rehabilitation of riparian zones and wetlands.

The inaugural flood water quality data collected in the Tully and Murray catchments has demonstrated the importance of obtaining observations from the key processes that control the marine loads that are of concern. In the Wet Tropics catchments studied, in addition to chanelised flow, overbank flooding is a primary material transport mechanism and it is very difficult to adequately capture this process in monitoring and/or modelling schemes that are entirely river based. There is therefore a clear need to obtain estimates of the contribution that floods make to marine loads in other GBR catchments.

Introduction

Concern over anthropogenically enhanced loads of sediment and nutrients to the Great Barrier Reef (GBR) lagoon has led to the development of 'Water Quality Improvement Plans' (WQIPs) for a number of catchments adjacent to the Coral Sea, including the Tully and Murray catchments (Kroon, 2008). These plans identify the current status of constituent loads along with a set of management practices to reduce them. In the Tully and Murray catchments in northern Queensland, Australia, the current sources and annual average loads of sediment and nutrient have been estimated using flow and concentration data (Furnas, 2003) and the SedNet model (Brodie *et al.* 2003; Hateley *et al.* 2006; Armour *et al.* 2009) Both of these approaches (measurement and modelling) provide estimates of the annual average load delivered to the ocean by flows from rivers in the GBR catchments. However, particularly in the Wet Tropics, many catchments are subject to frequent flooding, when the water that runs overbank can bypass the river gauges. This ungauged overbank flow may carry a significant load to the ocean that is additional to the current river based load estimates.

This report quantifies overbank flood loads in the Tully and Murray catchments. Flood water sediment and nutrient concentration data were obtained during thirteen floods that occurred between 2006 and 2008. The flood discharge estimates for these events were derived from measurements of catchment wide rainfall, rather than the flows recorded in the Tully and Murray Rivers. Flood concentration and discharge data were then combined to estimate the loads of sediment and nutrient delivered to the GBR lagoon during overbank floods. The contribution of the floods is compared with previous estimates of the annual average loads derived from gauged river discharge and sediment and nutrient concentrations measured at the mouth of the Tully River.

Methodology

Study area and hydro-climate

Figure 1 illustrates the Tully and Murray catchments of northern Queensland, Australia where this study was carried out. The two catchments have a combined area of 2,072 km^2, of which 40% (832 km^2) is within the floodplain boundary (Karim *et al.* 2008). The topography varies from steep rainforest covered mountainous areas in the west, to low relief floodplain containing agriculture in the east. The mean annual rainfall is between 2,000 and 4,000 mm, depending on the location in the catchment. Most rainfall (60-80%) occurs during the wet season from December to April. The two main rivers, the Tully and Murray, discharge into the GBR lagoon.

Figure 2 demonstrates that flooding is common on the Tully-Murray floodplain, with the rivers breaking their banks three to four times a year on average. The mean annual flood has a discharge around twice that of the bank full discharge. As the floodplain topography is very flat and the rivers quite close, water from the two rivers often merges during a flood event.

During the three wet seasons between 2006 and 2008, we monitored nine overbank floods on the floodplain that ranged in size from short duration (one day) just-overbank events (flood numbers 8, 9 and 11), with a return period of roughly three times per year, to a long ten-day overbank flood (flood number 6), with a return period of one in four years (Figure 2). Four other floods occurred in 2006, for which no water quality data were recorded, making a total of thirteen floods in three years; hence the floods sampled are a representative range of the current flood size and frequency in these catchments.

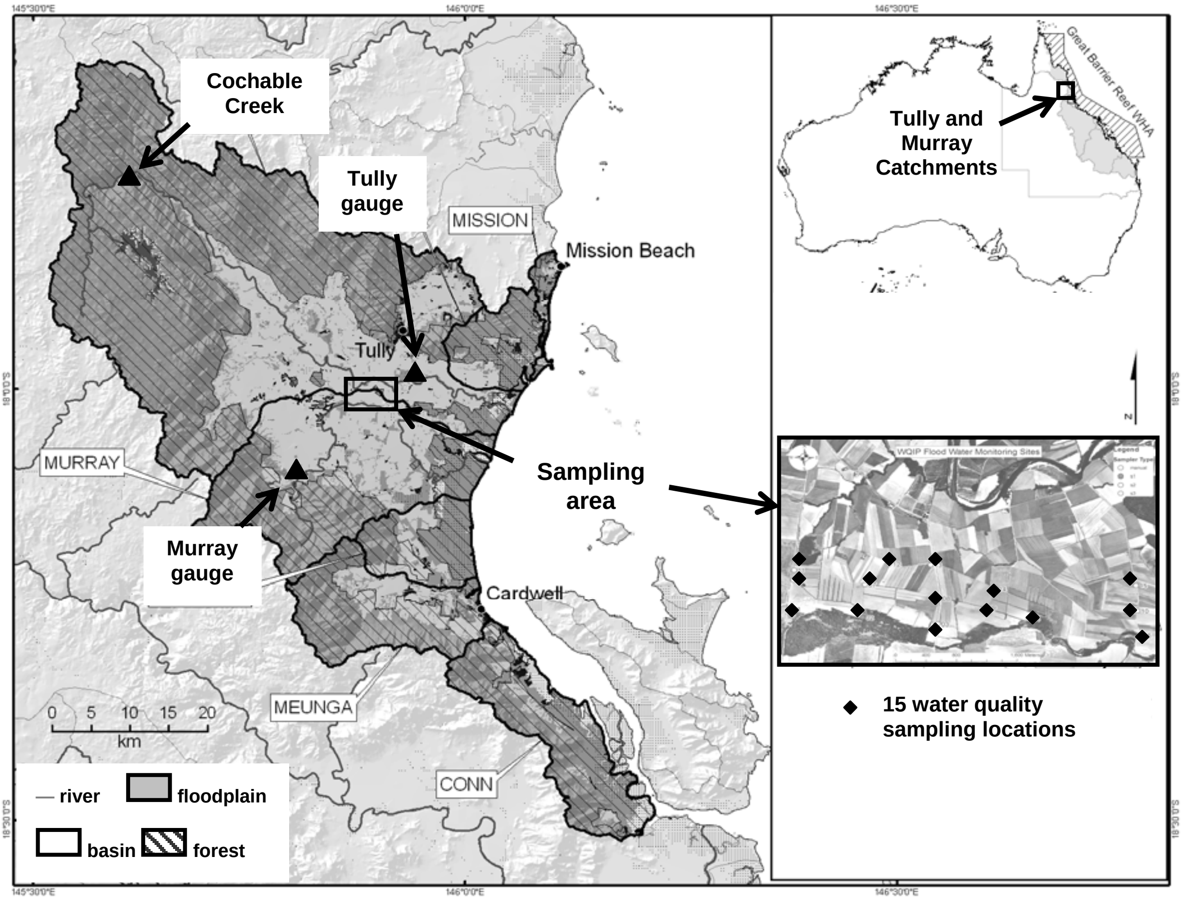


Figure 1: The Tully and Murray catchments in northern Queensland showing the floodplain water quality sampling area and the gauging stations at Cochable Creek and the Tully and Murray Rivers. Base map reproduced from Kroon (2009).

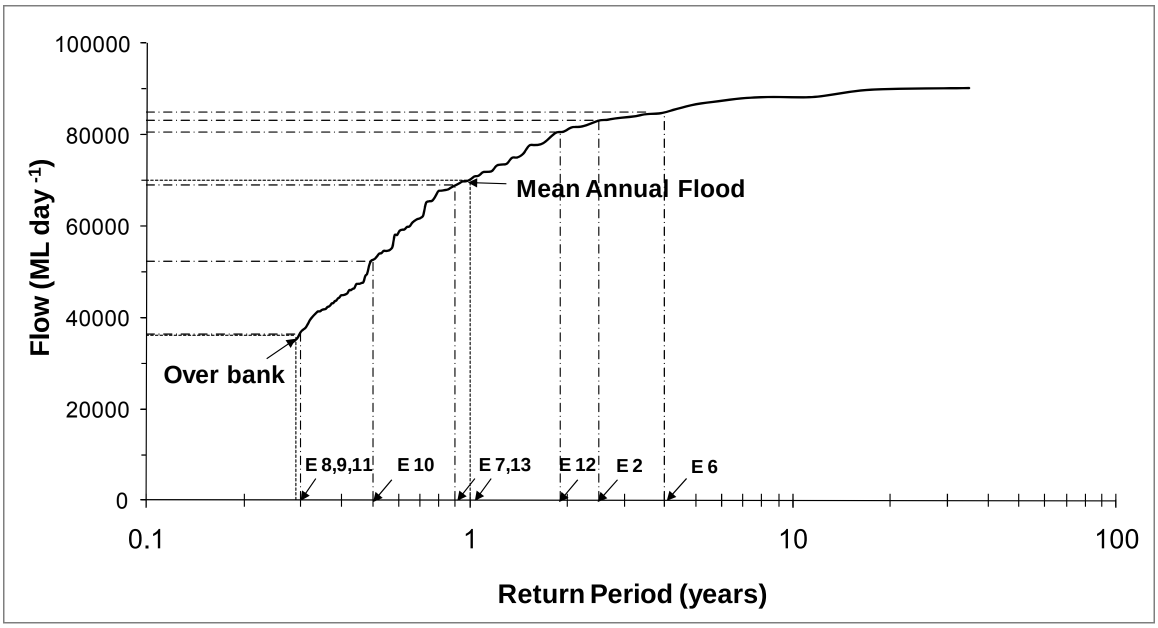


Figure 2: The relationship between flood size (overbank peak flow) and frequency (return period) at the Euramo gauge on the Tully River. The gauged peak discharges for the nine flood events (E1 to E9) when water quality was recorded are also shown. Reproduced from Wallace *et al.* (2009).

Flood sediment and nutrient load estimation

Marine loads of sediment and nutrients that are exported from coastal catchments are usually estimated as the product of river discharge and the concentration of the material of interest. However, during overbank floods, standard river gauges may not record the true catchment discharge very accurately as water spills out onto the floodplain and flows to the ocean without passing the gauge. Furthermore, the concentration of sediment and nutrients in flood waters may be different from the concentrations recorded within rivers during channelised flow. To accurately estimate sediment and nutrient export during floods it is therefore necessary to measure the concentrations of these materials in overbank flood water and to multiply these by the correct flood discharge. The following sections describe how these measurements and estimates were made in the Tully and Murray catchments.

Flood discharge estimation

To obtain the correct discharge from an entire catchment (‘Q_d’) during a flood, two corrections need to be applied to the flow measured by a standard river gauge. The first is a correction to the measured daily discharge (‘$Q_{g,d}$’) from the catchment area above the gauge (A_a’) to allow for runoff generated from the area downstream of the river gauge (‘A_b’), that is,

$$Q_d = (\frac{A_a + A_b}{A_a}).Q_{g,d} \qquad (1)$$

However, when the water level is overbank, $Q_{g,d}$ will be an underestimate of the discharge from A_a, because river and overland flow that originates in the floodplain above the gauge can bypass it during floods. The true flood runoff (Q_{flood}) can be derived from daily rainfall (‘$P_{g,d}$’) if an appropriate runoff coefficient (R_C’) can be derived for overbank events, in which case,

$$Q_{flood} = R_C(A_a + A_b)\sum P_{g,d} \qquad (2)$$

where rainfall $P_{g,d}$ is integrated over the period immediately before and during the flood event (see Figure 4). Flood runoff coefficients for the eight overbank events in 2006 and 2007 were estimated using the NAM rainfall-runoff model (DHI, 2008), which was applied in two sub-catchments upstream of the Tully River and two sub-catchments upstream of the Murray River. The NAM model accounts for losses due to evaporation and infiltration into the soil and was calibrated using flow data gauged in the upper catchments at Cochable Creek and Upper Murray (Figure 1). As most floods occur well into the wet season when the soils in the catchment are highly saturated and ground water tables close to the surface, soil moisture was set to 90% and groundwater depth to 0.5 metres for the overbank events. Using this method flood event runoff coefficients were found to increase with rainfall from 0.5 to 0.8, Figure 3.

A second method for estimating the runoff coefficient for flood events using a hydrograph decomposition method has been described by Wallace and others (2008). The basis of this method is illustrated in Figure 4, which shows a flood event and how it is broken down into its baseflow and prior and post event ‘tail flows’. The amount of runoff due to the particular rainfall event is given by the sum of areas B and C on this diagram and this method was applied to the three flood events in 2007 with R_C of 0.66, 0.71 and 0.78, similar to the values obtained above using the rainfall-runoff model (Figure 3). These R_C values are larger than the mean annual R_C for the Tully (0.68) and Murray (0.48), but this is to be expected as the latter are for all rainfall events and the former are for large flood generating events only.

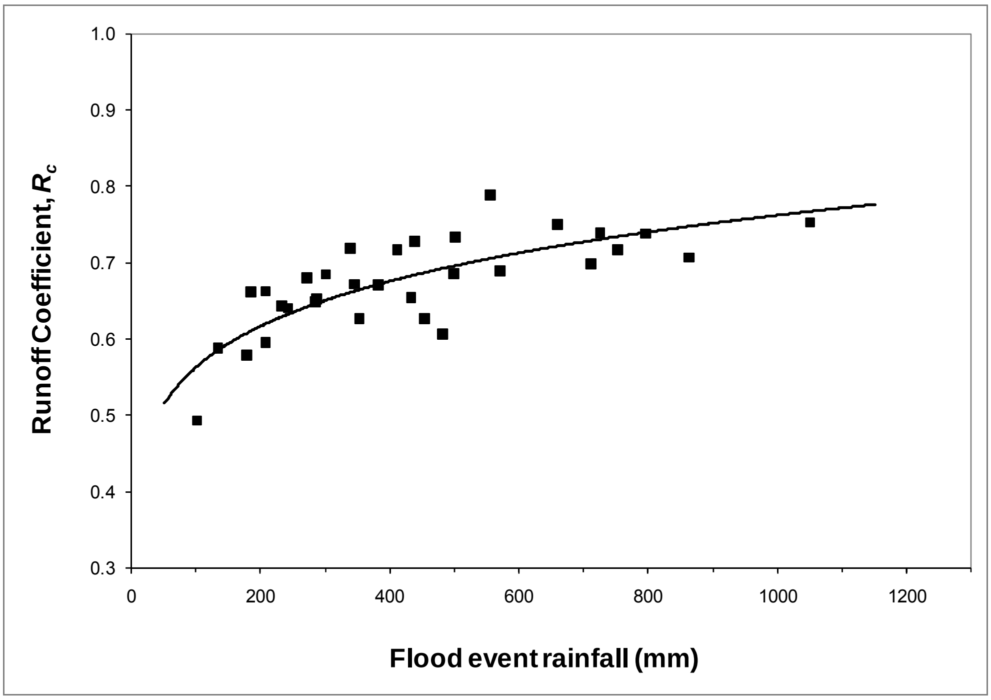


Figure 3: The variation in flood event runoff coefficient R_c with rainfall. The fitted line has the form $R_c = 0.308\ P_g^{0.13}$ ($r^2 = 0.61$).

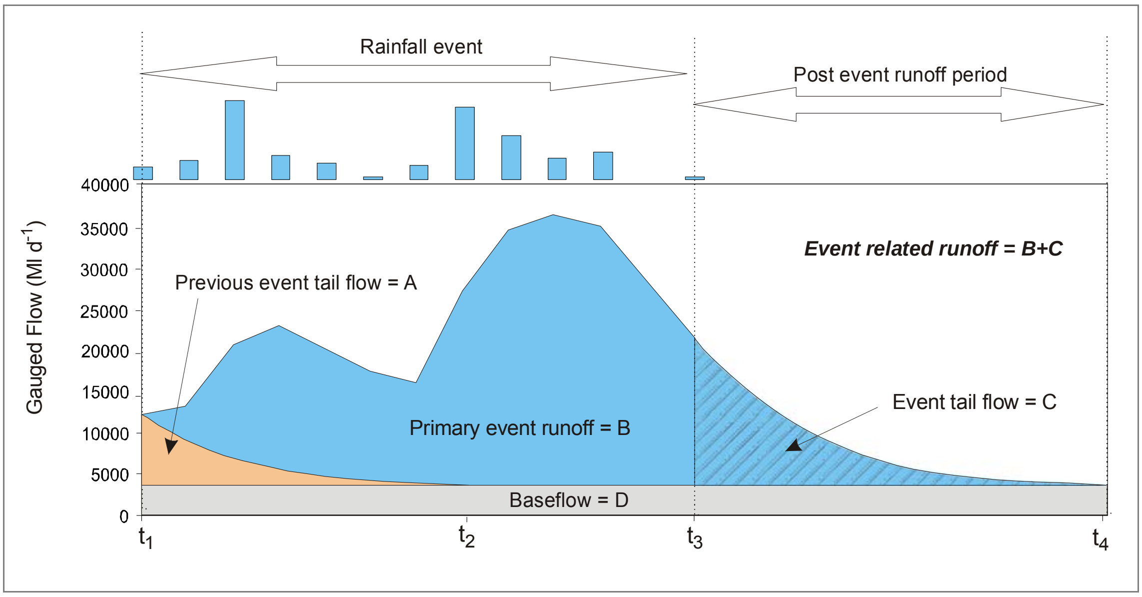


Figure 4: A schematic representation of a bank full event showing the rainfall and post-rainfall periods and the components of the gauged flow that allow the event runoff coefficient to be calculated.

Daily rainfall data for use in catchment and sub-catchment rainfall runoff modeling was obtained from 17 rainfall measurement stations located within the Tully and Murray catchments (Wallace *et al.* 2008). Gauged mean daily discharge and stage height data for the Tully River at Euramo (station 113006A), the Murray River at Upper Murray (station 114001A) and Cochable Creek (station 113004A), Figure 1, were obtained from the Queensland Department of Natural Resources and Water.

Flood water quality sampling

Water samples were collected during nine of the 13 overbank flood events that occurred in the Tully-Murray floodplain between 2006 and 2008. Samples were taken from flood water on the floodplain at distances ranging 200-1,200 metres north of the Murray River (Figure 1). The number of sample locations (15) was chosen to try to ensure that the mean concentrations of sediment or nutrient measured at any time had a coefficient of variation of less than 50% (see Wallace *et al.* 2007 for details). For the nine flood events studied an average of 35 samples were collected per event, equivalent to six samples per day.

Water samples were collected by either fixed installation (fully automatic, semi-automatic and rising stage samplers) or manual sampling. Automated samplers were activated by the presence of flood water and retrieved and stored water samples at regular intervals during the flood events. Three automated samplers were in operation on the floodplain, one fully automatic (ISCO) refrigerated sampler and two custom made semi-automatic, unrefrigerated samplers. Eight fixed rising-stage samplers also collected samples during the flooding events. Further details of the design, construction and operation of the fixed installation samplers are given by Hawdon and others (2007).

Water samples from the semi-automatic collection systems were retrieved as soon as practicable after flooding had started (usually 1-3 days) using a small boat. At these times additional water quality, flood depth and water turbidity measurements were manually collected. All water samples were packed in ice and transported to the laboratory to be analysed for turbidity, total suspended sediment and nitrogen and phosphorus species. The complete sampling methodology, preservation techniques and analytical methods were in accordance with APHA standards (APHA, 1998).

Estimation of marine loads during floods

The daily loads of suspended sediment and nitrogen and phosphorus species exported to the GBR lagoon during flood events were calculated by multiplying the above corrected overbank daily discharge volumes by the measured daily average concentration of the constituent of interest. This assumes that all of the flood waters reach the ocean, and this is supported by our hydrological and hydro-dynamic modelling. On days where concentration data were not measured, values were linearly interpolated between previous and later measurements. Loads of suspended sediment, nitrogen and phosphorus for each flood event were taken as the sum of the daily loads in each event. Event mean concentrations of suspended sediment, nitrogen and phosphorus were calculated by dividing the total event load by the total event discharge. A flood ‘event’ was defined as the period during which flood water was detected by our instruments on the floodplain. Further details of the estimation of marine loads are given by Wallace and others (2008).

Results and Discussion

Suspended sediment concentrations

The variation in daily mean suspended sediment concentrations (TSS) during the three flood events (flood numbers 6, 7 and 8) in 2007 is shown in Figure 5a. TSS concentrations peaked early in each event and declined quite rapidly thereafter. The exception to this was the first flood in 2007 (event 6) where TSS concentrations increased for the first three days, reaching a maximum of 62 mg L^{-1}. This peak value is much lower than the maximum TSS concentration reported by Furnas (2003) (230 mg L^{-1}) for high flows in the Tully River. However, the mean levels of TSS in the flood waters (10-60 mg L^{-1}) are similar to the mean figures quoted by Furnas for water in the Tully River (32 mg L^{-1}). Faithful *et al.* (2007) also reported low TSS concentrations, generally well below 50 mg L^{-1}, during high flows in the Tully and Murray rivers following Tropical Cyclone *Larry* (March 2006; flood event 2 in this study).

The high TSS values observed at the beginning of the first flood event in 2007 resemble peaks that are observed in rivers flows (e.g. see Furnas, 2003) and are referred to as the 'first flush'. These initial high flows of the wet season have elevated sediment concentrations as they pick up fine sedimentary material that has accumulated on the land during the dry season. An additional possible mechanism for the first flush in the Wet Tropics rivers is associated with the gradual deposition and accumulation of fine sediment in streams during the relatively low flow conditions of the dry season. Small runoff events during the dry season can deliver sediment to the streams, but are unlikely to generate flows that are energetic enough to maintain the sediment in suspension to the river mouth. However, the high flow velocities and discharge that follow the onset of the first flood rains could remobilise these fine sediments, therby contributing to high initial TSS concentrations.

Further evidence for the first flush phenomenon in floods can be seen in the relationship between discharge and TSS in the early phases of the three 2007 flood events. Figure 5a shows that in the first three days of event 6, TSS increased along with discharge. However, in events 7 and 8 TSS concentrations decreased from the first day, even though discharge was still increasing. This suggests that at the start of event 6 a large store of labile sediment was available for suspension in runoff waters, but that during events 7 and 8 this store had been depleted. The difference in the TSS concentration behaviour in events 6 and 7 suggests that water on the floodplain is initially dominated by the higher TSS runoff generated in the lower parts of the catchment. Later in these floods lower TSS runoff from the upper catchment arrives and the waters mix, resulting in a net dilution of TSS with time. Conversley, the sustained high TSS concentrations for several days during the first flood of the season imply that water arriving from the upper catchment in this event has a higher concentration of sediment than in subsequent events, otherwise net dilution would also be observed. Thus, we conclude that first flush runoff is likely to mobilise a relatively consistent, catchment wide (land surface and in-stream) store of labile sediment. This conclusion is supported by catchment wide sediment modelling, where the majority of the ocean sediment flux is derived from the rainforest in the upper catchment (Armour *et al.* 2007). Since much of the oceanic flux of suspended sediment occurs during the first flush, this finding is likely to have significant implications for the kind of actions that can be taken to reduce sediment loads.

The flood event mean concentrations of suspended sediment for all nine flood events when water quality was measured are shown in Figure 6a. Event mean TSS concentrations in flood waters were low (10-30 mg L^{-1}) and similar to the average value for high flows from sub-catchments in the Tully-Murray area (25 mg L^{-1}) reported by Bainbridge *et al.* (2009). The event mean measured TSS concentrations are somewhat less than the mean annual average figures quoted by Furnas (2003) and Armour *et al.* (2009) for water in the Tully River (i.e. 32 and 44 mg L^{-1} respectively).

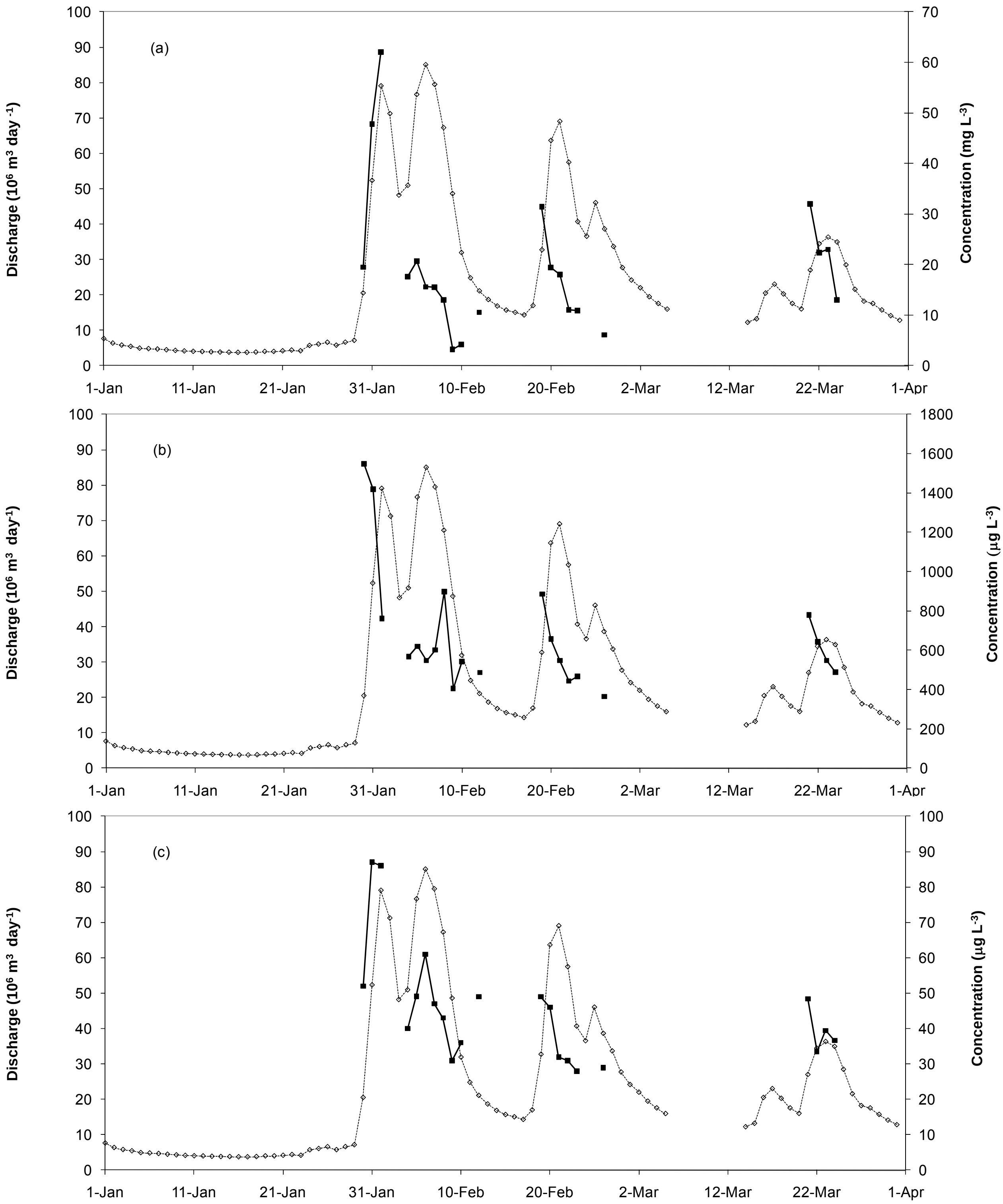


Figure 5: Discharge (○-----○) from the Tully River during the three flood events (numbers 6, 7 and 8) in 2007 and concentrations (■ ——■) of (a) total suspended sediment, (b) total nitrogen and (c) total phosphorus.

Event mean TSS concentrations were highest in the first flood of each season, giving further evidence that the 'first flush' phemonon observed in rivers also occurs in flood waters.

Nutrient concentrations

Examples of the variation in daily mean concentrations of total nitrogen (TN) and total phosphorus (TP) for the three floods in 2007 are shown in Figure 5b and 5c. TN concentrations were highest on the first day of each flood and declined with time over the duration of the event.

Peak daily TN concentrations reached ~1,500 µg L^{-1} in the first flood event of 2007 (event 6), but peak TN declined to ~800 µg L^{-1} in the subsequent floods in that year (events 7 and 8). During the first flush phase of event 6, TN concentration decreased, while TSS increased (compare Figure 5a and 5b). The decreasing TN trends could arise if some of the constituent species of TN are relatively more abundant in one part of the catchment than another. For example, if runoff generated near to the floodplain has relatively higher concentrations of TN compared with that derived from more distant upland slopes, then initially floodwater would be dominated by runoff generated in the lower parts of the catchment. Later in the flood event runoff from the upper catchment would move to the floodplain and the mixing of runoff derived from areas of relatively high and low TN would result in a net dilution of TN with time.

Daily mean total phosphorus concentrations tended to follow the rate of discharge over the course of event 6 (Figure 5c), but showed an inverse relationship in subsequent events. Peak concentrations of TP were much lower than N concentrations (i.e. ~90 µg L^{-1}) in the first flood event of the year. Subsequent floods had lower peak TP concentrations ~50 µg L^{-1}. These concentrations are very similar to those recorded in the post Cyclone *Larry* floods during 2006 (~40-80 µg L^{-1}; Wallace *et al.* 2007), so it would appear that the 'first flush' phenomenon is just as pronounced (relatively) in phosphorus as it was for nitrogen. Event mean concentrations of TP were more than an order of magnitude lower than TN concentrations (Figure 5c).

Figure 6 shows that event mean concentrations of TN and TP were highest on the first day of each flood event and tended to decline in subsequent events. Peak concentrations of TN were ~2,600 µg L^{-1} in the first flood event of 2008, but this peak declined to ~700 µg L^{-1} in the subsequent floods in that year. The first flush concentration in 2008 (2,600 µg L^{-1}) was much higher than the first flush in 2007 (720 µg L^{-1}) and this may be associated with the first flood of 2008 being quite small, with only around one fifth of the water volume of the first flood of 2007. The consistently lower TN concentrations in floods after the first flood of the season may be because much of the nutrient that can be washed off in floods has already been removed by the first overbank event in each season. TP concentrations were highest in 2008 (Figure 6c) with the first flood containing the peak concentration (120 µg L^{-1}), further evidence for the 'first flush' phenomenon in phosphorus.

The speciation within the total nitrogen concentration varies between the first and subsequent floods (Figure 7a). In the first floods of the wet season most of the nitrogen was in the form of DIN (ammonia, nitrite and nitrate). DON formed the next largest constituent, with the smallest contribution from particulate nitrogen (PN). However, in all subsequent floods DON was the largest fraction of the total nitrogen load. For channelised flows in the Tully River, most nitrogen is in the form of DIN, similar to the first flush flood waters reported here (Figure 7a; Furnas 2003). However, the dominant concentration of DON in flood waters after the first flood of the season is in sharp contrast to the speciation of nitrogen in river waters and this will affect the speciation of the total load to the ocean (see later).

The speciation within the TP concentration showed a dominance of particulate phosphorus (PP) in both the first flush flood and subsequent floods (Figure 7b). Filterable reactive phosphorus (FRP) is the next largest component with dissolved organic phosphorus (DOP) concentrations tending to have the lowest concentrations. The speciation in phosphorus in flood waters is similar to that observed in river waters (see Furnas 2003; data shown in Figure 7b).

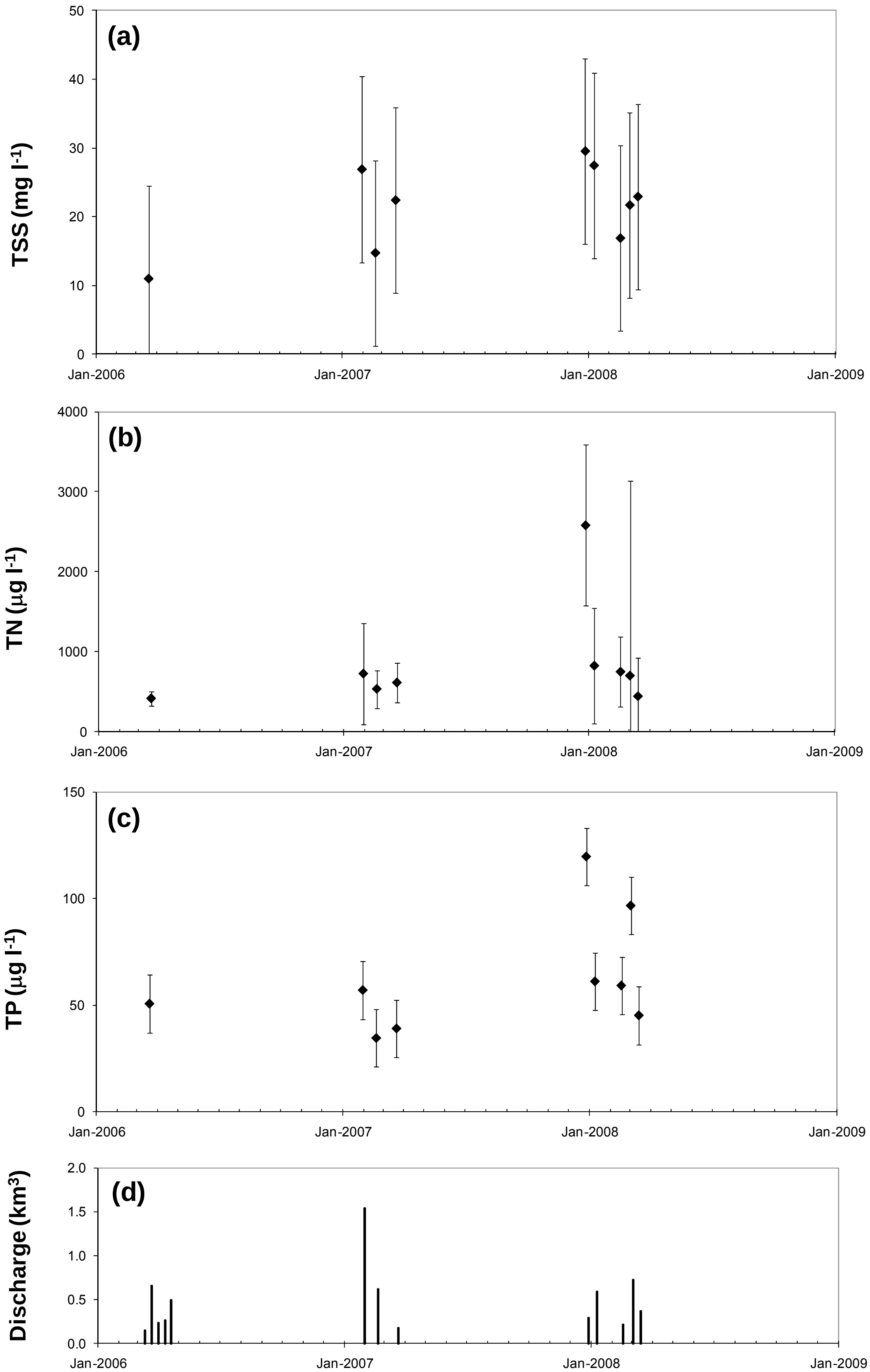


Figure 6: Event mean concentrations (± 1 standard deviation) of (a) TSS, (b) TN and (c) TP in nine of the thirteen overbank floods between 2006 and 2008. Total event discharge (d) is also shown for all thirteen floods.

Flood discharge

The time series of discharge from the Tully and Murray catchments for the three flood events in 2007 is shown in Figure 8. The first correction simply scales the discharge to account for the catchment area downstream of the river gauges, producing flows that are much greater than those recorded, particularly in the Murray River where only 14% of the catchment is above the gauge. Adding the correction for overbank flow further increases the estimated discharge, the effect being greater in larger floods (see Figure 8). For example, in event 6 the combined area and overbank peak flow (117,106 m^3 day^{-1}) for the Tully River was 38% greater than the recorded peak flow (85,106 m^3 day^{-1}). Further details of how the flood discharge corrections were derived for the Tully and Murray Rivers are given by Wallace *et al.* (2008).

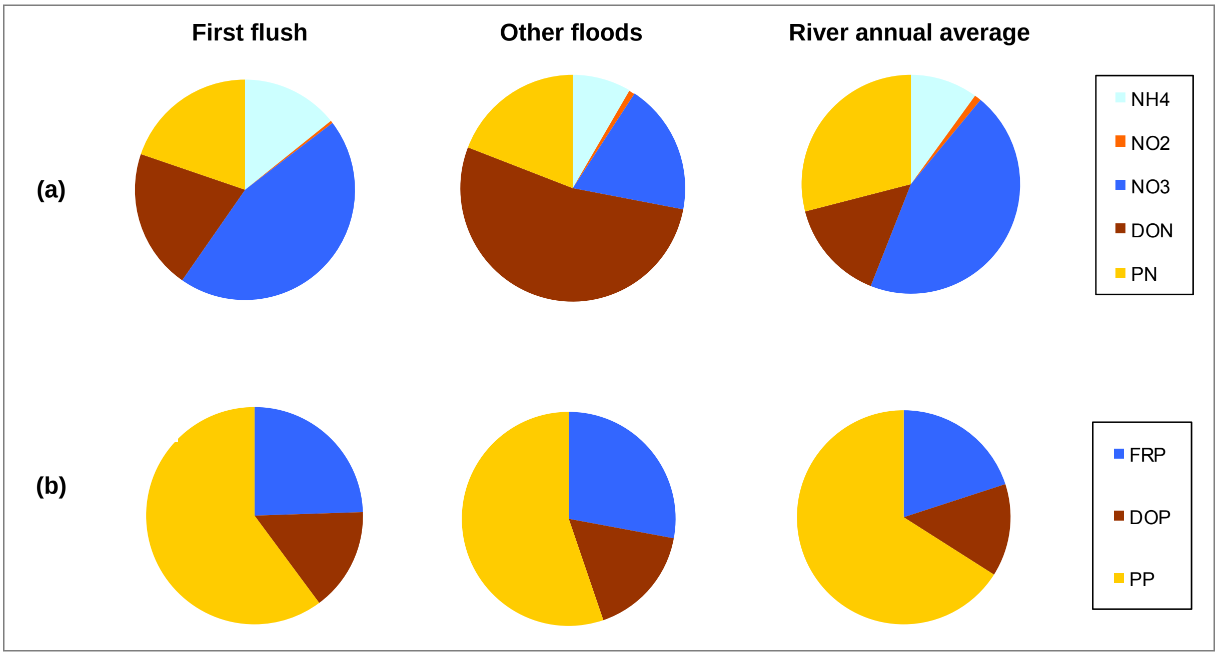
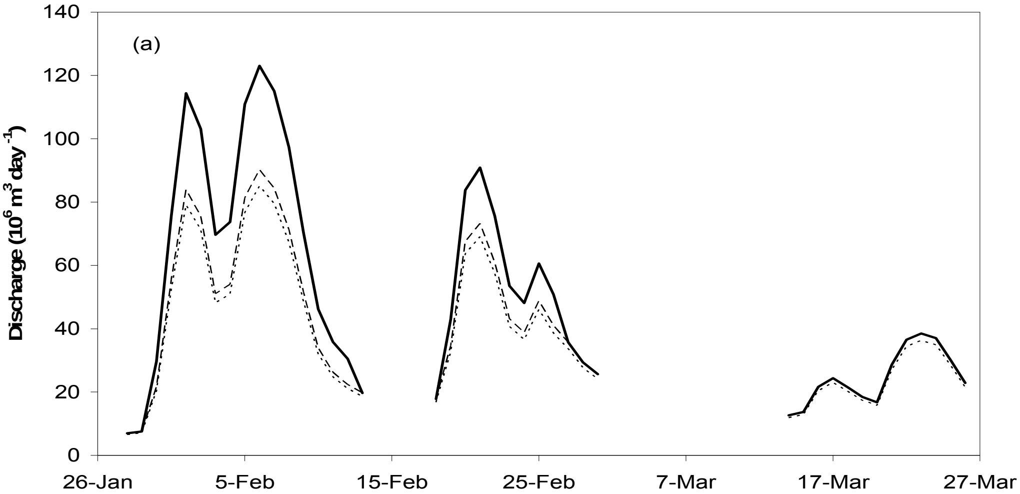


Figure 7: The relative concentration of (a) nitrogen and (b) phosphorus species in the first and subsequent flood events of each wet season. Ammonia (NH_4), nitrite (NO_2), nitrate (NO_3), dissolved organic nitrogen (DON), particulate nitrogen (PN), filterable reactive phosphorus (FRP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP). The annual average speciation of nitrogen and phosphorus for the Tully River is also shown for comparison (from Furnas, 2003).



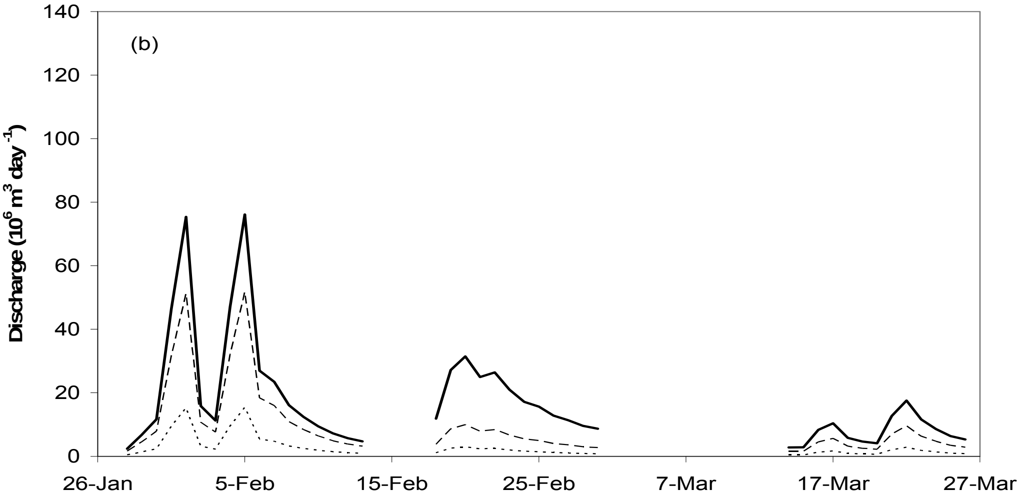


Figure 8: Comparison of the discharge from the (a) Tully and (b) Murray catchments during the three flood events of 2007; gauged (………), corrected for area downstream of the gauge (- - - - -) and corrected for downstream area and overbank flow (———).

Table 1 summaries the total discharge estimates for the thirteen flood events between 2006 and 2008. Floods ranged in duration from three to thirteen days with return periods of 0.3 and four years respectively. Very large amounts of water left the Tully and Murray catchments each year as overbank flow; annual totals range 2.0-2.7 km^3. The gauging efficiency of the Tully River gauge (measured discharge/corrected discharge) ranged from 0.36 to 0.88, with an average of 0.69 for all flood events. This implyies that the overbank flood discharge was ~46% greater than the measured flow (on average). The area correction for the Tully catchment accounts for 6% of this increase, so the remaining 40% is due to overbank flows bypassing the river gauge. The Upper Murray gauge efficiency is much lower, ranging from 0.11 to 0.27, with an average of 0.17. In this catchment the area correction adds 236% to the gauged flow and bypass flow adds a further 206% (on average). The overbank flood discharge for the Murray is therefore over four times the flow measured at the Upper Murray gauge, mainly due to the small area (30% of the entire catchment) upstream of this gauge. For the combined Tully and Murray catchments the overbank flood discharge during all thirteen flood events between 2006 and 2008 was 77% greater than the measured flow; 24% of this was due to the area correction and 53% due to bypass flow.

Table 1: Gauged and corrected runoff from the Tully and Murray catchments for the thirteen flood events between 2006 and 2008.

					Tully			Murray		
Over bank start date	Over bank end date	Event duration (days)	Peak flow at Tully gauge (ML day^{-1})	Return period (years)	Flood discharge gauged (km^3)	Flood discharge corrected (km^3)	Gauge efficiency	Flood discharge gauged (km^3)	Flood discharge corrected (km^3)	Gauge efficiency
11-Mar-06	15-Mar-06	5	60053	0.7	0.08	0.09	0.88	0.01	0.06	0.14
20-Mar-06	25-Mar-06	6	83207	2.5	0.34	0.48	0.71	0.05	0.18	0.27
30-Mar-06	02-Apr-06	4	59377	0.6	0.16	0.24	0.69	0.01	0.05	0.20
09-Apr-06	13-Apr-06	5	47859	0.5	0.18	0.19	0.91	0.03	0.08	0.15
18-Apr-06	24-Apr-06	7	73773	1.3	0.34	0.50	0.69	0.02	0.09	0.22
31-Jan-07	12-Feb-07	13	85073	4	0.76	1.14	0.66	0.08	0.40	0.20
19-Feb-07	26-Feb-07	8	69059	0.9	0.38	0.46	0.84	0.02	0.16	0.11
21-Mar-07	23-Mar-07	3	36312	0.3	0.13	0.19	0.69	0.01	0.05	0.16
27-Dec-07	29-Dec-07	3	36148	0.3	0.08	0.22	0.36	0.01	0.07	0.11
09-Jan-08	16-Jan-08	8	50292	0.5	0.24	0.44	0.55	0.02	0.15	0.16
17-Feb-08	19-Feb-08	3	35371	0.3	0.09	0.17	0.52	0.01	0.05	0.18
02-Mar-08	08-Mar-08	7	80636	1.9	0.41	0.55	0.75	0.02	0.17	0.14
14-Mar-08	18-Mar-08	5	71168	1.1	0.27	0.40	0.69	0.01	0.10	0.13

Fluxes to the GBR lagoon

Table 2 shows the range of published values for the total load of suspended sediment, nitrogen and phosphorus that are available for the Tully and Murray catchments. Several of these studies include sub-catchments that are outside the Tully and Murray hydrological catchments, i.e. the Whitfield, Dellachy, Meunga and Kennedy Creeks to the south, and the North Hull River to the north. To make comparisons on the same areal basis, we have therefore scaled any figures reported for the larger catchment area (e.g. by Furnas, 2003; Armour *et al.* 2007, 2009) down to the Tully and Murray hydrological catchments only (i.e. from 2,790 km^2 to 2,072 km^2). Sediment and nutrient load estimates for these catchments vary by a factor of 3 to 4. The average loads derived from data are lower than those derived using the SedNet model; however, this difference may not be significant given the high coefficient of variation (~40%) in these averages.

Table 2: A comparison of sediment, nitrogen and phosphorus loads from the Tully and Murray catchments derived using flow and concentration data or the SedNet model.

Source	Suspended sediment (tonnes $year^{-1}$)	Total nitrogen (tonnes $year^{-1}$)	Total phosphorus (tonnes $year^{-1}$)	Estimation method
NLWA (2001)	76149	588	64	SedNet model
Brodie *et al*. (2003)	181950	2019	217	SedNet model
Hateley *et al*. (2006)	138133	2351	206	SedNet model
Hateley et al. (2006) [1]	*103229*			*SedNet model*
Joo (2006); Joo and Yu (2006)[2]	103229			SedNet model
Armour et al. (2007)[3]	107652	2125	222	SedNet model
Furnas (2003)	126251	1279	135	Flow and concentration data
Joo (2006); Joo and Yu (2006)[2]	55699			Flow and concentration data
Hateley et al. (2006) [1]	216854			*Flow and concentration data*
Model average	**121422**	**1771**	**177**	**SedNet model**
standard deviation	*40352*	*801*	*76*	
Coefficient of variation (%)	*33%*	*45%*	*43%*	
Data average	**90975**	**1279**	**135**	**Flow and concentration data**
standard deviation	49888			
Coefficient of variation (%)	*55%*			
All estimates average	**112723**	**1672**	**169**	**All estimates**
standard deviation	*41486*	*727*	*68*	*(not incl. ambient only)*
Coefficient of variation (%)	*37%*	*43%*	*40%*	

[1] ambient flow only
[2] quoted by Hateley *et al.* (2006)
[3] revised by Karim *et al.* (2008)

The estimated total load of suspended sediment, nitrogen and phosphorus contained in the flood water for the nine flood events analysed in this study are shown in Table 3. Total nitrogen (TN), phosphorus (TP) and sediment (TSS) loads for the four events in 2006 where there are no flood water quality measurements were estimated using the event mean concentrations derived from the other nine events. Table 3 also shows the annual average total loads derived from all of the other published studies in the Tully-Murray catchments (taken from Table 2). The values of annual average speciation in nitrogen and phosphorus for the published estimates were calculated using the mean speciation fractions reported by Furnas (2003) and Armour *et al.* (2007).

Total annual TSS export during overbank floods varied between 40,000 and 56,000 tonnes, with an uncertainty of ~±50%. The flood load, which occurs in only 4-5% of the year, was therefore 36-50% of the total annual average load. The flood loads are much greater (by 77%) that those which would have been obtained had the suspended sediment export calculation been based on gauged discharge alone.

Table 3: Sediment and nutrient loads contained in runoff leaving the Tully and Murray catchments during the thirteen flood events between 2006 and 2008; total suspended solids (TSS), total nitrogen (TN), particulate nitrogen (PN), dissolved organic nitrogen (DON), dissolved inorganic nitrogen (DIN), total phosphorus (TP), particulate phosphorus (PP), dissolved organic phosphorus (DOP) and filterable reactive phosphorus (FRP). For comparison the annual average fluxes of these constituents from all of the published studies in the Tully and Murray catchments are also shown (see Table 2).

	DIN (tonnes)	**DON (tonnes)**	**PN (tonnes)**	**Total N (tonnes)**	**FRP (tonnes)**	**DOP (tonnes)**	**PP (tonnes)**	**Total P (tonnes)**	**TSS (tonnes)**
Event 1 2006				280				18	7152
Event 2 2006	37	171	64	273	5	9	19	34	7265
Event 3 2006				240				18	6132
Event 4 2006				284				21	7258
Event 5 2006				496				37	12684
Total				**1573**				**128**	**40490**
C.V. (%)	*27*	*19*	*35*	*12*	*42*	*27*	*26*	*23*	*48*
Event 6 2007	423	476	216	1115	24	21	43	88	41410
Event 7 2007	97	180	51	329	4	7	10	21	9100
Event 8 2007	39	80	30	148	1	2	6	10	5431
Total	**558**	**736**	**297**	**1592**	**30**	**30**	**59**	**119**	**55941**
C.V. (%)	*54*	*21*	*55*	*17*	*54*	*27*	*43*	*34*	*56*
Event 9 2008	485	103	163	751	9	4	21	35	8598
Event 10 2008	133	266	85	484	5	5	26	36	16155
Event 11 2008	40	94	27	161	3	2	8	13	3647
Event 12 2008	155	228	122	505	35	6	29	70	15687
Event 13 2008	60	128	31	220	11	2	10	23	11390
Total	**872**	**820**	**428**	**2121**	**63**	**18**	**95**	**176**	**55476**
C.V. (%)	*69*	*54*	*66*	*38*	*68*	*77*	*64*	*55*	*50*
All published estimates (Table 2)	801	357	514	1672	27	22	119	169	112723

Estimates of TN and TP that left the Tully and Murray catchments during floods are also given in Table 3. TP loads are much lower (<10%) than the TN loads, which is consistent with previous measurement and modelling exercises for these catchments (Furnas, 2003; Armour *et al.* 2007, 2009). The amount of nitrogen and phosphorus carried in floodwater alone is similar to or even greater than the annual average riverine nitrogen and phosphorus loads. However, again TN and TP load estimates based on gauged discharges alone are only just over half of those estimated when the flood load is included.

The relative proportions of the constituent nitrogen species differ markedly in flood waters and river water (Table 3). In flood waters dissolved organic nitrogen (DON) averaged 42% of TN compared to 21% in river water. Dissolved inorganic nitrogen (DIN) averaged 38% of TN in flood waters and 48% in river water. Thus, the tonnage of DON that is exported to the GBR lagoon during floods can exceed the tonnage of DIN (e.g. as in 2007).

The water quality difference between the flood waters and 'average' river flows implies that the main nutrient load in flood waters (especially after the first flush) is in the form of DON rather than DIN, the major sources of which may be quite different. DON is not usually considered as a potential source of enhanced nutrient load to the ocean, since its flux from the land is assumed to have not changed significantly since European settlement and/or it is of low biological availability. However, there is evidence that some forms of DON (amino acids, e.g. glycine, glutamic acid and urea) can be broken down by bacteria and macroalgae (Tyler *et al.* 2001). Furthermore, Wiegner and others (2006) have also demonstrated that ~23% of the DON in rivers in the eastern United States is bio-available. Recent work in tidal marshes by Mozdzer (2006) has also demonstrated that macrophytes such as *Phragmites australis* and *Spartina alterniflora* are capable of directly assimilating DON at rates as high as twenty percent of those at which they assimilate DIN (ammonia). Significant fractions of DON are also available for assimilation by marine bacteria (Stepanauskas *et al.* 1999) and phytoplankton (Seitzinger *et al.* 2002). The implication is, therefore, if DON is present in flood water at concentrations similar to or greater than DIN and it can be assimilated at reasonable rates, then it will have a significant effect on biological systems (freshwater, estuarine and marine) in addition to DIN.

There remains the question of whether DON fluxes that may originate mainly from natural sources (e.g. rainforests) have changed over the last one hundred years or so. This is possible due to removal of wetlands and the installation of land drainage systems in coastal floodplains. Over seventy percent of the coastal wetlands in the Tully and Murray catchments have been removed in the past century, so it is likely that less of the flood waters remain on the floodplain. Furthermore, land drainage will have sped up runoff rates and amounts, especially during floods. There is some evidence for these effects from the work by McCulloch (2006), who has shown from analysis of corals in the GBR lagoon that runoff volumes per unit rainfall may have doubled since European settlement. Provided DON levels have not decreased over the same period, then nitrogen loads to the ocean could have increased substantially due to DON alone.

In the 2006 to 2008 floods, the overall amount of TP exported ranged from 119 to 176 tonnes (Table 3), an order of magnitude lower than for TN. However, as with nitrogen, there are differences between the estimated relative contributions of the constituent species found in flood water and river water. Filterable reactive phosphorus (FRP) is estimated to form ~16% of the annual phosphorus export via the river while the results of this study indicate that flood events export 31%. The annual average amount of particulate phosphorus (PP) in river water (70%) is higher than the equivalent figure for floods (52%). The main differences in the phosphorus species in flood and river water therefore appear to be the lower particulate and higher dissolved fractions in flood waters.

The above marine loads are for three years where the annual discharge exceeds the long term (1972-2008) annual average discharge (i.e. annual flows in 2006, 2007 and 2008 were 1.14, 1.32 and 1.21 times the long term average respectively). We therefore estimated the long term average contribution of overbank floods and compared this with the average of all published estimates in Table 4. To do this the 1972 to 2008 daily discharge records for the Tully and Murray Rivers were separated into overbank flow and in bank flow, depending on whether the daily discharge was greater or less than the flow rate at the Euramo and Upper Murray gauges associated with the initial detection of water on the floodplain by our automatic water samplers (31,400 and 2,333 ML day^{-1}, respectively). For the published estimates, in bank and overbank loads were calculated using the proportions of flow that occurred above and below the above inundation threshold (Table 4). The overbank flood loads were then updated using the corrected flood discharge and flood event mean sediment, nitrogen and phosphorus concentrations measured in the present study. This analysis shows that on average 34% of the TSS load is delivered during overbank floods and that correcting this total annual load to allow for flood discharge has very little effect (Table 4). This is because the potential load enhancement due to the increased flood discharge is compensated by more dilute TSS concentrations in flood waters (e.g. average TSS concentration in flood waters was ~22 mg L^{-1} compared with ~30 mg L^{-1} in river water). However, this is not the case for nitrogen and phosphorus, where a higher concentration of these materials in flood waters leads to a 47% increase in the estimated annual average total nitrogen load and a 32% increase in the annual average total phosphorus load (Table 4). Around half of this total load of nitrogen and phosphorus is delivered to the ocean during overbank floods. When flooding is taken into account therefore annual average sediment loads do not increase significantly, whereas nutrient loads increase markedly. This implies that sediment fluxes may be limited by their sources in the catchment (i.e. they are supply limited), whereas nutrients fluxes are more related to discharge (i.e. they are transport limited).

Table 4: Estimates of the long-term (1972-2008) annual average sediment and nutrient loads leaving the Tully and Murray catchments. Total loads are separated into those occurring while flow is in bank and while flow is overbank (i.e. during flooding). For comparison the annual average loads from all of the published studies in the Tully and Murray catchments are also shown (see Table 2).

	TN (tonnes)	TP (tonnes)	TSS (tonnes)	TN (tonnes)	TP (tonnes)	TSS (tonnes)
In-bank	1129	114	76097	1129	114	76097
Flood	543	55	36626	1322	109	38842
Total	**1672**	**169**	**112723**	**2450**	**223**	**114939**

Conclusions and Recommendations

It is clear that overbank floods can make a large contribution to the marine load of sediment and nutrients, despite the relatively low concentrations of these materials in flood waters. Since flood flows are generally underestimated by standard river gauges, current marine load estimates of material fluxes (based on gauged flows, measured river concentrations and modelling) from Australian Wet Tropical catchments with frequent flooding are probably too low, by quite significant amounts, depending on estimation method and constituent. For example, current annual average loads of phosphorus and nitrogen from the Tully and Murray catchments are 30-50% too low. On the other hand, sediment loads do not increase when flooding is taken into account and this may be because this material is source limited whereas nutrient fluxes are transport limited.

Water quality improvement plans (e.g. Davies, 2006; Kroon, 2008; Drewry *et al.* 2008) require marine loads to be monitored in order to 'measure' the effect of land based changes in nutrient use and management. However, this study has shown that annual marine loads will be very dependent on the number and size of overbank flood events in any year. This will make the monitoring of any trends in ocean loads difficult as any trend may be small in relation to natural inter-annual variability. Further analysis is required to quantify how large a change in load needs to be over a given period before it can be detected within the inter-annual variability. Despite the relatively high number of water quality samples, our load estimates still have a high uncertainty, e.g. up to ±69% for DIN. This means that monitoring of marine loads will also take a significant number of samples, preferably of both river and flood flows – otherwise there will be very large uncertainties in mean ocean loads, making it difficult (or even impossible) to detect any load reductions due to land use or management changes.

Current water quality improvement plans (e.g. Davies, 2006; Kroon, 2008; Drewry *et al.* 2008) focus on farm interventions in agriculture that will potentially reduce dissolved inorganic nitrogen (DIN) loads. However, it appears that flood waters can carry more dissolved organic nitrogen (DON) than dissolved inorganic nitrogen (DIN) and this is the opposite of their concentrations in river water. Consequently DON loads to the ocean may be around twice those previously estimated from riverine data. It is possible that this DON load may have increased due to land drainage and it may also be biologically available, so reductions in DON (and sediment) loads that arise outside the floodplain may also be needed to meet marine water quality targets. Reducing DON loads will require different interventions to those used in agriculture to reduce DIN, for example, measures that slow down and reduce drainage, such as the introduction and/or rehabilitation of riparian zones and wetlands (e.g. Kroon, 2008).

References

APHA (1998) Standard Methods for the Examination of Water and Wastewater. 20th Edition. American Public Health Association, Washington, DC.

Armour, J.D., Hateley L.R. and Pitt, G.L. (2009) Catchment modelling of sediment, nitrogen and phosphorus nutrient loads with SedNet/ANNEX in the Tully-Murray basin. *Marine and Freshwater Research* 60: 1091-1096.

Armour, J.D., Hateley, L.R. and Pitt, G.L. (2007) *Improved SedNet and Annex modelling of the Tully-Murray catchment*. A report prepared for the Tully Water Quality Improvement Plan. Department of Natural Resources and Water, Mareeba. 27 pp.

Bainbridge, Z.T., Brodie, J.E., Faithful, J.W., Sydes, D.A. and Lewis, S.E. (2009) Identifying the land-based sources of suspended sediments, nutrients and pesticides discharged to the Great Barrier Reef from the Tully-Murray Basin, Queensland, Australia. *Marine and Freshwater Research* 60: 1081-1090.

Brodie, J., McKergow, L.A., Prosser, I.P., Furnas, M., Hughes, A.O. and Hunter, H. (2003) *Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area*. ACTFR Report No. 03/11. Australian Centre for Tropical Freshwater Research, James Cook University, Townsville (http://www-public.jcu.edu.au/idc/groups/public/documents/technical_report/jcudev_015447.pdf)

Davies, R. (2006) *Douglas Shire Water Quality Improvement Plan*. Douglas Shire Council. Canberra (176 pp.).

Drewry, J., Higham, W., and Mitchell, C. (2008) *Water Quality Improvement Plan. Final Report for Mackay Whitsunday Region*. Mackay Whitsunday Natural Resource Management Group (111 pp.).

DHI (2008) *NAM technical reference and model documentation*. Danish Hydraulic Institute Water and Environment, Denmark (96 pp.).

Furnas, M. (2003) *Catchments and corals: Terrestrial runoff to the Great Barrier Reef*. Australian Institute of Marine Science, Townsville, 334 pp. (http://data.aims.gov.au/extpubs/attachmentDownload?docID=3914)

Hateley, L., Armour, J., Pitt, G., Sherman, B.S., Read, A., Chen, Y., Brodie, J. and Cogle, A.L. (2006) Sediment and nutrient modelling in the Far North Queensland NRM region. Vol. 2. In: *The use of SedNet and ANNEX models to guide GBR catchment sediment and nutrient target setting*. A.L. Cogle, C. Carroll and B.S. Sherman (eds.). Department of Natural Resources, Mines and Water, Brisbane, QNRM06138.

Hawdon, A.A., Keen, R.K., Kemei, J.K., Vleeshouwer, J.M. and Wallace, J.S. (2007) *Design and Application of Automated Flood Monitoring Systems in the Wet Tropics*. CSIRO Land and Water Science Report 49/07 (27 pp.).

Karim, F.M., Wallace, J.S., Kinsey-Henderson, A. and Wilkinson, S. (2008) *Assessment of Sediment and Nutrient Transport across the Tully-Murray Floodplain using the SedNet Model*. An initial study as part of the Marine and Tropical Science Research Facility (MTSRF) Project 3.7.4. Wetlands and floodplains: connectivity and hydro-ecological function. CSIRO Land and Water Science Report No 59/08 (24pp.).

Kroon, F.J. (2008) *Tully Water Quality Improvement Plan*. CSIRO Sustainable Ecosystems, Atherton, Queensland (104 pp.).

Kroon, F.J. (2009) Integrated research to improve water quality in the Great Barrier Reef region. *Marine and Freshwater Research* 60: Preface, i-iii.

McCulloch, M. (2006) Coral record of human impacts on land-sea interactions in the inner Great Barrier Reef. In: Abstracts. Catchments to Coasts. Australian Marine Sciences Association 44th Annual Conference (AMSA 2006) and The Society of Wetland Scientists 27th International Conference (SWS), Cairns, Queensland, Australia, 9-14 July 2006.

Mozdzer, T. (2006) Utilization of dissolved organic nitrogen by the temperate macrophytes *Phragmites australis* and *Spartina alterflora*. In: Abstracts. Catchments to Coasts. Australian Marine Sciences Association 44th Annual Conference (AMSA 2006) and The Society of Wetland Scientists 27th International Conference (SWS), Cairns, Queensland, Australia, 9-14 July 2006.

Seitzinger, S.P., Sanders, R.W. and Styles, R. (2002) Bioavailability of DON from natural and anthropogenic sources to estuarine plankton. *Limnology and Oceanography* 47: 353-366.

Stepanauskas, R., Leonardson, L. and Tranvik, L.J. (1999) Bio-availability of wetland derived DON to freshwater and marine bacterioplankton. *Limnology and Oceanography* 44: 1477-1485.

Tyler, A.C., McGlathery, K.J. and Anderson, I.C. (2001) Macroalgae mediation of dissolved organic nitrogen fluxes in a temperate coastal lagoon. *Estuarine, Coastal and Shelf Science* 53: 155-168.

Wallace, J.S., Hawdon, A., Keen, R. and Stewart, L.S. (2007) *Water quality during floods and their contribution to sediment and nutrient fluxes from the Tully-Murray catchments to the GBR lagoon.* Report to FNQ NRM Ltd for their Water Quality Improvement Plan. CSIRO Water for a Healthy Country Science Report (35 pp.).

Wallace, J.S., Stewart, L.S., Hawdon, A. and Keen, R. (2008) *The impact of floods on sediment and nutrient fluxes from the Tully-Murray catchments to the GBR lagoon*. Report to Terrain NRM Ltd and MTSRF for input to the Water Quality Improvement Planning process. CSIRO Water for a Healthy Country Science Report (56 pp.).

Wallace, J., Stewart, L., Hawdon, A., Keen, R., Karim, F. and Kemei, J. (2009) Flood water quality and marine sediment and nutrient loads from the Tully and Murray catchments in north Queensland, Australia. *Marine and Freshwater Research* 60: 1123-1131.

Wiegner, T.N., Seitzinger, S.P., Gilbert, P.M. and Brink, D.A. (2006) Bioavailability of dissolved organic nitrogen and carbon from nine rivers in the eastern United States. *Aquatic Microbial Ecology* 43: 277-287.