Marine Pollution Bulletin 58 (2009) 976–986

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Agricultural lands are hot-spots for annual runoff polluting the southern Great Barrier Reef lagoon

Robert Packett [a,b,c], Cameron Dougall [d,*], Ken Rohde [e], Robert Noble [b,c]

[a] National Action Plan for Salinity and Water Quality, Rockhampton, 4700, Australia
[b] The Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Rockhampton, 4700, Australia
[c] Department of Natural Resources and Water, Rockhampton, 4700, Australia
[d] Department of Natural Resources and Water, Emerald, 4720, Australia
[e] Department of Natural Resources and Water, Mackay, 4740, Australia

ARTICLE INFO

Keywords:
Great Barrier Reef
Water quality
Hotspots
Inshore pollution
Fitzroy Basin
Agriculture

ABSTRACT

The world's largest coral reef ecosystem, the Great Barrier Reef (GBR), continues to be degraded from land-based pollution. Information about the source of pollutants is critical for catchment management to improve GBR water quality. We report here on an 11-year source to sea study of pollutant delivery in runoff from the Fitzroy River Basin (FRB), the largest GBR catchment. An innovative technique that relates land use to pollutant generation is presented. Study results indicate that maximum pollutant concentrations at basin and sub-catchment scales are closely related to the percentage area of croplands receiving heavy rain. However, grazing lands contribute the majority of the long-term average annual load of most common pollutants. Findings suggest improved land management targets, rather than water quality targets should be implemented to reduce GBR pollution. This study provides a substantial contribution to the knowledge base for the targeted management of pollution 'hot-spots' to improve GBR water quality.

1. Introduction

1.1. Great Barrier Reef water quality issues

Globally, coral reefs and associated inshore ecosystems continue to be degraded from land-based pollution via flood runoff (Fabricius, 2005; Pandolfi et al., 2005, 2003). The Great Barrier Reef (GBR) along the coast of Queensland, Australia is the largest World Heritage Area and represents about 17% (in area) of the world's coral communities (Wilkinson, 2002). Recent studies suggest that degradation of inshore reefs may be linked to an increase in pollutants from land-based flood runoff since the European settlement of GBR catchments. Agricultural activities are thought to be a primary contributor to this increase in pollutant delivery (DeVantier et al., 2006; Fabricius et al., 2005; McCulloch et al., 2003).

The Fitzroy River Basin (FRB) has been identified as a major source of pollutants to the GBR lagoon (The State of Queensland and Commonwealth of Australia, 2003). Agricultural activities account for ~95% of land use in the FRB and historically there have been numerous water quality issues at a sub-catchment scale (Noble et al., 1997). Recent estimates of modelled post-development, long-term annual suspended sediment export from the FRB to the GBR lagoon range from 3 to 4.5 million tonnes per year. This represents ~33% of the modelled annual suspended sediment load from all GBR catchments and represents a substantial increase compared to pre-development contributions from the FRB (Dougall et al., 2005).

Coral bleaching caused by rapid climate change and warming coastal waters has now become a regular occurrence in the southern GBR and current climate change forecasts predict an increase in bleaching events. In addition, there is likely to be an increase in intense storm frequency for northern Australia, which could generate extended flood plumes (Intergovernmental Panel on Climate Change, 2007). It is now well accepted that poor water quality can compromise corals and other reef organisms and impede the recovery of reef systems from bleaching events (Wilkinson, 2002). Recent studies of the impacts of nutrients and pesticides on corals, seagrass and algae have highlighted the potential for some agricultural pollutants to damage marine organisms at relatively low concentrations (Smith et al., 2006; Nugues et al., 2004; Jones et al., 2003; Haynes et al., 2000). Water quality is therefore predicted to play a major role in the resilience and capacity of the GBR to recover from bleaching events and adapt to rapid climate change (Hennessy et al., 2007; McCook et al., 2007).

Recent initiatives, such as the Reef Water Quality Protection Plan (The State of Queensland and Commonwealth of Australia,

* Corresponding author.
E-mail addresses: robert.packett@nrw.qld.gov.au (R. Packett), cameron.dougall@nrw.qld.gov.au (C. Dougall).

0025-326X/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2009.02.017

2003), aim for changes in land management to improve water quality and decrease pollutant loads. A water quality target-setting framework has been proposed to monitor improvements in catchment management. However, this agenda is inhibited by a lack of knowledge on the sources, transport and fate of flood-borne pollutants from GBR catchments. Guidelines for high flow (flood) pollutant concentrations are not available and there is an urgent need for research on load-based (quantity of pollutants in the particular flood event) rather than concentration-based assessment of floods (ANZECC and ARMCANZ, 2000).

Traditionally, large volume floods that have return periods of decades have been the main consideration for pollutant delivery from large dry tropical catchments like the FRB (Australian Government and Queensland Government, 2005; Williams, 2001). This has mainly been due to the fact that large loads of pollutants can be delivered as far as middle and outer reefs during major flood events. However, in recent years, more attention has been given to inshore reef zones and the possible impacts from smaller volume floods (Devlin et al., 2003; Brodie, 2002). Smaller volume floods occur at a far higher frequency and often have a direct impact on the inshore water quality of the GBR lagoon. There is also the possibility of indirect impacts to middle and outer reef zones as a result of inshore impacts, for example, via changes in community structure brought about by increased nutrient availability (Fabricius and De'ath, 2004; Schaffelke, 1999).

Information about the source and transport of pollutants in large as well as small floods is crucial for effective catchment management to improve the quality of water in runoff discharging into the GBR lagoon.

1.2. The Fitzroy River Basin (characteristics)

The FRB, in the dry tropics of central Queensland, Australia is the largest drainage system in area (~142,600 km^2) to discharge into the GBR lagoon and accounts for ~36% of the total GBR catchment (Fig. 1). Average annual rainfall for the FRB varies in a gradient from ~530 mm in the west to ~850 mm in central regions and ~2000 mm in the northeast ranges near the coast. Widespread heavy rainfall is usually generated by monsoonal depressions and tropical cyclones during summer. Isolated thermal storms in early summer can also deliver considerable, and, at times, intense rainfall to less extensive areas of the catchment. The relatively short wet seasons are typically separated by long dry periods, and drought conditions can often persist for several years.

The dominant land use in the FRB is cattle grazing (~88% of area) while cropping and horticulture occurs on ~7% of the basin (mainly on cracking clays). National parks and other managed areas account for ~ 4%, with coal mining and other activities making up the remaining 1% of land use. The basin has undergone extensive modification by clearing of woodland communities dominated by Brigalow (*Acacia harpophylla*) for grazing and cropping (Bailey, 1984). By 1999, around 60% of the remnant vegetation in the Fitzroy had been substantially altered or cleared (Accad et al., 2001). A long-term study in the FRB on the impacts of agriculture has demonstrated a significant loss in the natural productivity of cropping and grazing lands indicating a potential and continuing decline in overall catchment condition (Radford et al., 2007). The same study also found that annual runoff from cropped or pastured catchments was approximately twice that from native vegetation (Thornton et al., 2007). Recent studies of beach ridge sedimentation near the Fitzroy River mouth indicate a substantial increase in sediment transport to the coast in the last 100 years. An increase in the percentage of basaltic soils in these recent sediment deposits was also observed, most likely a result of tree clearance and agricultural activity (Brooke et al., 2008). The FRB has therefore undergone significant modification since European settlement (1856 onwards) and like other GBR catchments this has resulted in substantial increases in pollutant delivery to the GBR lagoon (Baker, 2003; McCulloch et al., 2003).

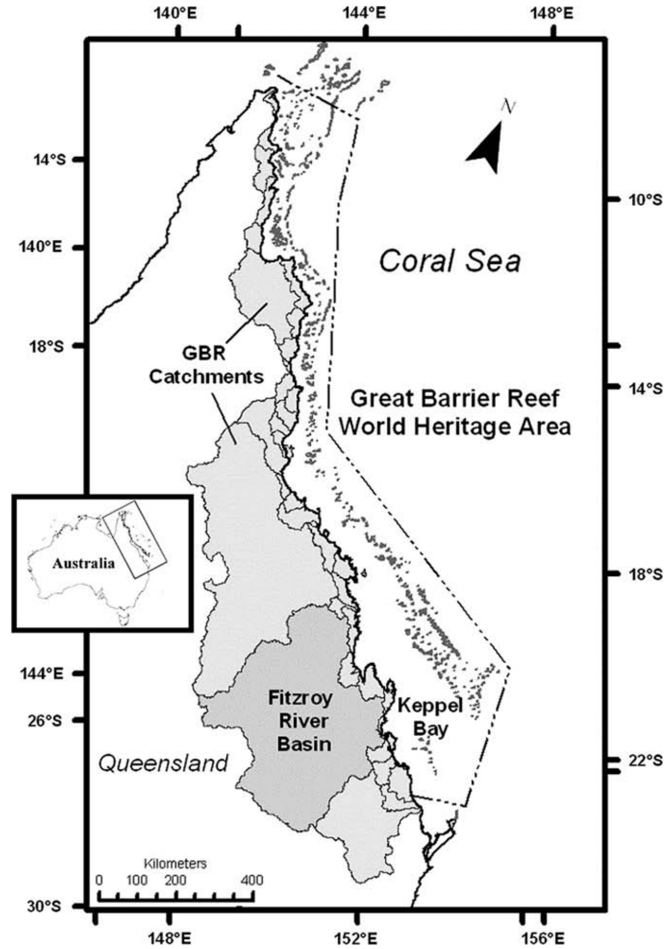

Fig. 1. The Fitzroy River Basin Queensland, Australia in relation to the Great Barrier Reef World Heritage Area. Other GBR catchments are shown in light grey.

1.3. Study overview

Historically there has been limited information available in regards to the source and delivery of pollutants from the FRB to the GBR lagoon. This reduces the ability of regional catchment management organisations such as the Fitzroy Basin Association to arrive at practical water quality targets. Guidelines are only available for a limited range of pollutants during base-flow and ambient conditions. The Queensland Water Quality Guidelines (QWQG) suggest it is inappropriate to apply the current guideline concentrations to high discharge events and that there is insufficient information available to provide load-based guidelines (Environmental Protection Agency, 2006). Further, the ANZECC guidelines suggest that there is an urgent need for the development of more load-based guidelines, rather than concentration-based approaches to water quality targets (ANZECC and ARMCANZ, 2000).

The term "pollutants" refers to suspended sediments, nutrients, organic carbon (OC) and pesticides. It is difficult to determine with certainty the range of concentrations for the first three chemical constituents that would have been in floodwaters from the FRB prior to catchment modification. However, the only reference values available for what are considered environmentally acceptable concentrations are greatly exceeded in almost all cases for floodwater constituent concentrations reported here. Therefore, in a general sense, we have adopted the term pollutants to indicate elevated concentrations from human activity in the FRB. This approach is indirectly supported by other recent studies and reports (Australian Government and Queensland Government, 2005; Baker, 2003; McCulloch et al., 2003).

We report on 11 years of field data (spanning 15 years) of flood-borne pollution to the GBR lagoon from the FRB via a load-based approach. We introduce an innovative, yet relatively simple and accessible method for relating land use to pollutant generation and transport.

Study aims were to:

(1) Sample flood runoff over a number of representative years in order to quantify the concentrations and total loads of pollutants discharging from the FRB to the southern GBR lagoon;
(2) Relate land use to the concentrations and total loads of pollutants in flood events and
(3) Based on study findings, suggest effective catchment management actions to reduce pollution delivery to the GBR lagoon in the short and medium term and assess the effectiveness of load-based water quality guidelines.

In this paper, we concentrate on water quality at the FRB outlet more so then the sub-catchments, because this is most pertinent to the GBR receiving waters, and on determining the sources of the flood runoff and pollutants.

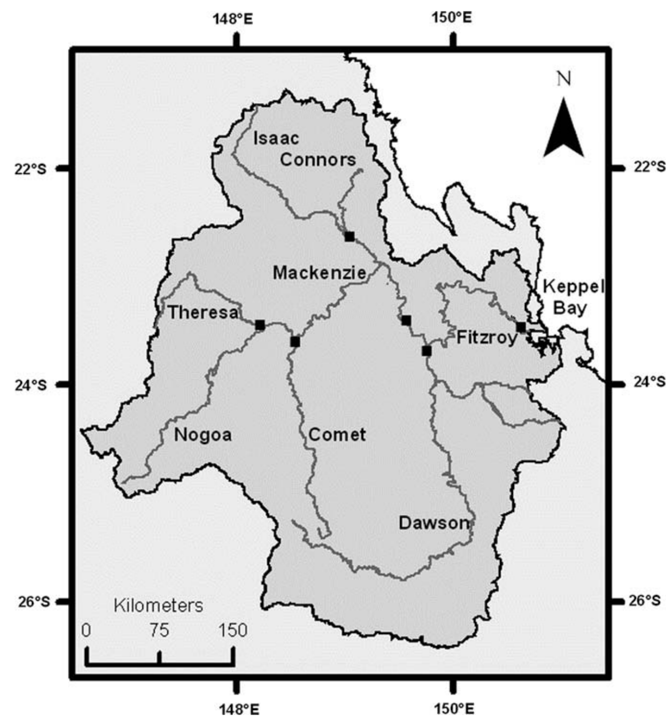

Fig. 2. The Fitzroy River Basin and major tributaries. Black squares indicate flood water sampling locations. Rockhampton is located at the end of Fitzroy River near the entrance to Keppel Bay.

2. Methods

Floodwaters were sampled at a sufficient frequency to determine representative concentrations and total loads of pollutants at various sites throughout the FRB. Fitzroy River samples refer to the basin outlet into the Fitzroy estuary and therefore the GBR lagoon. Major tributaries of the basin that were sampled include the Nogoa, Comet, Mackenzie, Isaac/Connors, Dawson and Fitzroy Rivers and Theresa Creek (Nogoa River sub-catchment). The Connors River contributes around 50% of the long-term annual discharge to the lower Fitzroy system and this is mainly due to tropical rainfall in the north-eastern coastal ranges of the Isaac/Connors catchment (Fig. 2).

2.1. Floodwater sampling and pollutant constituent analysis

The study was made up of two study periods, period 1 from 1994 to 1998 and period 2 from 2002 to 2008. Surface water samples for the floods of 1994, 1996, 1997, 1998 and 2008 were collected at Laurel Banks, ~76 km upstream from the mouth of the Fitzroy River as part of a continuing monitoring program of comprehensive cross-sectional surveys for suspended sediments (Horn et al., 1998). We have only included daily mean water surface concentrations (0.2–0.5 m below surface) from that study to align with the methodologies used for study period 2. Time series manual grab samples for the floods of 2002–2007 were collected 0.2 m below the surface in a fast flowing section of the river (from road bridges or from the bank) as near as possible to a gauge station. Timing of sampling was dependent on the expected duration for the event. Sub-catchment scale samples were generally collected twice daily (morning and evening), while lower Fitzroy River samples (basin outlet) were normally collected on a daily basis (or twice daily near peak discharge). All Fitzroy River samples for the 2002–2007 period were collected at Rockhampton just below the barrage at the head of the estuary ~57 km upstream from the mouth of the Fitzroy River.

The concentration of total suspended solids (TSS), total phosphate (TP) and total nitrogen (TN) were determined for all whole of basin samples and at most sub-catchment scales in all floods sampled. Dissolved nutrient and organic carbon (OC) concentrations were determined for many samples at various scales. Pesticide concentrations were sampled where possible but at a lower frequency than for TSS and nutrients and were often detected in flood flows at all catchment scales. Floodwater samples were analysed via quality assured procedures specific to environmental waters. Particle sizing analysis was undertaken with a Mastersizer 2000™ (laser technique).

2.2. Rainfall, discharge data and event area calculations

To determine the source areas of pollutants, daily rainfall grids in 5 km^2 grid cells (Jeffrey et al., 2001) covering the FRB were obtained from the Queensland Department of Natural Resources and Water (NRW) SILO database (<http://www.nrw.qld.gov.au/silo/>). Stream discharge data in cubic metres per second (m^3 s^{-1}) and megalitres per day (ML day^{-1}) were obtained from the NRW Hydrographic group. Event areas were then calculated for each flood via the following steps using a Geographic Information System (GIS):

1. Discharge hydrographs were examined to identify the approximate rainfall period leading up to the flood runoff. Rainfall data was then secured for the periods of interest for each flood event;
2. the first and last days of the rain event were determined by excluding days where less than 25 mm of rain fell in a 24 h period. Grids with cells where rainfall exceeded 25 mm for a 24 h period were then summed, and a new "total rain event grid" was created;
3. the new "total rain event grid" was then classified into two units, <50% and >50% of the event rainfall total, the area that received the highest 50% of the total event rainfall was selected to produce an "event area map" (methods are expanded in later

sections and an example map given in Fig. 7). The >50% total rain threshold was used for all events in the study in order to isolate those areas that contributed the majority of runoff, and therefore the majority of pollutants in the floodwaters, and
4. this "event area map" was combined with digital land use and catchment boundary layers to calculate the area of land used for cropping and grazing as a percentage of the total event area at sub-catchment and whole of basin scales.

In summary, only the highest 50% of the total rainfall was included in a GIS based method for each runoff event to produce an event area map. The percentage of land in the event area used for cropping was then calculated. The relationship between the percentage of event area used for cropping and the concentrations and total load of pollutants in runoff for an event was then compared to other events.

2.3. Load and event mean concentration calculations

Event load calculations were based on the flow-weighted mean concentration method where the average concentration for a period over the event hydrograph is multiplied by the average flow to give a load. These successive loads are then summed to obtain the total load of each constituent for the event. An event mean concentration (EMC) was then calculated by dividing the total load by the total runoff volume for each event (Kim et al., 2007; Waters and Packett, 2007; Lin, 2004). Constituent load calculations for the Connors River floods of 2002 and 2004 and for the Dawson River 2004 flood were derived from historical and recent concentration estimates. The 2006 Dawson values were derived from a number of floodwater samples collected close to the event source on major tributaries of the Dawson River. For all other calculations a minimum of four samples were used with an average number of eight samples covering the rising, peak and falling stages of the hydrograph.

The methods described above were implemented by entering the time series constituent concentration values and discharge data in cubic metres per second ($m^3 s^{-1}$) for each event into the "Loads Tool" (<http://www.wqonline.info/products/tools.html>). This software is specifically designed for the calculation of loads and EMC values for constituents in rivers and waterways. Defaults for time step were set to "Total load", output type was set to "Event" and the "Linear interpolation of concentration" method was used for all load and EMC calculations.

3. Results

3.1. Fitzroy River Basin hydrology

There was a substantial variation in annual discharge from the FRB during the study. This yearly variation in discharge is also observed in the long-term flow records for the FRB. Very large floods with total discharge volumes of ∼16–20 million megalitres (ML) have been recorded only three times in the last 100 years (1918, 1954 and 1991). Medium to large volume floods (∼6–15 million ML) have a return period of ∼10–15 years. Over the last 80 years, total annual discharge (October to September) has exceeded five million ML on only 23 occasions. Mean and median long-term annual discharge for the Fitzroy River is 4.8 and 2.7 million ML yr^{-1}, respectively.

Total monthly flow volumes from 1990 to 2008 give an indication of the antecedent conditions prior to and during the study periods and are shown in Fig. 3.

Small volume floods have dominated the annual flow regime from the FRB during the study (Fig. 3). The 2008 event is considered a medium to large flood and occurred 17 years after the very large 1991 event. Annual discharges for the study period are considered fairly representative for the FRB in a long-term sense.

Useful rainfall intensity data was not available for most event areas owing to the scale of the study and the spatial distribution of rain gauges. Total rainfall for events ranged from 160 to 175 mm over 2 to 3 days respectively for smaller events and up to 840 mm (over 12 days) for the major 2008 event. Rainfall intensities of up to 50 mm h^{-1} were recorded during the 2008 rain event; however, higher intensities are thought to have occurred during the study period. Daily rainfall totals, averaged over events, ranged from 50 to 70 mm day^{-1} for both sub-catchment and whole of basin scales, maximum daily totals were often far higher.

3.2. Water quality

3.2.1. Total suspended solids

TSS concentration ranges (mg L^{-1}) for Fitzroy River floods are highly variable (Fig. 4). The high degree of variation in TSS concentrations from event to event indicates differences in the source of sediment depending on where heavy rainfall occurred, which we explore further in the water quality and land use section. Sub-catchment pollutant concentrations were often higher than whole of basin concentrations for the same flood event. For example, the minor flood from Theresa Creek (Nogoa River sub-catchment) in December 2003 had a maximum TSS concentration of >12,000 mg L^{-1}.

The highest maximum TSS concentrations for floods sampled at the basin outlet often originated from sub-catchments with substantial areas under intensive agriculture (for example 1994, 1996, 2002, 2003 and 2004 floods, data not presented). A series of minor flow events for the late 2004 to early 2005 period were combined and treated as one event (Figs. 3 and 4).

Suspended sediment particle size analyses were performed on 10 water samples for floods at sub-catchment and whole of basin scales, with five samples analysed for each scale (Fig. 5). Most of the sediment was very fine, at sub-catchment scale ∼90% was <14 microns and at the basin outlet ∼90% was <10 microns.

Sub-catchment analyses included samples from the Mackenzie (2004, which included floodwaters from the Nogoa and Comet Rivers), Dawson (2004 and 2005) and Connors (2005) Rivers. For the lower Fitzroy River (whole of basin), samples were analysed for the 2003, 2004 and 2005 floods. These results are consistent with a recent study of sediment source and particle size, which reported that very fine clay particles made up the bulk of benthic sediments in the Fitzroy River estuary (Douglas et al., 2006).

3.2.2. Total and dissolved phosphorus, nitrogen and organic carbon

TP and TN concentrations were determined for 132 samples collected from floodwaters at the FRB outlet from 1994 to 2008. Minimum and maximum TP concentrations ranged from 0.63 to 2.2 mg L^{-1} respectively and median and mean concentrations were 0.16 and 0.63 mg L^{-1} respectively. Minimum and maximum TN concentrations ranged from 0.36 to 4.1 mg L^{-1} respectively and median and mean concentrations were 0.1.4 and 1.6 mg L^{-1} respectively. TP and TN concentrations were always higher at sub-catchment scale (not reported) compared to the lower Fitzroy River (whole of basin scale) during floods. For all floodwater samples at all catchment scales TN concentrations were always substantially higher than corresponding TP concentrations. Maximum nutrient concentrations most often coincided with runoff originating from land used for cropping.

Total nutrients samples collected from the 2002 through to 2007 flood events ($n = 53$) were analysed for dissolved and particulate composition. On average, 20% of TP was dissolved. Around 90% of the dissolved TP was inorganic. Dissolved nitrogen made

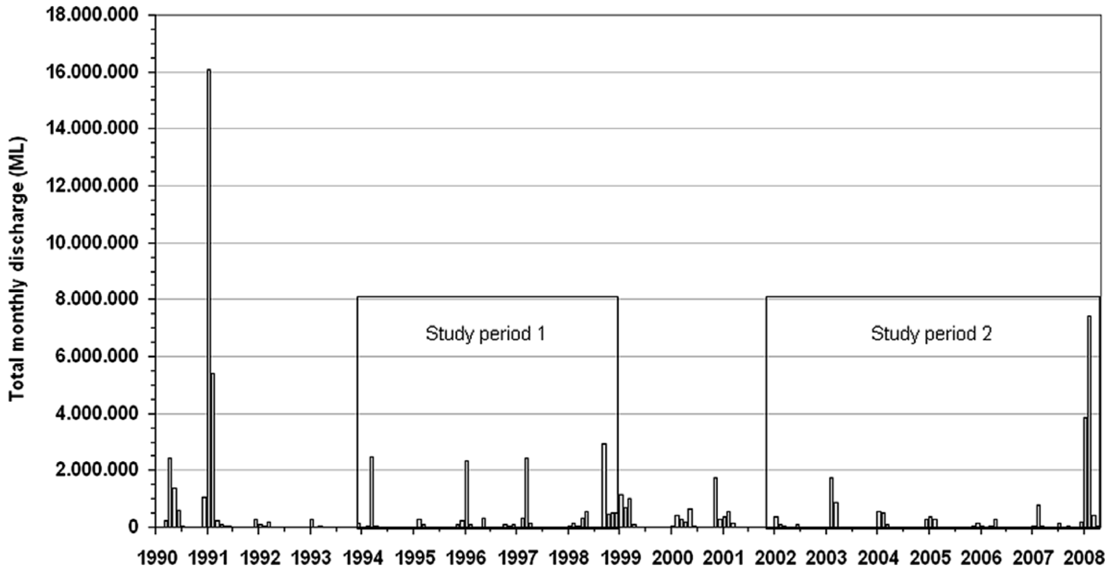

Fig. 3. Total monthly discharge volumes in megalitres (ML) for the Fitzroy River at The Gap gauging station (GS130005A) ~142 km upstream from the mouth of the Fitzroy River for the period January 1990 to April 2008.

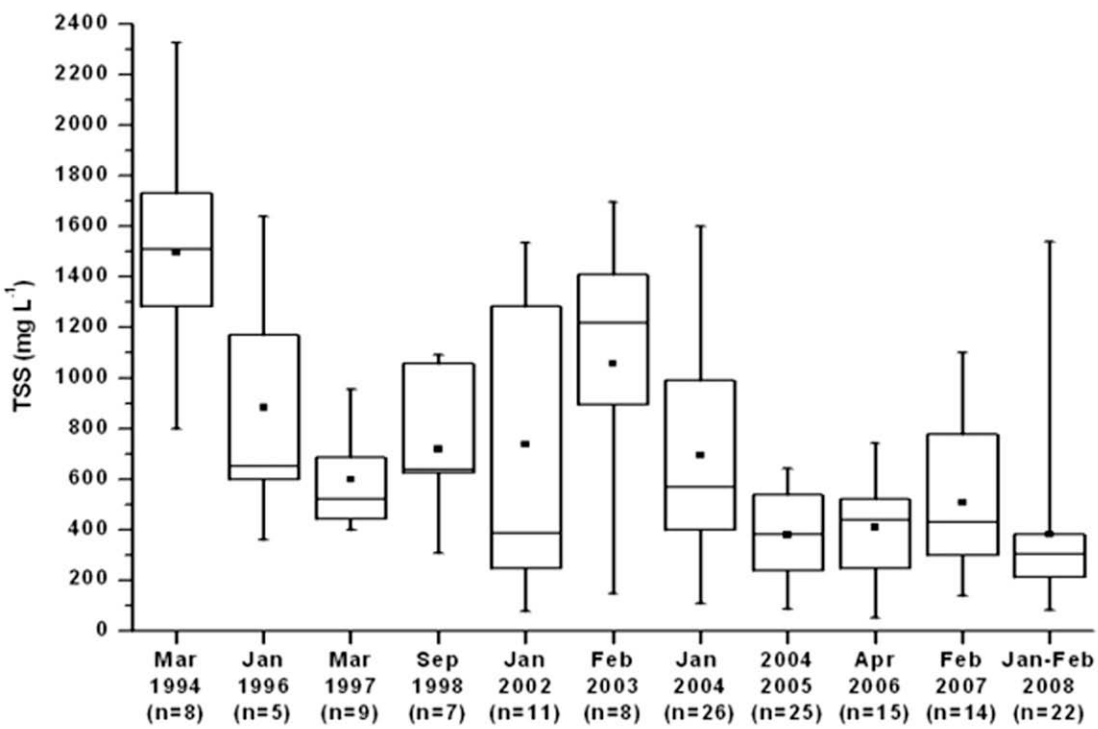

Fig. 4. Total suspended sediment concentrations in the Fitzroy River. Box and whisker plots indicate minimum (bottom whisker), 25% (bottom of box), median (line in box), mean (solid square), 75% (top of box) and maximum (top whisker) TSS concentrations measured for floodwaters at the Fitzroy River Basin outlet.

up 53% of TN and ~52% of the dissolved nitrogen was inorganic. Over the same period 57 floodwater samples collected at the FRB outlet were analysed for total organic carbon (TOC). Minimum, maximum and mean concentrations for TOC were 2, 23 and 14.5 mg L^{-1} respectively. Dissolved OC made up 64% of TOC on average.

3.2.3. Pesticides

Tebuthiuron and atrazine were the most commonly detected herbicides with ~90% of all water samples analysed returning a reportable concentration (Fig. 6). A range of other pesticides were also detected less frequently, including hexazinone, prometryn, floumeturon and dieldrin.

Highest maximum atrazine and diuron concentrations were associated with runoff from event areas with the highest percentage of cropping lands recorded during the study. For example, the highest maximum concentrations of atrazine were observed during the 2002 Comet River and early 2004 Nogoa River flood events with 22% and 20% respectively of the event areas under cropping. At sub-catchment scale, maximum atrazine concentrations were

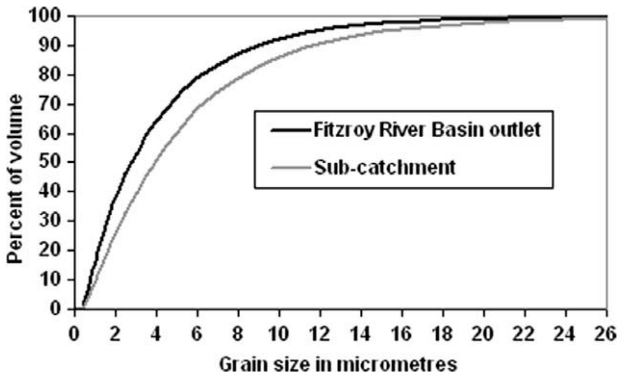

Fig. 5. Average particle size distribution (cumulative) for sub-catchment and whole of basin scales ($n = 5$ at each scale).

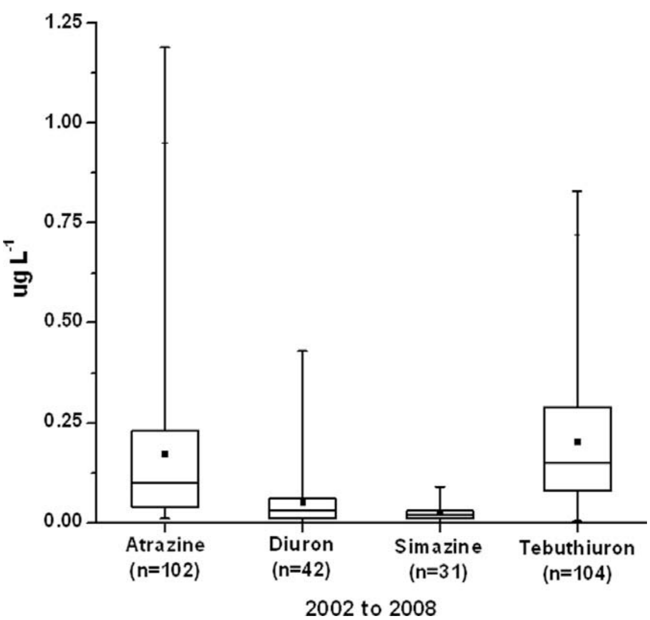

Fig. 6. Range of concentrations for commonly detected herbicides for floodwaters sampled between 2002 and 2008 at the Fitzroy River Basin outlet.

2.20 and 4.26 $\mu g\,L^{-1}$ respectively. At basin scale, maximum atrazine concentrations were 0.80 and 0.95 $\mu g\,L^{-1}$ respectively. Similarly, the highest maximum diuron concentration at sub-catchment scale was 0.20 $\mu g\,L^{-1}$ for both these events. In comparison, the maximium tebuthiuron concentration during these events at sub-catchment scale was 0.01 $\mu g\,L^{-1}$.

Highest maximum tebuthiuron concentrations were associated with events in late 2004 and early 2005 originating from event areas where grazing was the dominant land use, ~98% in both cases. For example, the highest maximum tebuthiuron concentrations at basin scale observed during these events were 0.83 and 0.72 $\mu g\,L^{-1}$ respectively. In comparison, maximum atrazine and diuron concentrations were 0.30 and <0.01 $\mu g\,L^{-1}$ respectively.

3.3. Event loads and event mean concentration values

Event loads were calculated for all events in the two study periods but water samples for the 1994 to 1998 period (study period 1) were not analysed for pesticides, OC and some nutrient species. Only load calculations for the basin outlet, lower Fitzroy River at Rockhampton (input to the Fitzroy River estuary and therefore the GBR lagoon), are reported here (Table 1).

It is assumed that there would have been detectable pesticide concentrations for the 1994 to 1998 period based on data during low, or no flow, conditions (Noble et al., 1997). Gaps in data for the 2002–2008 period indicate that OC concentrations were not determined and that pesticide concentrations were below 0.01 $\mu g\,L^{-1}$ or there were too few reportable results for a load to be calculated. Combined years (2004–2005 and 2005–2006) indicate a series of minor flows that spanned the end and beginning of the respective years and were treated as one extended flood event (Table 1; see Fig. 3).

Event mean concentrations (EMC's, total load divided by total flow volume) are a convenient way of summarising the often highly variable constituent concentration values for an event (Table 2). Comparisons can then be made between events at similar or different catchment scales (Lin, 2004).

3.4. Water quality and land use

Land use had a substantial effect on event runoff water quality. While this was more noticeable at a sub-catchment scale, the im-

Table 1
Calculated total event loads for suspended solids, nutrients and pesticides for the Fitzroy River Basin outlet. Total suspended solids (TSS) loads ranged from 0.34 to 4.2 million tonnes respectively, with total and dissolved nutrient loads (when reported) closely related to TSS loads for each flood event. Maximum pesticide loads coincided with the major 2008 flood event with 2.1 tonnes of atrazine and 1 tonne of tebuthiruron exported from the FRB during this event.

	Month	Volume	Load (tonnes)										Load (kg)			
River	Year	(ML)	TSS	TP	TDP	FRP	TN	TDN	Amm	Nox	TOC	DOC	Atr	Diu	Sim	Teb
Fitzroy	Mar 1994	2, 099,719	3,103,008	3256		125	7114		35	955						
Fitzroy	Jan 1996	2,331,612	2,661,456	2074		111	6887		104	1085						
Fitzroy	Mar 1997	1,843,102	1,157,309	1387		126	2358		68	391						
Fitzroy	Sep 1998	2,115,549	1,594,000	1439		163	3480		30	481						
Fitzroy	Jan 2002	341,472	177,000	223	37	17	421	232	6	119	1214	730	86	21	5	57
Fitzroy	Feb 2003	1,644,591	1,880,010	2283	128	117	5514	1484	80	662	31,679	13,083	59	9	16	89
Fitzroy	Jan 2004	945,587	634,220	493	80	74	1409	684	6	380	12,235	6346	401	100		186
Fitzroy	2004–2005	852,001	300,572	359	72	69	1273	741	19	404			122	11		210
Fitzroy	2005–2006	162,726	33,830	46	12	10	154	62	1	33	1152	894	10		4	64
Fitzroy	Apr 2006	258,656	105,078	122	20	20	341	151	3	80	2934	1726	20	6		90
Fitzroy	Feb 2007	738,506	451,660	465	43	36	1205	477	15	172	8740	6242	40	2	14	141
Fitzroy	Jan–Feb 2008	11,097,700	4,242,740	5496		1742	12,772		420	1329			2153	12	82	1081

TSS = Total suspended solids, TP = Total phosphorus, TDP = Total dissolved phosphorus, FRP = Filterable reactive phosphorus, TN = Total nitrogen, TDN = Total dissolved nitrogen, Amm = Ammonia (as N), Nox = oxides of nitrogen, TOC = Total organic carbon, DOC = Dissolved organic carbon, Atr = Atrazine, Diu = Diuron, Sim = Simazine, Teb = Tebuthiuron. Note that pesticides loads are reported in kilograms while all other constituents are reported in tonnes. Blank spaces in Table 1 for the 1994–1998 periods indicate that chemical analysis was not determined for a constituent. Blank spaces for the 2002–2008 periods indicate that chemical analysis was not determined for a constituent except for pesticides. Blank spaces for pesticides for the 2002–2008 periods indicate that the concentration of a pesticide was either below the Limit of reporting (LOR) or there were not a sufficient number of results above the LOR (<0.01 $\mu g\,L^{-1}$) to allow for a load calculation.

Table 2
Calculated EMC's for sub-catchment and Fitzroy River Basin outlet for floodwaters sampled from 1994 to 2008. High TSS and corresponding total nutrient values were closely related to land use. For example, the highest TSS EMC values measured at the FRB outlet (Fitzroy River in table) were from floodwaters originating from event areas where there was a substantial percentage of land used for cropping (1994, 1996 and 2003). Similarly, high TSS EMC's at a sub-catchment scale were associated with a substantial percentage of the event area used for cropping, for example Comet River 2002 and 2006, Dawson River 2003 and 2006, Nogoa River 2003 and 2004, and Isaac River 2005. The relationship between land use and pollutant generation is expanded in later sections.

	Month	Volume (ML)	EMC (mg L^{-1})										EMC (μg L^{-1})			
River	Year		TSS	TP	TDP	FRP	TN	TDN	Amm	Nox	TOC	DOC	Atr	Diu	Sim	Teb
Fitzroy	Mar 1994	2,099,719	1477	1.32		0.05	2.89		0.01	0.39						
Fitzroy	Jan 1996	2,331,612	1141	0.89		0.05	2.95		0.04	0.45						
Fitzroy	Mar 1997	1,843,102	623	0.75		0.07	1.28		0.04	0.21						
Fitzroy	Sep 1998	2,115,549	754	0.68		0.08	1.65		0.01	0.23						
Comet	Jan 2002	205,663	2045	1.87			2.97						2.14	0.05	<0.01	0.01
Dawson	Jan 2002	68,915	383	0.69	0.36	0.32	1.44	0.74	0.06	0.01			0.14	0.68	<0.01	<0.01
Connors	Jan 2002	71,023	300													
Fitzroy	Jan 2002	341,472	518	0.65	0.11	0.05	1.23	0.68	0.02	0.35	3.56	2.14	0.25	0.06	0.01	0.17
Dawson	Feb 2003	1,090,582	1135	0.90			3.30						0.03	0.01	0.01	0.11
Fitzroy	Feb 2003	1,644,591	1143	1.39	0.08	0.07	3.35	0.90	0.05	0.40	19.26	7.96	0.04	0.01	0.01	0.05
Nogoa	Dec 2003	33,915	6489	1.42			4.68						0.16	<0.01	<0.01	0.01
Nogoa	Jan 2004	120,623	2861	0.76			2.57						2.69	<0.01	<0.01	
Connors	Feb 2004	93,655	343													
Comet	Jan 2004	236,736	770	0.98			1.89						0.15	<0.01	<0.01	0.03
Dawson	Jan 2004	206,732	433													
Fitzroy	Jan 2004	945,587	671	0.52	0.08	0.08	1.49	0.72	0.01	0.40	12.82	6.65	0.43	0.11	<0.01	0.20
Dawson	Dec 2004	67,167	324	0.59			1.53						0.20	0.07	<0.01	0.16
Connors	Jan 2005	235,050	363	0.40		0.03	1.55		0.03	0.29			0.01	<0.01	<0.01	0.02
Fitzroy	2004–2005	852,001	353	0.42	0.08	0.08	1.49	0.87	0.02	0.47			0.14	<0.01	<0.01	0.25
Isaac	Oct 2005	27,601	1216	1.13	0.10	0.08	2.60	0.66	0.03	0.19	17.87	8.34	0.04	<0.01	<0.01	0.14
Dawson	Dec 2005	138,723	576	0.57			1.79				14.19	7.06	0.20	<0.01	<0.01	0.02
Dawson	Jan 2006	21,168	335	0.55		0.24	1.52				16.47	8.91	0.16	<0.01	<0.01	0.02
Fitzroy	2005–2006	162,726	208	0.28	0.07	0.06	0.95	0.38	0.01	0.20	7.08	5.49	0.06	<0.01	0.02	0.39
Comet	Apr 2006	116,215	2445	1.76	0.20	0.19	2.94	0.77	0.04	0.33	26.39	7.86	0.33	<0.01	0.02	0.34
Dawson	Apr 2006	91,808	1113													
Fitzroy	Apr 2006	258,656	406	0.47	0.08	0.08	1.32	0.58	0.01	0.31	11.35	6.68	0.08	0.03	<0.01	0.35
Connors	Jan 2007	861,000	329	0.31	0.06	0.05	1.09	0.59	0.04	0.20	12.90	10.06	<0.01	<0.01	<0.01	0.10
Fitzroy	Feb 2007	738,506	612	0.63	0.06	0.05	1.63	0.65	0.02	0.23	11.84	8.45	0.05	0.01	0.02	0.19
Fitzroy	Jan–Feb 2008	11,097,700	382	0.50		0.16	1.15		0.04	0.12			0.19	0.01	0.01	0.10

For abbreviations used see Table 2. Note that pesticide concentrations are reported in μg L^{-1}, whereas all other concentrations are presented in mg L^{-1}. Blank spaces in Table 2 for the 1994–1998 periods indicate that chemical analysis was not determined for a constituent. Blank spaces for the 2002–2008 periods indicate that chemical analysis was not determined for constituents other than for pesticides. Blank spaces for 2002–2008 indicate that the concentration of a pesticide was either below the Limit of reporting (LOR) or there were not a sufficient number of results above the LOR (<0.01 μg L^{-1}) to allow for an EMC calculation.

pact of land use could be reliably detected in most cases for floodwater quality at the FRB outlet. An example of the combined event area and land use maps (24 in total) generated to quantify land use impacts on water quality at both sub-catchment and whole of basin scales is given in Fig. 7 for the 1994 flood event.

White and light grey areas in Fig. 7 indicate grazing lands where <50% and >50% of total event rain fell respectively. Similarly, black and dark grey areas indicate cropping land use where <50% and >50% of total event rain fell respectively. In other words, the dark areas under the grey transparent layer in Fig. 7 represent the highest rainfall totals on cropping lands. For this event in 1994, cropping comprised ∼20% of the high rainfall area of the event. This was the highest percentage of cropland area for an event recorded at whole of basin scale and also resulted in the highest TSS, TP and second highest TN EMC's for all events at this scale.

Calculations of the contributing land use% for each event were separated into sub-catchment and whole of basin scale groups. TSS EMC increased with increasing cropping % in event areas for both sub and total catchment scales (Fig. 8).

Data for the Nogoa 2003 sub-catchment event were not included as this event had an EMC of 6489 mg L^{-1} and was considered an outlier, even though there was a high percentage of the event area under cropping (24%). Data for the Fitzroy River for the 2002 and 2006 floods (event volumes <350,000 ML) were not included in the regression analysis. EMC values for these minor events were relatively low due to the effect of dilution from water held in storages in the lower Fitzroy River system (water holes, weirs and a barrage with a combined total volume ∼120,000 ML^{-1}).

Linear regressions between the percentage of the event area used for cropping and total nutrient EMC's resulted in R^2 values of 0.65 for TN and 0.57 for TP at a sub-catchment scale ($n = 10$). At basin scale, the R^2 values were 0.56 for TN and 0.71 for TP ($n = 9$).

3.5. Relationships between constituents and relationships between discharge and constituents

The relationship between TSS and TP via linear regression resulted in the highest coefficient of determination for all catchment scales in all years (Table 3). In general, TSS concentrations were a reasonable indicator for TP, TOC, turbidity, and to a lesser degree, TN.

Relationships between TSS and pesticide concentration were far less reliable at all catchment scales in most years. TSS and discharge (Q) relationships were generally poor, particularly for minor floods in the lower Fitzroy River where water held in storages could affect rising stage concentrations. For example, the minor flood of 2002 resulted in the highest concentrations of TSS and pesticides well after peak discharge. Sub-catchment relationships for TSS and Q were generally of a higher *R*-squared value than those observed at the basin outlet (Rockhampton).

4. Discussion

Land use had a significant effect on the maximum concentration, EMC and event load of pollutants delivered during flood

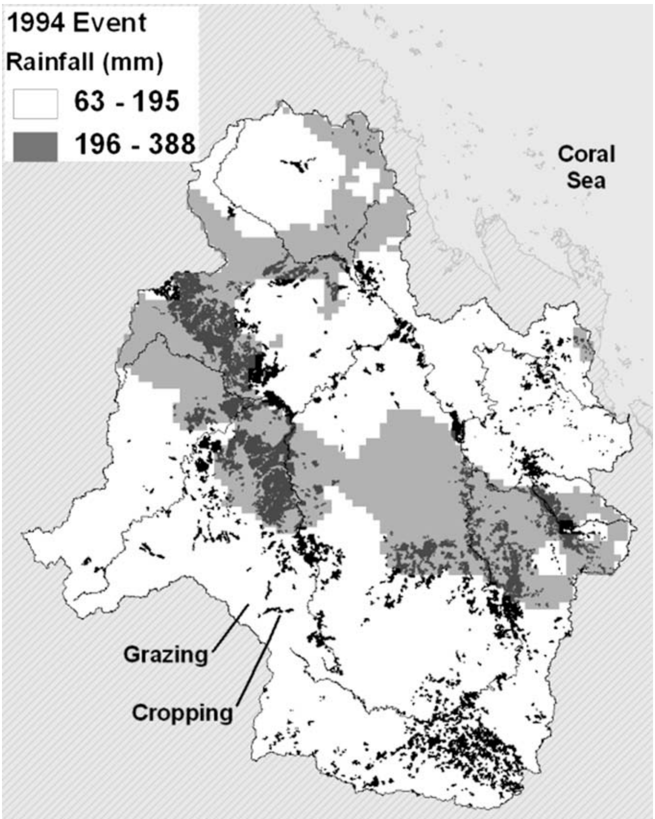

Fig. 7. An example of the event area maps generated in this study to quantify the percentage land use types that produced the majority of flood runoff. Light grey areas indicate cumulative rainfall and dark grey areas under the light grey layer indicate crop lands.

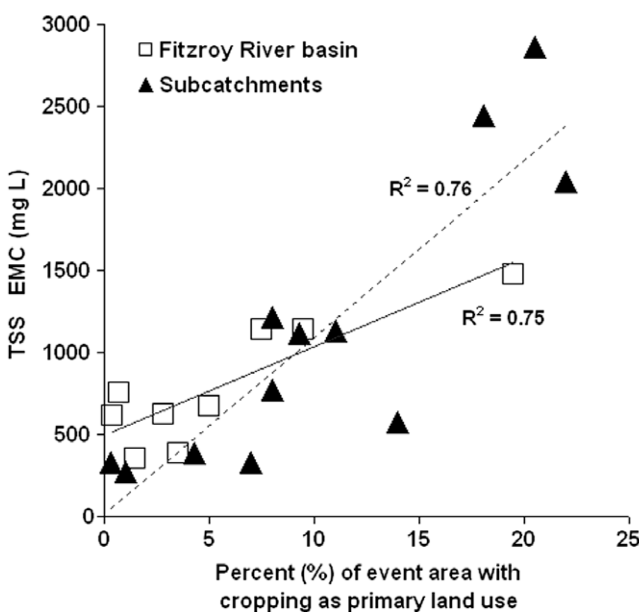

Fig. 8. EMC concentrations for TSS and cropping % of event area. Linear regressions for TSS event mean concentration and the percentage of contributing event area used for cropping at sub-catchment and total catchment scales.

events from the FRB to the lower Fitzroy River, estuary and GBR lagoon. At a sub-catchment scale, the maximum concentrations for both TSS and nutrients were closely related to land use. This was less obvious at the whole of basin scale. EMC's for events at both catchment scales tended to follow similar patterns with generally higher TSS, TN and TP values observed for sub-catchments compared to the basin outlet. In all years and at both catchment scales an increase in the percentage of the event area used for cropping resulted in an increase in pollutant concentrations and EMC's. Croplands could therefore be considered "hot-spots" for pollutant generation in the FRB and possibly for other large dry tropical catchments in northern Australia.

Table 3
Relationships for paired TSS and constituent water samples collected from lower Fitzroy River floods.

Independent variable	Dependent variable	Flood year	(*n*)	*R*-squared value
TSS	TP	2007	14	0.94
TSS	TN	2004	45	0.60
TSS	TOC	2004	25	0.84
TSS	Turbidity	2007	14	0.89

These findings are similar to the results of other studies dealing specifically with large-scale land use effects on water quality in Australia and other countries (Hunter and Walton, 2008; Kim et al., 2007; Bramley and Roth, 2002). Although there can be substantial in-stream deposition of suspended sediments between the sub-catchments and basin outlet, fine TSS transport was relatively efficient overall, often greater than 40%. This is due to the very fine particle sizes commonly found in runoff throughout the FRB.

The annual discharge from the large dry tropical catchment of the FRB is highly variable, but generally, at least 1 minor flood reaches the GBR lagoon each year. Large volume floods have historically been a focus of attention due to the possible impacts of poor water quality on middle and outer reefs. These infrequent floods can deliver large volumes of low salinity water and large loads of pollutants. Our data shows that small volume floods from the FRB can deliver undiluted loads of pollutants to inshore areas of the southern GBR lagoon in most years. If the concentration of pollutants is a critical issue for inshore water quality, then these annual minor floods may be of more significance than large infrequent floods.

TSS concentrations were generally a reasonable indicator of nutrient and OC concentrations. The relationships between TSS and OC are similar to the findings of Ford et al. (2005), which reported that soil OC was the main form of carbon exported during high flow events from the FRB with DOC the dominant component of the TOC load.

Our data is the first report of long-term annual pesticide loads exported from the FRB to the southern GBR Lagoon. The highest concentrations of the herbicides atrazine and diuron in most years were associated primarily with floods originating from croplands, where they are commonly used for weed control. Tebuthiuron, used for controlling woody weeds, was closely associated with runoff from grazing lands. It can be seen from Table 1 that ~2.1 tonnes of atrazine and ~1 tonne of tebuthiuron were exported into the GBR Lagoon from the 2008 flood event. The impacts of atrazine and diuron on corals have recently been studied by Jones et al. (2003). Tebuthiuron is now ubiquitous throughout the FRB and it should be of concern that this chemical is detected in practically every floodwater sample entering the GBR Lagoon.

Sub-catchments were variable in their patterns of pollutant generation and delivery. The Connors River system consistently had the lowest concentrations of pollutants and the largest volume of water over the study period. In comparison, discharge from the neighbouring Isaac River catchment is more ephemeral and can contribute relatively high EMC values from flood events originating from dry-land cropping regions (e.g. 2005 event). These two sub-catchments typify how land use and climate can determine long-term pollutant generation and delivery to the coast. The Connors catchment has a relatively high rainfall region in the north-eastern mountain ranges with grazing lands of high ground cover year round and limited cropping areas. The Isaacs catchment experiences far lower average annual rainfall has extensive areas of dry grazing lands, which are often in drought, and substantial cropping areas in the southwestern highland regions. Both the northern Nogoa (Theresa Creek) and the Comet sub-catchments contribute high EMC's for flood events generated over extensive dry-land and irrigated croplands. The large Dawson sub-catchment produced few moderate floods during the study with the 2003 event contributing both high discharge volumes and high EMC values. The minor event in 2006 also produced high EMC values compared to other years. The common factor for both years (2003 and 2006) was the higher percentage of event area under dry-land cropping compared to other years (2002, 2004 and 2005).

Antecedent conditions are likely to have been an important factor in the generation of pollutants during runoff events. Ground cover has been shown to be an important factor in erosion and pollutant generation in this region (Carroll et al., 2000). Periods of very low rainfall are likely to have reduced ground cover on both dry-land cropping and grazing event areas. In contrast, general rainfall is likely to have increased ground cover prior to runoff events and reduced pollutant generation in some years. Although ground cover was not measured directly in this study, an estimate of rainfall, runoff and therefore potential ground cover may be generalised from monthly total flow volumes in Fig. 3. The majority of the study period was relatively dry because runoff from the FRB was low or non-existent in most years between the wet season floods. Long-term rainfall and runoff records show that this period was representative of expected annual events for the FRB. For either wet or dry antecedent conditions, we suggest that the ratio of cropping land use to event area will remain the dominant factor in the generation of pollutants at elevated concentrations.

During this study, data was not available for comparisons to be made between events of the effect of rainfall intensity on pollutant generation; this was mainly due to the spatial distribution of suitable rainfall gauges. However, examination of limited rainfall intensity data and daily rainfall totals for a number of events suggests that land use rather than rainfall intensity was the main driver of elevated pollutant generation. The highest maximum concentrations of pollutants (excluding tebuthiruron) recorded during the study were generated from relatively intense rainfall events over croplands.

In the future, high intensity rainfall events may become more frequent across northern Australia if current rapid climate change predictions are correct. It is widely accepted that rainfall intensity (mm/h^{-1}) can have a major effect on soil erosion and pollutant generation. More frequent intense rainfall events over croplands and grazing lands may lead to increases in pollutant generation compared to the current climatic conditions. It would therefore be important to consider the impacts of climate change in land management strategies aimed at reducing pollutant delivery to the GBR lagoon.

Throughout the study period, wet season flood events were commonly followed by low or zero discharge until the next summer wet season. Water storages in the lower Fitzroy River include a series of natural water holes, a weir and a barrage with a total combined volume of $\sim$120,000 ML^{-1}. Residual floodwaters held in these storages from the previous wet season move into the Fitzroy River estuary, forming part of the rising stage of the next seasonal flood. The concentrations of pollutants in this stored floodwater were normally far lower than the current seasonal floodwaters that followed. This reduction in concentration is thought to be caused by the flocculation and deposition of suspended sediments and particulate nutrient fractions and the assimilation of dissolved nutrients into the aquatic ecosystem. Therefore, the water held in storages over many months tended to reduce the total event load to the estuary, although the effect was minimal when event volumes exceeded $\sim$500,000 ML^{-1}.

While pollutant concentrations were generally higher in sub-catchments than those at the FRB outlet for the same flood, this was not always the case. The 2007 flood, which was generated in the Connors River system, produced a lower sub-catchment TSS EMC than that measured at the basin outlet even though this was an isolated runoff event. For practically all measured chemical parameters the basin outlet EMC's were substantially higher and this is thought to be the result of re-entrainment of suspended sediments and nutrients held in water storages in the lower Mackenzie/Fitzroy system from the previous wet season event (Table 2). The April event of 2006 had filled the storages with floodwaters from the Comet and Dawson River systems and this would have been mobilised during the 2007 flood adding to the Connors River load. It can also be seen from Table 2 that not all flood flows were sampled at a sub-catchment scale. However, sufficient events were sampled for interpretation of catchment response to rainfall over differing land use types at sub-catchment and whole of basin scales.

Improved management of both cropping and grazing land should be a priority. As cropping was the primary short-term contributor of TSS, dissolved and particulate nutrients, OC and atrazine and diuron, we suggest that catchment management actions to reduce the movement of pollutants from the FRB should focus on cropping lands as they appear to be 'hot-spots' for pollutant generation. Grazing lands management would still be of major importance, particularly given the large areas of the FRB where this land use has the capacity to generate runoff with relatively high concentrations of pollutants compared to undeveloped lands. Runoff from grazing lands will continue to deliver large loads of suspended sediments, nutrients and tebuthiuron to the GBR lagoon unless current management practices are substantially altered. Poorly managed or over-grazed lands may also be important 'hot-spots' for pollutant generation.

The majority of suspended sediments delivered to the GBR from the FRB are deposited near the Fitzroy River mouth while dissolved nutrients are transported with the plume out into the GBR lagoon (Packett, 2007). Recent studies into the impacts of land-sourced pollution on inshore coral ecosystems have identified dissolved nitrogen, phosphorus and OC as drivers of pulsed algal blooms. Particulate forms of these nutrients are also believed to cause chronic eutrophication in the longer term and lead to indirect impacts on corals and other reef assemblages (Smith et al., 2006; Fabricius et al., 2005). Improved management of both croplands and grazing lands to reduce the amount of dissolved nutrients and OC in runoff may therefore be an important target for reduced pollutant delivery to the southern GBR lagoon.

Overall, the worst-case annual scenarios for inshore southern GBR lagoon water quality are small to moderate volume floods from event areas dominated by cropping. The 2003 Dawson event driven by a tropical cyclone was one such flood event. We suggest that the temporal and spatial diversity of events and the sub-catchment land use characteristics of the FRB would produce load targets with only limited usefulness for assessing changes in catchment management. Instead, we suggest that targets based on changes in on-ground agricultural management practices would offer a more direct and measurable method for reducing pollutant loads from the FRB (and other large GBR catchments) to the GBR lagoon.

5. Conclusions

The results of sampling 17 sub-catchment and 11 whole of basin flood events indicate that pollutants can be transported to the

GBR lagoon from distant sources in the FRB on an annual basis. Small to medium volume floods produce higher EMC values than less frequent large volume floods.

Lands used for cropping repeatedly produced the highest concentrations of suspended sediments, nutrients and a range of herbicides, apart from tebuthiuron, which was mainly generated from grazing lands. In general terms, the higher the ratio of cropping land use to the total event catchment area, the greater the potential maximum pollutant concentration. Croplands were found to be 'hot-spots' for elevated pollutant concentrations in runoff to the GBR lagoon.

Lands used for grazing are the primary source of the long-term average annual pollutant load to the southern GBR lagoon.

We found that using total event rainfall maps in combination with digital land use layers can indicate, and possibly predict, the range of concentrations for a number of pollutants at a sub-catchment and whole of basin scales. This innovative and relatively simple technique relies on tools and data readily available to natural resource managers and community groups.

Based on the findings of this study, we suggest that setting high flow water quality targets for either pollutant concentration or load may not work well for large, dry, ephemeral catchments such as the FRB. A more effective and direct method to decrease the concentrations and loads of pollutants in runoff discharging into the GBR lagoon would be to develop targets for on-ground changes in catchment management.

Acknowledgements

This study was supported by a number of organizations including the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management; the National Action Plan for Salinity and Water Quality; The Queensland Department of Natural Resources and Water (in particular the Rockhampton Hyrdographic group) and the Queensland Environmental Protection Agency (including the Queensland Parks and Wildlife service). We acknowledge the resources provided by the agencies mentioned above and thank individuals from within these agencies for their assistance. We also wish to thank members of the Fitzroy River Basin community who generously provided crucial input by collecting floodwater samples for a number of events at sub-catchment scale on a voluntary basis. A number of people reviewed various manuscript drafts and we wish to thank Mark Silburn, John Armour, David Waters and Katharina Fabricius for their valuable comments and suggestions.

References

Accad, A., Neldner, V.J., Wislosn, B.A., Niehus, R.E., 2001. Remnant vegetation in Queensland: analysis of pre-clearing, remnant 1997–1999 regional ecosystem information. Queensland Herbarium, Environmental Protection Agency, Brisbane.

Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (ANZECC and ARMCANZ). 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality, vol. 1. The Guidelines, ANZECC and ARMCANZ.

Australian Government and Queensland Government, 2005. Reef Water Quality Protection Plan Annual Report 2004–05.

Bailey, A. (Ed.), 1984. The Brigalow Belt of Australia. The Royal Society of Queensland, Brisbane, Australia.

Baker, J., 2003. A Report on the Study of Land-Sourced Pollutants and their Impacts on Water Quality In and Adjacent to the Great Barrier Reef. Queensland Government, Brisbane, Australia.

Bramley, R.G.V., Roth, C.H., 2002. Land-use effects on water quality in an intensively managed catchment in the Australian humid tropics. Marine and Freshwater Research 53, 931–940.

Brodie, J.E., 2002. Keeping the wolf from the door: managing landbased threats to the Great Barrier Reef. In: Proceedings of 9th International Coral Reef Symposium 2, pp. 705–714.

Brooke, B., Ryan, D., Pietsch, T., Olley, J., Douglas, G., Packett, R., Radke, L., Flood, P., 2008. Influence of climate fluctuations and changes in catchment land use on late Holocene and modern beach-ridge sedimentation on a tropical macrotidal coast: Keppel Bay, Queensland, Australia. Marine Geology 251, 195–208.

Carroll, C., Merton, L., Burger, P., 2000. Impact of vegetative cover and slope on runoff, erosion, and water quality for field plots on a range of soil and spoil materials on central Queensland coal mines. Australian Journal of Soil Research 38, 313–327.

DeVantier, L.M., De'ath, G., Turak, E., Fabricius, K.E., 2006. Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef Coral Reefs. Coral Reefs 25, 329–340.

Devlin, M., Brodie, J., Waterhouse, J., Mitchell, A., Audas, D., Haynes, D., 2003. Exposure of Great Barrier Reef inner-shelf reefs to river-borne contaminants. In: Second National Conference on Aquatic Environments: Sustaining Our Aquatic Environments – Implementing Solutions, 20–23 November, 2001, Queensland Department of Natural Resources and Mines, Brisbane, Townsville, Australia.

Dougall, C., Packett, R., Carroll, C. 2005. Application of the SedNet model in partnership with the Fitzroy Basin community. In: Zerger, A., Argent, R.M. (Eds.), MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005.

Douglas, G., Ford, P., Palmer, M., Noble, R., Packett, R., 2006. Fitzroy River, Queensland, Australia. II. Identification of sources of estuary bottom sediments. Environmental Chemistry 3 (5), 377–385.

Environmental Protection Agency, 2006. Queensland Water Quality Guidelines Version 2, March 2006. The State of Queensland, Brisbane.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50, 125–146.

Fabricius, K.E., De'ath, G., McCook, L., Turak, E., Williams, D.M., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. Marine Pollution Bulletin 51, 384–398.

Fabricius, K.E., De'ath, G., 2004. Identifying ecological change and its causes: a case study on coral reefs. Ecological Applications 14, 1448–1465.

Ford, P., Tillman, P., Robson, B., Webster, I., 2005. Organic carbon deliveries and their flow related dynamics in the Fitzroy estuary. Marine Pollution Bulletin 51, 119–127.

Haynes, D., Muller, J., Carter, S., 2000. Pesticide and herbicide residues in sediments and sea grasses from the Great Barrier Reef world heritage area and Queensland Coast. Marine Pollution Bulletin 41, 279–287.

Hennessy, K., Fitzharris, B., Bates, B.C., Harvey, N., Howden, S.M., Hughes, L., Salinger, J., Warrick, R. 2007. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Australia and New Zealand. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 507–540.

Horn, A., Joo, M., Poplawski, W., 1998. Queensland Riverine sediment transport rates, a progress report. Water quality group report no. 2/98. Department of Natural Resources, Indooroopilly, Queensland.

Hunter, H.M., Walton, R.S. 2008. Land-use effects on fluxes of suspended sediment, nitrogen and phosphorus from a river catchment of the Great Barrier Reef. Australian Journal of Hydrology. doi: 10.1016/j.jhydrol.2008.04.003.

Intergovernmental Panel on Climate Change. 2007. Summary for policymakers of the synthesis report of the IPCC fourth assessment report, DRAFT COPY 16 NOVEMBER 23:04 – subject to final copyedit. <http://195.70.10.65/ipccreports/ar4-wg2.htm>.

Jeffrey, S.J., Carter, J.O., Moodie, K.M., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16 (4), 309–330.

Jones, R., Muller, J., Haynes, D., Schreiber, U., 2003. The effects of the herbicides diuron and atrazine on corals of the Great Barrier Reef (Australia). Marine Ecology Progress Series 251, 153–167.

Kim, G., Chung, S., Lee, C., 2007. Water quality of runoff from agricultural-forestry watersheds in the Geum River Basin, Korea. Environmental Monitoring and Assessment 134, 441–452.

Lin, J.P., 2004. Review of Published Export Coefficient and Event Mean Concentration (EMC) Data. ERDC TN-WRAP-04–03. US Army Engineer Research and Development Centre, Vicksburg, MS.

McCook, L.J., Folke, C., Hughes, T.P., Nyström, M., Obura, D., Salm, R. 2007. Ecological resilience, climate change and the Great Barrier Reef. In: Johnson, J.E., Marshall, P.A. (Ed.), Climate Change and the Great Barrier Reef: A Vulnerability Assessment, Great Barrier Reef Marine Park Authority, Townsville, Australia, pp. 75–96.

McCulloch, M., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003. Coral record of increased flux to the inner Great Barrier Reef since European settlement. Nature 421, 727–730.

Noble, R.M., Duivenvoorden, L.J., Rummenie, S.K., Long, P.E., Fabbro, L.D., 1997. Downstream Effects of Land Use in the Fitzroy Catchment. Summary Report. Department of Natural Resources, Queensland, Australia.

Nugues, M.M., Smith, G.W., Hooidonk, R.J., Seabra, M.I., Bak, R.P.M., 2004. Algal contact as a trigger for coral disease. Ecology Letter 7, 919–923.

Packett, R. 2007. A mouthful of mud: the fate of contaminants from the Fitzroy River, Queensland, Australia and implications for reef water policy. In: Proceedings of the 5th Australian Stream Management Conference. Australian Rivers: Making a Difference, Charles Sturt University, Thurgoona, New South Wales.

Pandolfi, J.M., Jackson, J.B.C., Baron, N., Bradbury, R.H., Guzman, H.M., Hughes, T.P., Kappel, C.V., Micheli, F., Ogden, J.C., Possingham, H.P., Sala, E., 2005. Are US coral reefs on the slippery slope to slime? Science 307, 1725–1726.

Pandolfi, J.M., Bradbury, R.H., Sala, E., Hughes, T.P., Bjorndal, K.A., Cooke, R.G., McArdle, D., McClenachan, L., Newman, M.J., Paredes, G., Warner, R.R., Jackson, J.B.C., . Global trajectories of the long-term decline of coral reef ecosystems. Science 301, 955–958.

Radford, B.J., Thornton, C.M., Cowie, B.A., Stephens, M.L., 2007. The brigalow catchment study: III. Productivity changes on brigalow land cleared for long-term cropping and for grazing. Australian Journal of Soil Research 45, 512–523.

Schaffelke, B., 1999. Synthesis of Marine Water Quality Data Offshore the Fitzroy River region. Report to the National Land and Water Audit Demonstration Project (NLWRA). Great Barrier Reef Marine Park Authority, Townsville, Australia.

Smith, J.E., Shaw, M., Edwards, R.A., Obura, D., Pantos, O., Sala, E., Sandin, S.A., Smriga, S., Hatay, M., Rohwer, F.L., 2006. Indirect effects of algae on coral: algae-mediated, microbe-induced coral mortality. Ecology Letters 9 (7), 835–845.

The State of Queensland and Commonwealth of Australia. 2003. Reef Water Quality Protection Plan: For Catchments Adjacent to The Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane.

Thornton, C.M., Cowie, B.A., Freebairn, D.M., Playford, C.L., 2007. The brigalow catchment study: II. Clearing brigalow (*Acacia harpophylla*) for cropping or pasture increases runoff. Australian Journal of Soil Research 45 (7), 496–511.

Waters, D., Packett, R. 2007. Sediment and nutrient generation rates for Queensland rural catchments – an event monitoring program to improve water quality modelling. In: Proceedings of the 5th Australian Stream Management Conference. Australian Rivers: Making a Difference. Charles Sturt University, Thurgoona, New South Wales.

Wilkinson, C. (Ed.), 2002. Status of Coral Reefs of the World: Global Coral Reef Monitoring Network. Australian Institute of Marine Science, and Townsville, Australia.

Williams, D.McB., 2001. Impacts of Terrestrial Run-Off on the GBRWHA. Report to CRC Reef, Townsville, Australia.