Fitzroy Sediment Story

November 2015

Prepared by Stephen Lewis, Bob Packett, Cameron Dougall, Jon Brodie, Rebecca Bartley and Mark Silburn

FITZROY BASIN ASSOCIATION

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Fitzroy sediment story.

A Report for the Fitzroy Basin Association

Report No. 15/74

November 2015

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Contents

List of Figures

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List of Tables

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Executive Summary

A review of the available information in regards to the origin, transport and impacts of fine sediment and particulate nutrients from the Fitzroy River Basin to the southern Great Barrier Reef (GBR) lagoon was undertaken. It was found that the evidence suggests an increase in water, sediment and nutrient loads from the basin compared to predevelopment conditions.

The increase in fine sediment delivery to coastal waters has increased water turbidity during flood plumes and later via resuspension due to wave action and swell. Increases in particulate nutrients such as nitrogen and phosphorus bound to fine sediments also decrease photic depth via chronic eutrophication and biomass in the marine water column after floods. Decreased photic depth has negative effects on coral fringing reefs and seagrass meadows in Keppel Bay and further afield during large flood events. It is the largest flood plumes that have the most widespread impact on reef and seagrass systems. From a reef health perspective, the priority should be targeted management to reduce sediment erosion from catchments that contribute the majority of large flood plumes.

Sediment tracing and load monitoring studies have found that basaltic lands used for cropping are a major source of fine sediment and nutrients from a concentration (and per hectare yield) perspective compared to lands used for grazing. Broad-scale cropping occurs on large areas in the Theresa Creek, Nogoa and Comet rivers sub-catchments and to a lesser degree (area-wise) in the Callide Creek and Dawson River sub-catchments. Cropping also occurs on the floodplains of most streams where black soil alluvium is found throughout the Fitzroy Basin. Continued and improved best management practice is considered a high priority for these intensively cropped basalt areas to reduce fine sediment and nutrient transport to the southern GBR lagoon.

It was found that the Connors River sub-catchment contributes a high number of large floods on a long-term annual average basis. This catchment also produces a reliable base flow of relatively high quality water for downstream water users such as the centres of Rockhampton and the Capricorn Coast. Maintaining or improving ground cover in the Connors sub-catchment is considered a priority management action in regards to future sediment and nutrient transport to Keppel Bay. Any changes in land use that involve intensive agriculture such as cropping could result in an increase in sediment and nutrient loads to the coast from this sub-catchment.

Improved management of grazing lands to reduce sediment supply from gully and scald erosion is considered a priority in the Fitzroy Basin. Sediment tracing studies in the Burdekin Basin have shown that subsoils appear to be the major component of fine sediment found in stream monitoring studies. Evidence of severe gullying and scalds can be found in the grazing lands of the Fitzroy Basin and preliminary data from a study underway suggests that cattle ramps cut into the banks of lower order streams may be contributing a larger volume of fine sediment to waterways than previously thought. There is an urgent need to quantify the contribution of fine sediment and particulate-

bound nutrients from cattle-induced riparian damage. There is also a need to conduct field research to monitor the sediment that reaches corals and seagrass and trace this sediment back to a specific source in the catchment.

1. Introduction

The Fitzroy River drains the single largest area (approximately 143,000 km^2) of the Great Barrier Reef (GBR) catchments and discharges into the largest estuary of GBR (~60 km in length) and then into Keppel Bay (Figure 1). The Keppel Islands within the bay host a series of inshore fringing coral reefs, which are periodically exposed to discharge from the Fitzroy River. Modification of the Fitzroy River catchment including the introduction of sheep and cattle from the 1840s (Seabrook et al. 2006; Lewis et al. 2007), extensive clearing of the Brigalow lands from the 1950s (Lloyd 1984; Wilson et al. 2002; Seabrook et al. 2006), mining (predominately coal and gold) and intensive agricultural development (mainly for broadacre cropping) has caused an increase in run-off as well as loads of suspended sediments and nutrients delivered to the GBR (Kroon et al. 2012; Dougall et al. 2014). However, the effects of these elevated constituent loads within Keppel Bay and beyond are less clear and considerable research on the sources, transport, fate and risk of suspended sediments has been undertaken over the past three decades. While Webster and Ford (2010) synthesised some of this work, their study particularly focussed on the Fitzroy River estuary and did not fully capture the sediment dynamics operating across the catchment to GBR lagoon. In turn, Brooke et al. (2006) produced a comprehensive sediment budget for the Fitzroy River estuary, floodplain and Keppel Bay, although the conclusion on the final sediment fate appears tarnished by an apparent over-estimation of the sediment load exported from the Fitzroy River. Furthermore, renewed interest in the study of the Fitzroy River has occurred since the extreme flooding of 2011 and new insights have been made on key catchment-to-reef processes and the potential effects of Fitzroy River discharge on the reefs of the Keppel Islands.

This review synthesises the research adapting a similar approach to the Bartley et al. (2014a; 2014b; see also Lewis et al. 2015) synopsis on the Burdekin River by formulating a series of specific questions from the marine environment back to the catchment area (and identifying specific catchment sources) and presenting the latest process understanding. The following questions are considered: (1) Do Fitzroy River discharge and particulate constituents reach vulnerable marine ecosystems, what are the effects (if any) and what parts of the GBR are influenced by both direct exposure and secondary effects? (2) How far are the particulate constituents transported in the GBR lagoon, what is their fate and when are they transported? (3) Where do the particulate constituents come from in the Fitzroy catchment, what are their sources and are there priority areas for management? (4) What are the key erosion processes that release the priority sediment to the rivers and have erosion rates in the Fitzroy catchment changed over time?

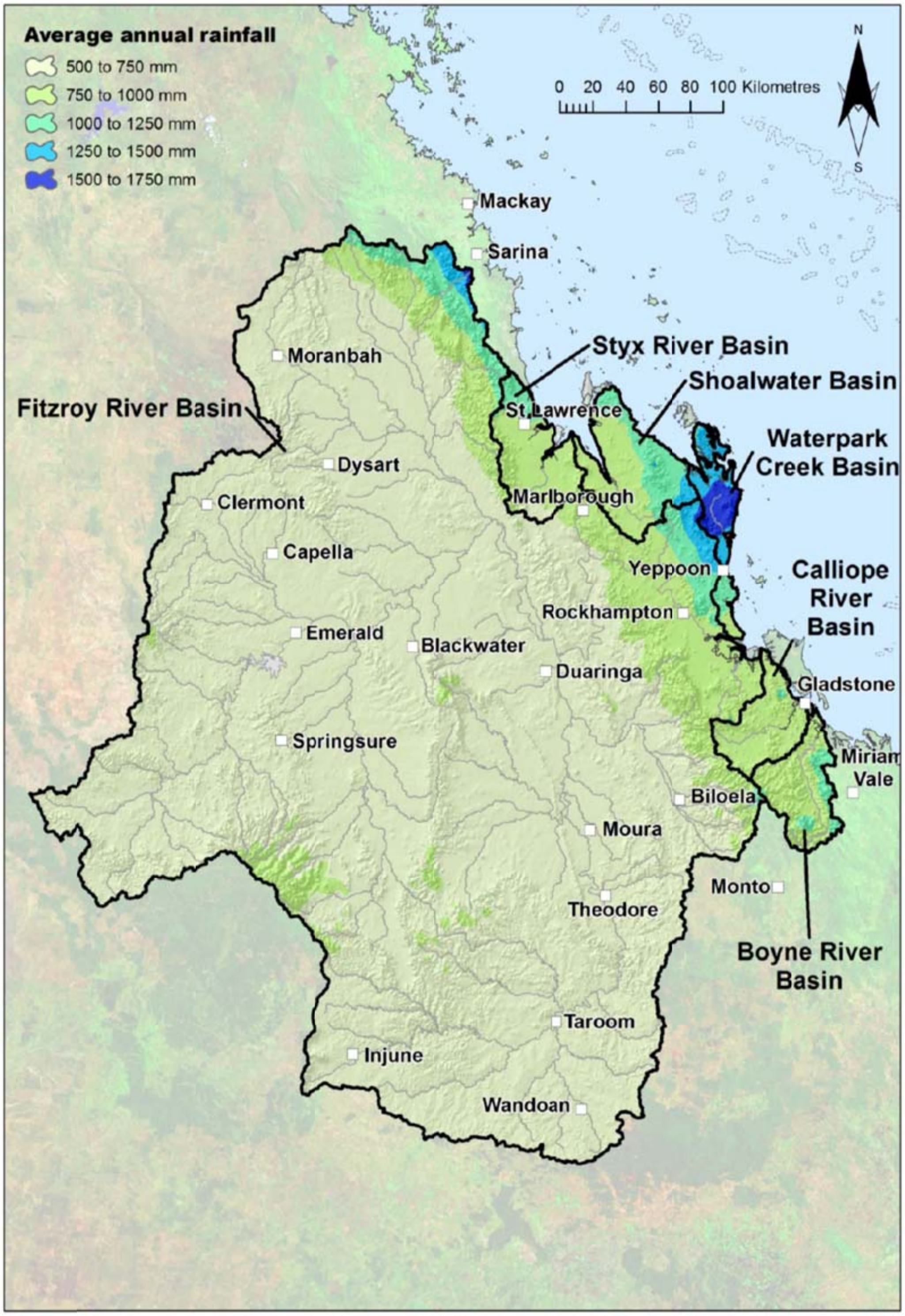

Figure 1. Average annual rainfall map for the Fitzroy River Basin (from Dougall et al. 2014).

2. Do Fitzroy River discharge and particulate constituents reach vulnerable marine ecosystems, what are the effects (if any) and what parts of the Great Barrier Reef are influenced by both direct exposure and secondary effects?

The extent of the freshwater plumes from large to extreme Fitzroy River events in 1991, 2008, 2011 and 2012 have been mapped and sampled (e.g. Devlin et al. 2001, 2011, 2012; Devlin & Brodie 2005). Indeed, the extreme 1991 flood event was the subject of a major research campaign with most of the results summarised in the 'Workshop on the impacts of flooding' GBR Marine Park Authority workshop series (No. 17) monograph (Byron 1992). In brief, the 1991 event coupled with low winds caused a large freshwater plume to extend eastwards out to the mid-outer GBR to Heron Island (Figure 2). Salinities as low as 7–8 were recorded near the Keppel Islands and major impacts associated with the freshwater plume included the widespread mortality of oyster and barnacle species in the Fitzroy River estuary and Keppel Bay (Coates 1992) and 'absolute mortality' of *Acroporid* and *Pocilloporid* corals to a depth of 1.3 m below low water datum in the reefs of the Keppel Islands (van Woesik et al. 1995). Recovery of the fringing reefs from the 1991 flooding was estimated at 10–15 years (Jones & Berkelmans 2014).

The 2011 extreme flooding from the Fitzroy River also triggered a considerable monitoring and research effort and in this case the plume moved northwards and was traced as far north as Mackay (Figure 3). Similarly to the 1991 event, the major impacts were recorded in Keppel Bay with Jones and Berkelmans (2014) documenting 40–100% mortality of corals down to 8 m depth for many of the fringing reefs of the Keppel Islands (see also Tan et al. 2012). The coral mortality in the Keppel Islands also resulted in associated declines in coral reef fish abundance, diversity and fish assemblage structure (Williamson et al. 2014). While Jones and Berkelmans (2014) showed that the impact of freshwater in Keppel Bay far outweighed the 'pollutants' delivered from the Fitzroy River (specifically photosynthesis II inhibiting herbicides, known as PSII herbicides), continued monitoring in the region has shown the coral fringing reefs of the Keppels have continued to decline following subsequent exposures to low salinity and turbid waters in 2012 and 2013 (Wenger et al., in press).This finding, coupled with the knowledge that the reefs showed little decline prior to 2011 despite moderate events in 2008 and 2010, suggest that chronic exposure of turbidity (i.e. lowered photic depth) and hence the delivery of suspended sediment from the Fitzroy River during this period has contributed to this decline.

Furthermore, Wenger et al. (in press) postulated that the fringing reefs of the Keppel Islands have reduced resistance to withstand repeated exposures of river flood plumes and associated constituents from the Fitzroy River. From a longer-term perspective, Rodriguez-Ramirez (2013) showed there was little variation in the living and dead coral assemblages of the Keppel Island fringing reefs. In fact, the coral death assemblages (aged using U-series dating) were all linked to disturbance events over the past three decades, suggesting that these reefs are well-adapted and resilient to periodic discharge from the Fitzroy River (Rodriguez-Ramirez 2013).

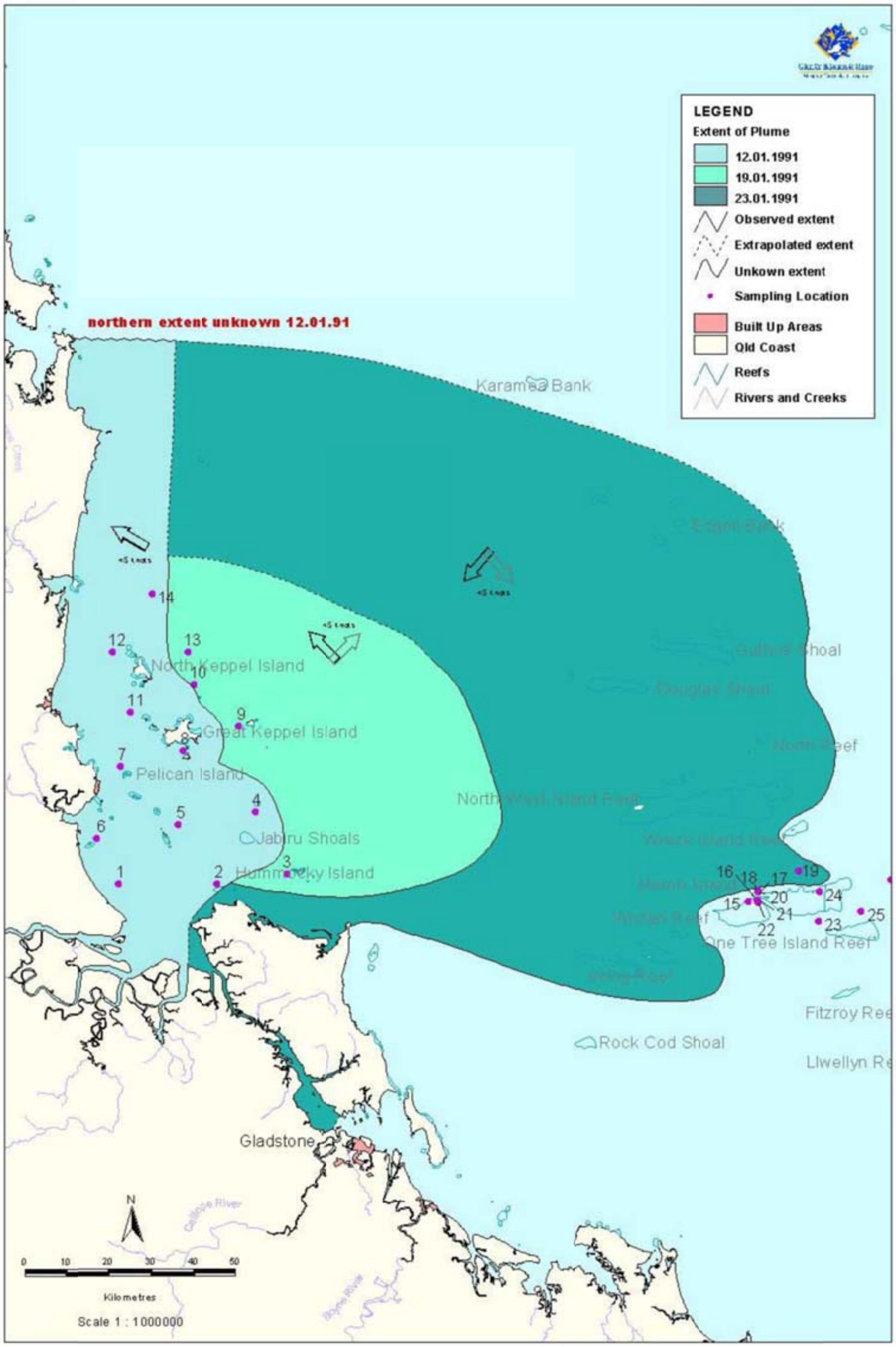

Figure 2. Aerial extent of the 1991 freshwater plume from the Fitzroy River (from Devlin et al. 2001).

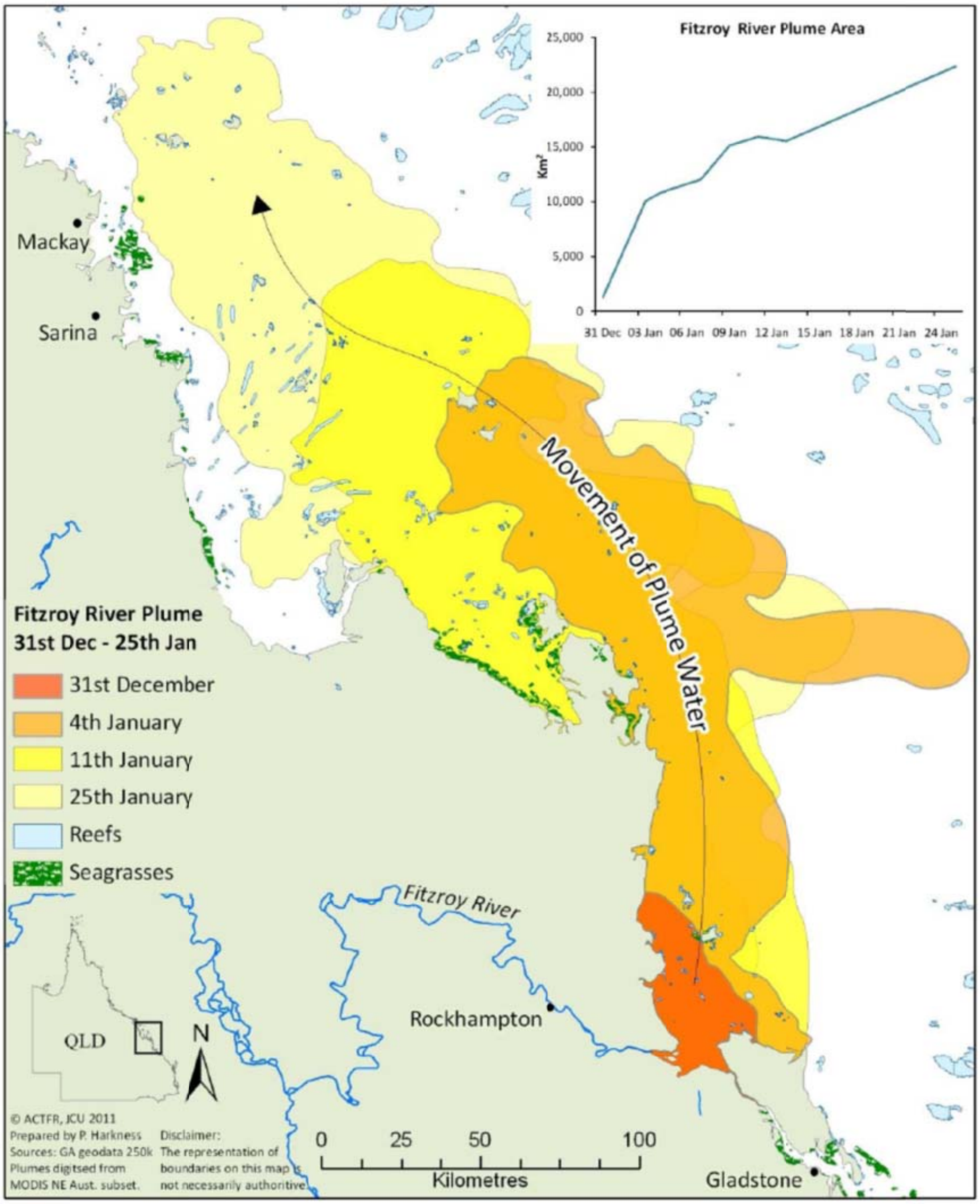

Figure 3. Extent of the freshwater plume from the Fitzroy River in 2011 (from Devlin et al. 2011).

Prominent luminescent lines in massive *Porites* corals from the southern GBR highlight the area of influence of the Fitzroy River in the marine environment and also provide a valuable record of historical annual discharge and Queensland rainfall variability (Lough 2007; Rodriguez-Ramirez et al. 2014). In that regard, Lough (2007) reconstructed historical Fitzroy River discharge back to 1678 using coral luminescence from coral cores collected from Humpy Island (Figure 4). The data are correlated with Fitzroy River discharge (the instrumental record starts from 1916) and suggest the variability of wetter and drier years has increased during the 20th Century. Rodriguez-Ramirez et al. (2014) produced a coral luminescence record between 1921 and 2011 using six *Porites* coral colonies from the Keppel Islands and showed that the variability in the record was significantly correlated with both the El Niño Southern Oscillation and the Pacific Decadal Oscillation. Importantly, these climate drivers considerably influence Fitzroy River discharge and hence any changes in their variability will have implications for the health of the inshore reefs in Keppel Bay. Annual luminescent lines correlated with Fitzroy River discharge were observed in a coral from Middle Percy Island, about 220 km from the Fitzroy River mouth and about 80 km off the shore, which highlights the area of influence from this river basin. There is little variability in water depth (<20 m depth) across the inner shelf out to Middle Percy Island, which likely explains the presence of annual lines (Lough et al. 2002).

The latest reconstruction of annual Burdekin discharge using coral luminescence (1648 to 2011) clearly shows that more frequent large and extreme discharge events have occurred since the latter half of the 19th Century and hence the ability to carry more constituents to the GBR (Lough et al. 2015); presumably this regional trend would also be evident in the Fitzroy River. Indeed, given the increase in more frequent large to extreme rainfall-river flow events coupled with the increased run-off due to land clearing (i.e. studies have shown up to double the run-off occurs from cleared Brigalow lands compared to natural: e.g. Thornton et al. 2007; Siriwardena et al. 2006), the additional fresh water discharged from the Fitzroy River could now be considered a pollutant in its own right (see Lough et al. 2015). If the frequency of larger events increase to below a 1-in-10 year reoccurrence interval, then the recovery times for the fringing reefs of the Keppel Islands would be compromised. Over a longer term perspective (past 1500 years), Brooke et al. (2008) suggested that there was a decline in major rainfall events in the Fitzroy catchment as the frequency of accumulation of relict beach ridges within Keppel Bay had lowered over this time. Over an even longer geological timeframe of glacial and interglacial periods, Croke et al. (2011) showed that fluvial activity in the Fitzroy River was much higher between 10 and 30 ka.

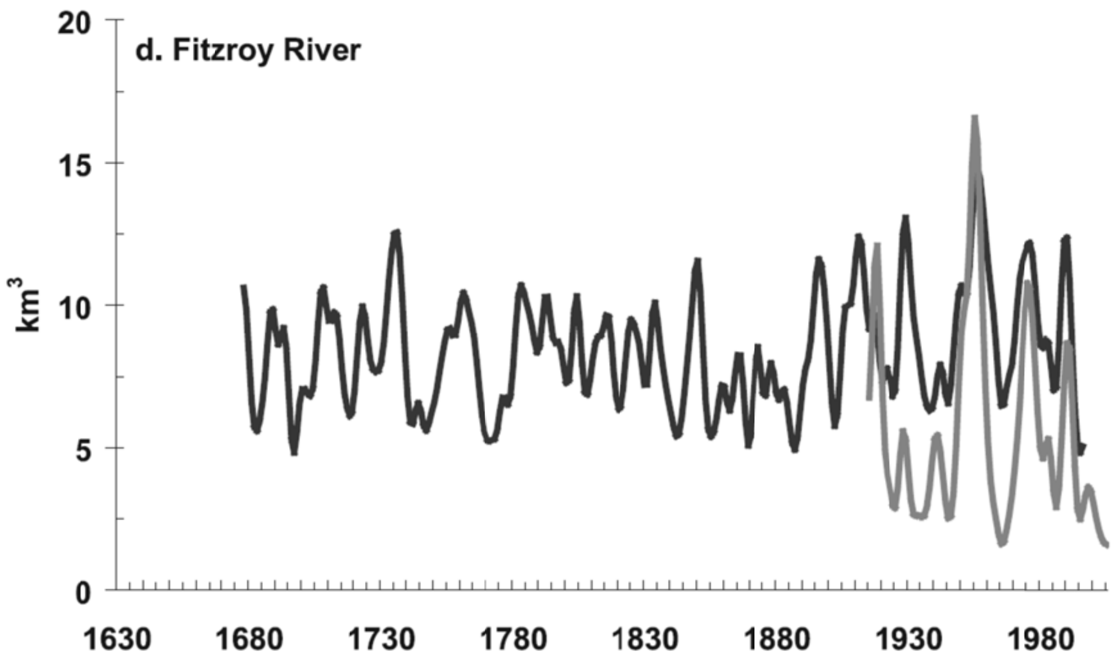

Figure 4. Coral luminescence reconstruction for the Fitzroy River. The Y-axis represents annual water volume in km^3, the black line represents the coral luminescence reconstruction and the grey line represents the gauged flow volume record (from Lough 2007).

Coral geochemical records (Ba/Ca and Y/Ca ratios: proxies of sediment loads) from the Keppel Islands also reveal the influence of the Fitzroy River on the Keppel Island fringing reefs. In particular, coral Ba/Ca ratios displayed very high spikes that were 2–14-fold higher than baseline levels after 1950, which coincides with the clearing of the Brigalow country (Rodriguez-Ramirez 2013). Indeed, sediment tracing work in the catchment also suggests increases in sediment erosion coinciding with this large-scale land clearing (see later sections of this report).

The latest estimates of pre-European sediment loads are quite variable with the Source Catchments modelling suggesting an annual load of 0.44 Mt.y^{-1} (Dougall et al. 2014) and Kroon et al. (2012) suggesting 1.1 Mt.y^{-1}. In fact, the latest published estimates of the 'current' Fitzroy River load are also quite variable with Source Catchments predicting a 'baseline' load of 1.74 Mt.y^{-1} (i.e. increase of ~4-fold: Dougall et al. 2014) while Kroon et al. (2012) suggest the average annual load is 3.40 Mt.y^{-1} (i.e. increase of ~3-fold). Using a flow-weighted approach from 15 years of monitored load data from the Fitzroy River provides an estimate of the current annual load of 1.52 Mt.y^{-1} (S. Lewis, unpublished data: using monitoring data from AIMS (unpublished), Packett et al. (2009), Joo et al. (2012), Turner et al. (2012, 2013) and Wallace et al. (2014)). Based on the sediment volumes calculated for the Fitzroy estuary, floodplain and Keppel Bay over the past 100 and 8000 years from Brooke et al. (2006), sediment export from the Fitzroy River has increased by 1.3-fold over the past 100 years, although Bostock et al. (2006a) found sediment accumulation rates in one sediment core from Keppel Bay increased 4-fold over the past 200 years. Increases in sediment accumulation rates (~1.5-fold) in sediment cores from the lagoons near Rockhampton also provide evidence for increased sediment loads from the Fitzroy River since European settlement, particularly in the past 90 years (Bostock et al. 2006b).

Earlier load estimate studies on the Fitzroy River have generally been on the higher end (e.g. > 2.0 $Mt.y^{-1}$) and have varied from 1.7 to 15.0 $Mt.y^{-1}$, although the estimates that have been constrained by monitoring data mostly place the load between 1.5 and 2.5 $Mt.y^{-1}$ (see Bostock et al. 2007; Brodie et al. 2009). Indeed some of the earlier load estimates used monitoring data from drier years to develop a sediment rating curve and hence did not take into account the 'supply-limited' nature of these dry tropical rivers (e.g. Amos et al. 2004). The earlier model estimates unlikely took into account the deposition of sediments on floodplains and within the channel and channel/gully geometry (see Hughes et al. 2010; Hughes & Croke 2011; Thompson et al. 2011). For example, an early estimate of the 1991 Fitzroy suspended sediment load using a rating curve (26 Mt: Kelly & Wong 1996) is clearly over-estimated given the load calculated for the 2011 major event based on intensive monitoring was ~3-fold lower (7.0 Mt: Turner et al. 2013).I In fact, the 2011 flow volume (37.94 GL) was near double that of the 1991 discharge (22.92 GL). The latest available data suggest the average 'current' suspended sediment load exported from the Fitzroy River is between 1.5 and 2.0 $Mt.y^{-1}$. Current research activities are examining new ways to model suspended sediment and particulate nutrient loads from the Fitzroy River using a Generalised Additive Modelling approach, which relies on the construction of sediment rating curves for specific periods of flow and takes into account the antecedent flow conditions (Robson & Dourdet 2015).

The influence of the Fitzroy River on the southern GBR has been highlighted by a significant correlation between discharge and satellite photic depth data (Logan et al. 2014, in review). Specifically, photic depth was reduced by 1–2 m across the inshore (Fitzroy inshore/Fitzroy coastal/Broad Sound) and mid-outer shelfs (Capricorn-Bunker Group) several months following the 2011 extreme discharge event (Figures 5 and 6). Indeed the correlations between Fitzroy discharge and photic depth in these areas were strong with r values between 0.61 to 0.74 (Figure 5) while the correlations for the outer shelf reefs (Swains Reefs) were weak (Logan et al. 2014). In fact, photic depth in the Fitzroy inshore, coastal and Keppel Bay has gradually declined since the moderate discharge event from the Fitzroy River in 2008 (the first moderate-major event since 1991) and has been at least 1–2 m lower than pre-2008 conditions (Figure 5). Photic depths in the wetter discharge years are generally about 2 m lower than photic depths during drier years in the Fitzroy region (Figure 6). Reduced photic depth was implicated in the alarming decline of seagrass meadow area (84% loss) in Cleveland Bay following a series of large Burdekin flow events from 2007–08 to 2010–11 (Petus et al. 2014). Furthermore, Fabricius et al. (2013) have shown that turbidity levels were considerably higher in months following large river inputs than levels observed at the end of the dry season. This finding suggests that the inputs of new terrestrial materials are important on turbidity levels, which contrasts previous assertions (e.g. Orpin & Ridd 2012), although newly delivered sediments can be 'flushed out' of embayments during the dry season and in cyclonic conditions (Lambrechts et al. 2010).

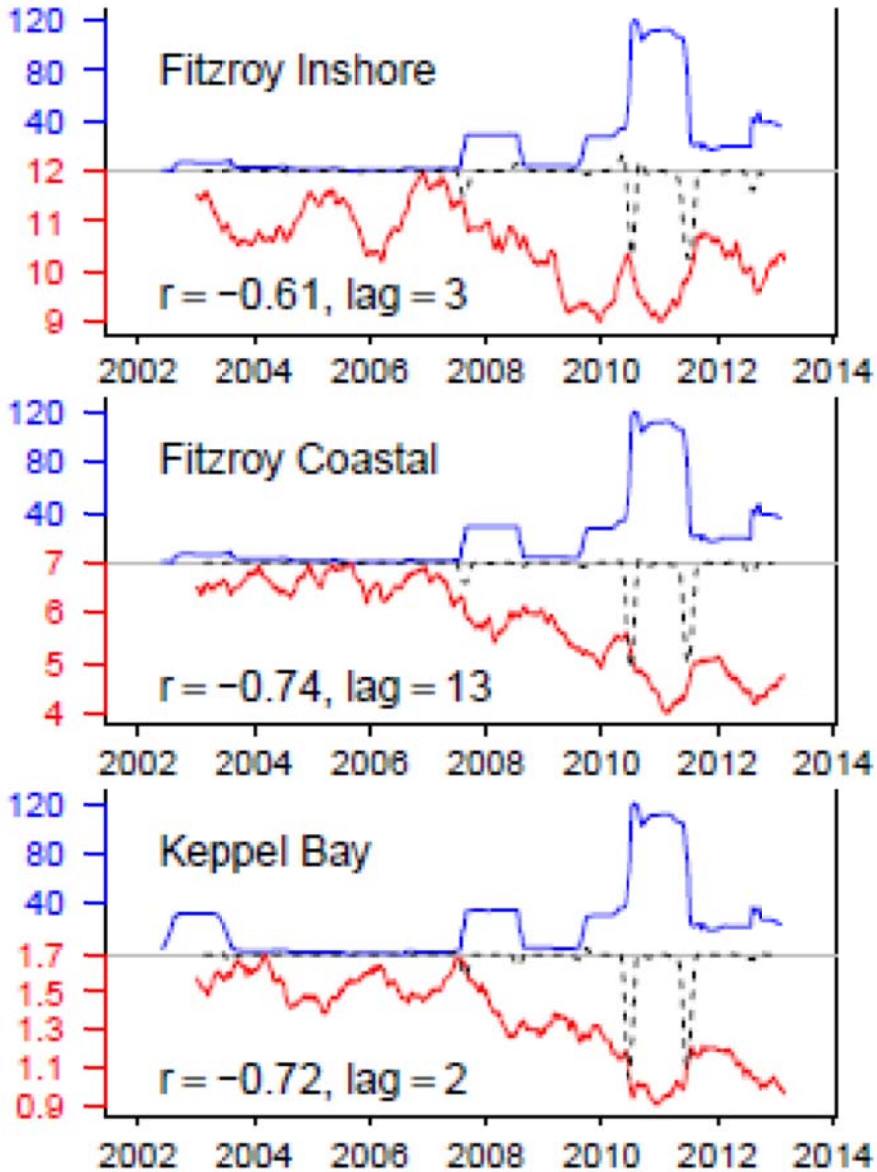

Figure 5. The response of photic depth and Fitzroy River discharge in Fitzroy inshore, Fitzroy coastal and Keppel Bay are strongly correlated (Logan et al. 2014). The y-axis (blue) on the right of the figure represent the daily discharge (in ML × 1000) while the y-axis on the left (red) represent the change in standardised photic depth (in metres).

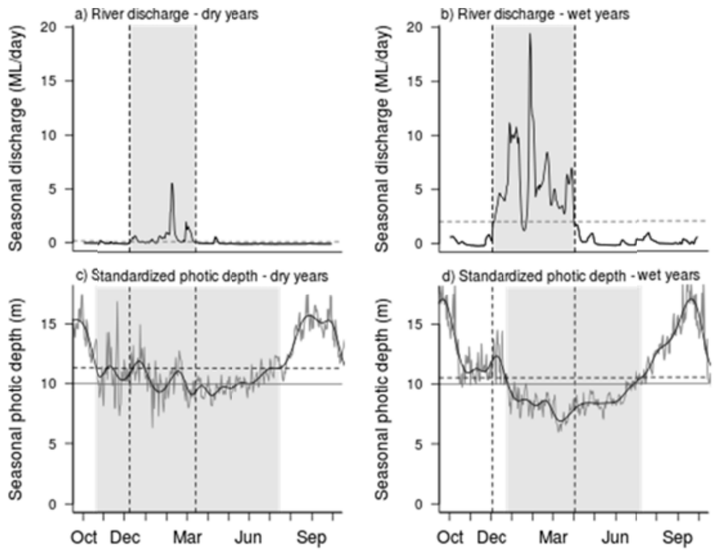

Figure 6. The response of photic depth to low flow and high Fitzroy River discharge events (Logan et al. 2014).

In conclusion, there is now a wealth of evidence that Fitzroy River discharge and associated particulate constituents influences photic depth and turbidity on the southern GBR and has the potential to induce negative effects on coral reefs and seagrass meadows in the region.

3. How far are the particulate constituents transported in the Great Barrier Reef lagoon, what is their fate and when are they transported?

Monitoring of the freshwater plume produced from the Fitzroy River has been carried out in 1991 (Brodie & Mitchell 1992; Devlin et al. 2001; Devlin & Brodie 2005), 2003 (Packett 2007), 2008 (Devlin et al. 2009), 2011 (Devlin et al. 2011) and 2012 (Devlin et al. 2012). In an average-sized event in 2003, Packett (2007) showed that about 90% of the suspended sediment was deposited within 5 km of the river mouth with concentrations falling below 30 $mg.L^{-1}$ by 10 km off the river mouth in Keppel Bay (Figure 7). The extent of this plume was traced to 15–20 km off the river mouth (Packett 2007) and it did not reach the Keppel Islands. The freshwater plumes from the much larger events in 1991, 2011 and 2012 extended much larger distances (Figures 2 and 3) and surface suspended sediment concentrations around the Keppel Islands ranged from 7 to 32 $mg.L^{-1}$ (1991: Brodie & Mitchell 1992) and ~20-30 $mg.L^{-1}$ (Devlin et al. 2011, 2012). Hence the data show that during moderate to large flood events from the Fitzroy River, freshwater plumes with suspended sediment concentrations in the order of 20-30 $mg.L^{-1}$ reach the Keppel Island Group and directly contribute to lower photic depth during this period. Presumably a fraction of this sediment is also deposited in this area and becomes available for resuspension in the months following the discharge event. While we are unaware of any particle size data being taken in the freshwater plume from the Fitzroy River, data from the State Loads Water Monitoring Program show that 60% of the suspended sediment delivered to the estuary is clay (<4 µm) and ~98.5% is clay and silt (<63 µm) (Turner et al. 2013; data from the Fitzroy River at Rockhampton from 2007–08 to 2010–11 seasons). Studies from the Burdekin River show that as the freshwater plume disperses away from the river mouth, the suspended sediments form organic-rich floc aggregates around fine-grained (<16 µm) 'mineral' sediment, which moves longer distances in the plume (Bainbridge et al. 2012). This organic-rich material has been shown to be particularly detrimental to corals under laboratory conditions (Weber et al. 2006, 2012). Hence, in the absence of new data, we consider it is the fine-grained mineral sediment (<16 µm) that is discharged from the Fitzroy River that should be targeted for management.

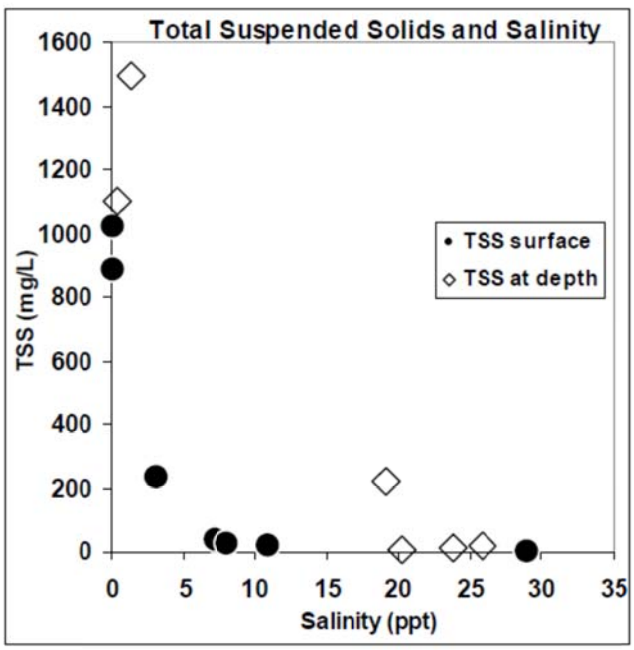

Figure 7. Total suspended solids (TSS) concentrations measured along the salinity gradient in the 2003 flood plume. The majority of the suspended sediment in the Fitzroy River was deposited in the estuary and river mouth (from Packett 2007).

A series of comprehensive studies were carried out to determine sediment budgets and fate of the Fitzroy River suspended sediment through the Cooperative Research Centre for Coastal Zone Estuary and Waterway Management in the early to mid-2000s. Under this research program, surface sediment distribution within Keppel Bay was mapped to reveal the main depositional area of the <63 µm sediment fraction delivered by the Fitzroy River (Figure 8). The results show that this fraction is largely confined to just off the mouth of the Fitzroy River between the mainland and Curtis Island

and to the north of the river mouth near the coast (Figure 8: Ryan et al. 2007). In fact, the sand size fraction (>63 µm) dominates around the Keppel Island Group and shows that this area is 'sediment starved' (Bostock et al. 2006a; Ryan et al. 2007). This finding suggests that newly delivered fine (<16 µm) sediment from the Fitzroy River, which is deposited in outer Keppel Bay during large flow events would considerably influence photic depth around the Keppel Islands when resuspended as there is little 'antecedent' fine sediment in this region to be resuspended. Hence, this explains why photic depth offshore from the Fitzroy River is greatly reduced in the months following moderate to large flow events (Logan et al. 2014, in review).

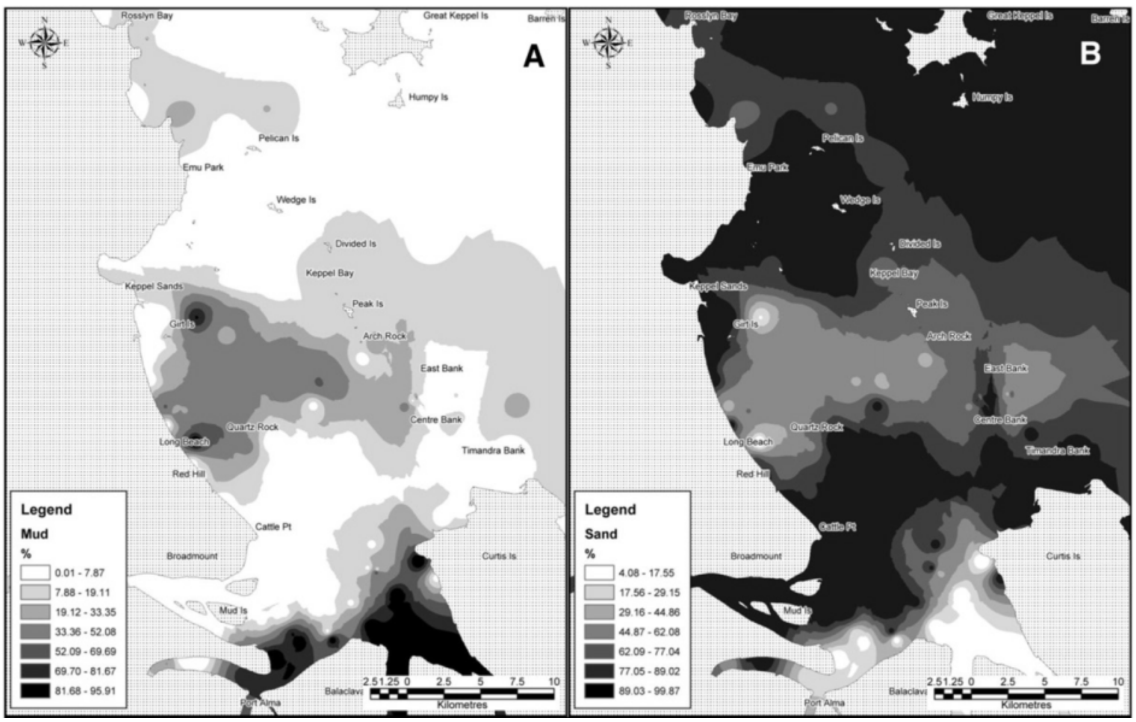

Figure 8. The distribution of the mud (<63 µm) and sand (>63 µm) fractions in Keppel Bay (from Ryan et al. 2007).

A large collection of sediment cores from the Fitzroy River estuary, floodplain, Keppel Bay and coastal dune deposits coupled with age control using Optically Stimulated Luminescence (OSL), radiocarbon, ^{210}Pb and ^{137}Cs techniques and swath mapping (seismic) profiles of the sediment bed allowed insights into sediment accumulation over the past 8000 (and 100) years and the calculation of sediment volumes within these areas. The results are presented in Bostock et al. (2006a, 2006b, 2007) and Brooke et al. (2008) and summarised as a complete sediment budget in Brooke et al. (2006). The sediment cores from Keppel Bay display periods of rapid accumulation over different periods of the Holocene (Bostock et al. 2006a); similar trends were also observed in sediment cores taken off the Burdekin River, which was related to its avulsion history (Lewis et al. 2014). A 10 m thick sediment wedge was observed near the mouth of the Fitzroy River, which quickly thinned out into Keppel Bay (Bostock et al. 2006a). Indeed 'most' of the sediment delivered from the Fitzroy

River was captured in the estuary near the river mouth and within tidal creeks and mangroves (Bostock et al. 2006b, 2007). A sizable proportion (in the order of 20–50%) of the sediment within the cores was <4 µm (Bostock et al. 2007).

The complete sediment budget produced by Brooke et al. (2006) calculated the total sediment volumes of the <63 µm fraction deposited over the past 100 years (expressed as rates deposited in $kt.y^{-1}$) in the northern and southern estuary and floodplain, the beaches and sand bars, mangroves and different parts of inner and outer Keppel Bay (Figure 9 and Table 1). By applying what was considered at the time the 'best estimate' of annual sediment load (4.575 $Mt.y^{-1}$) from the Short Term Modelling exercise (Dougall et al. 2005), Brooke et al. (2006) calculated that 55% (2.54 $Mt.y^{-1}$) of the <63 µm fraction average load exported from the Fitzroy River was deposited in the estuary, floodplain, mangroves and inner Keppel Bay, which left by difference, 45% of the load exiting Keppel Bay. However, the current 'best estimate' of sediment load for the Fitzroy River is in the order of 1.5 to 2.0 $Mt.y^{-1}$ and hence applying this revised estimate virtually all of the sediment delivered from the Fitzroy River is captured within the estuary, floodplain and inner Keppel Bay. Hence the sediment delivered to outer Keppel Bay and beyond (i.e. the sediment that would have the most impact in the marine environment) would only occur during moderate to major flood events and the source of this sediment is the most important to identify for catchment management. In fact, this finding shows that the management of the small fraction of the sediment load (<1%) that moves into outer Keppel Bay and beyond would produce the greatest benefits to photic depth to the reefs of the Keppel Islands and the Capricorn-Bunker Group. Similar findings have been made for the Burdekin River (Lewis et al. 2014, 2015).

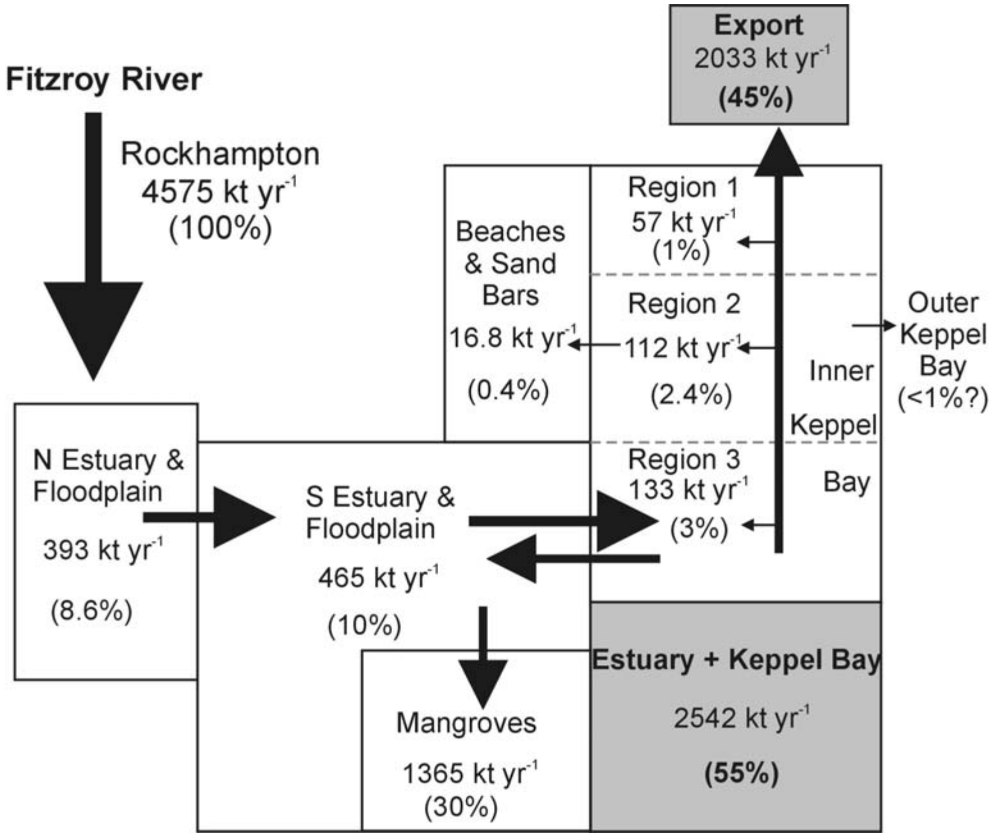

Figure 9. The sediment budget for the Fitzroy River <63 µm fraction sediment over the past 100 years (from Brooke et al. 2006).

Table 1. Sediment volumes deposited in the floodplain, estuary, beach ridges, sand bars and Keppel Bay for bulk and <63 µm particle size fractions over the past 8000 and 100 years (from Brooke et al. 2006).

Region	Surface Area (km^2)	Thickness (m)	Volume (m^3)	Total Mass (kg)	Mass Accum. (kt yr^{-1})	Mass of fines (%<63 µm) (kt yr^{-1})
Holocene average annual rates based accumulation over the last 8000 yrs						
Northern Floodplain	325	5	1.62×10^9	2.03×10^{12} (50% porosity)	254*	(97%) 246
Southern Floodplain and Estuary	820	15	1.23×10^{10}	1.54×10^{13} (50% porosity)	1922*	(80%) 1538
Beach Ridges and Sand Bars	225	9.5	2.14×10^9	2.14×10^{12} (60% porosity)	266	(5%) 13.3
Inner Keppel Bay Region 1	67	1	6.73×10^7	6.73×10^{10} (60% porosity)	9.6	(65%) 6.24
Inner Keppel Bay Region 2	133	2	2.66×10^8	2.66×10^{11} (60% porosity)	38	(65%) 25
Inner Keppel Bay Region 3	68	10	6.82×10^8	6.82×10^{11} (60% porosity)	97	(65%) 63
Holocene Total					**2586.6**	**1891.54**
Modern average annual rates based on accumulation rates from dated cores						
Tidal Creeks/ Mangroves	130	1.5 cm yr^{-1}	1.95×10^6	1.71×10^9 (65% porosity)	1706	(80%) 1365
Beach Ridges	4.342		5.57×10^7	6.69×10^{10} (60% porosity)	336	(5%) 16.8
Inner Keppel Bay Region 1 (VC05)	67	0.13 cm yr^{-1}	8.7×10^4	8.7×10^7 (60% porosity)	87	(65%) 57
Inner Keppel Bay Region 2	133	0.13 cm yr^{-1}	1.7×10^5	1.7×10^8 (60% porosity)	173	(65%) 112
Inner Keppel Bay Region 3	68	0.3 cm yr^{-1}?	2.04×10^5	2.04×10^8 (60% porosity)	204	(65%) 133
Modelled modern average annual rates (SedNet)						
Southern Floodplain	465	0.1 cm yr^{-1}	4.65×10^5	5.8×10^8 (50% porosity)	581	(80%) 465
Northern Floodplain	324	0.1 cm yr^{-1}	3.24×10^5	4.05×10^8 (50% porosity)	405	(97%) 393
Modern Total					**3492**	**2542**

* Includes data from core logs provided by past studies.

In conclusion, fine-grained (<16 µm) suspended sediment delivered from the Fitzroy River during moderate to large events likely travels the longest distance in the marine environment and impinges on coral reefs and seagrass meadows in the southern GBR. We have moderate confidence that this material in the flood plumes likely influences photic depth and turbidity along the southern GBR in both the short- (i.e. during the flood plume) and long-term (i.e. months following the discharge event) and should be the target for management efforts in the catchment.

4. Where do the particulate constituents come from in the Fitzroy catchment, what are their sources and are there priority areas for management?

Unfortunately no direct tracing has been performed on the suspended sediments transported in flood plumes in the vicinity of the Keppel Islands, although, tracing of sediments in: 1) flood events (Douglas et al. 2006a, 2008) 2) trapped in impoundments (Douglas et al. 2006a) 3) deposited within wetlands (Douglas et al. 2010) 4) within the Fitzroy River estuary (Douglas et al. 2006b) 5) Keppel Bay (Smith et al. 2008) and 6) within beach ridge deposits (Brooke et al. 2008) have been carried out under the Cooperative Research Centre for Coastal Zone Estuary and Waterway Management program. Additional studies have been carried out examining changing sediment sources in floodplain and channel deposits within the Theresa Creek catchment area (Hughes et al. 2009, 2010; Thompson et al. 2011). Virtually all of these studies point to the preferential erosion and transport of basaltic soils in the catchment and highlight the increased erosion, which has occurred since the clearing of large tracts of the Brigalow country from the 1950s (largely on grazing lands of mixed geologies) and development of cropping lands (primarily on basaltic soils).

Brooke et al. (2008) showed that the contribution of volcanic (i.e. basaltic) soils to beach ridge deposits increased considerably over the past 100 years using trace element tracing techniques on the <10 µm fraction. In addition, Smith et al. (2008) was able to distinguish the contributions of the major geological sources in the Fitzroy catchment using tracing techniques on the <10 µm sediment fraction deposited in Keppel Bay. This study indicated that relatively equal proportions were derived from the Bowen Basin, Surat Basin, Tertiary basalt and Thompson Fold Belt sources. However, when the abundance of these sources in the catchment was considered, it was evident that the Tertiary basalt (enrichment factor (EF)=3.1: the proportion of the geology source in the sediment to the proportion of geology area in the catchment) and Thompson Fold Belt (EF=2.6) sources were 'punching above their weight' (Table 2) (Smith et al. 2008).

Table 2. Proportion of the major geological sources in the Fitzroy River estuary, coastal zone and catchment (BB = Bowen Basin; NEFB = New England Fold Belt; SB = Surat Basin; TB = Tertiary basalts; TFB = Thompson Fold Belt) and their enrichment factors relative to the catchment abundance (from Smith et al. 2008).

	BB	NEFB	SB	TB	TFB
Coastal zone (%)[A]	20 ± 5	8 ± 3	24 ± 10	29 ± 7	18 ± 6
Estuary abundance (%)[B]	22 ± 13	23 ± 14	15 ± 10	10 ± 5	30 ± 7
Catchment abundance (%)[B]	46.0	19.0	18.6	9.5	6.9
Enrichment relative to catchment	0.4	0.4	1.3	3.1	2.6

[A] Estimated mean ± s.d. calculated using the Bayesian mixing model.

The geological map of the Fitzroy Basin shows that both the Tertiary basalts and the Thompson Fold Belt rocks are largely concentrated in the Theresa Creek, Nogoa River and Comet River catchments (Figure 10). In contrast to the tracing studies from Keppel Bay (i.e. Brooke et al. 2008; Smith et al. 2008), the tracing data from the sediment trapped in the impoundments within the catchment, the estuary and on the floodplain showed that the Tertiary basalt sources were under-represented in these areas compared to what was transported during flow events (Douglas et al. 2006a, 2006b, 2008, 2010). While the sediment tracing in the flow events were from relatively low flow years (2003 and 2004), the available data suggest the preferential transport of the basalt soils through the catchment and into the GBR (Douglas et al. 2006a, 2006b, 2008, 2010). Basalt soils tend to be dominated by smectite clays, which tend to be much finer in particle size, have much lower settling rates and hence are able to be transported further than other clay minerals. Similar findings (i.e. expandable, smectite-type clays are transported further) have been made in the neighbouring Burdekin River catchment (Bainbridge et al., in press) and around the world (e.g. Storlazzi et al. 2015).

Sub-catchment water quality monitoring programs within the Fitzroy Basin show the highest suspended sediment concentrations are derived from the intensive cropping lands, although as grazing makes up the largest area within the basin this land use contributes the highest overall load (Packett et al. 2009). However, the intensive cropping lands in the Fitzroy Basin are located in the Theresa Creek, Nogoa River and Comet River sub-catchments and largely coincide with the areas of basalt soils (Figure 11). Indeed the Nogoa River had the highest total suspended solids (TSS) event mean concentrations (EMC >2500 mg.L^{-1}) measured across the sub-catchments of the Fitzroy River (Packett et al. 2009). The Comet River sub-catchment, which also contains large areas of Tertiary basalt, yielded elevated suspended sediment EMC (>2000 mg.L^{-1}: Packett et al. 2009). Theresa Creek has been monitored as part of the Great Barrier Reef Catchment Loads Monitoring Program in 2010–11 (330,000 t; indicative load only ~5% of end-of-river load: Turner et al. 2013) and 2011–12 (89,000 t; only 7% of end-of-river load: Wallace et al. 2014). The annual mean concentrations during these events (260 and 180 $mg.L^{-1}$, respectively) are much lower than the Event Mean Concentration (EMC) reported for the neighbouring Nogoa River catchment (and also much lower than the Comet River sub-catchment) reported by Packett et al. (2009) (6489 and 2861 $mg.L^{-1}$ in 2003 and 2004, respectively). Joo et al. (2005) also showed that the Nogoa and Comet sub-catchments produced the highest sediment loads of the Fitzroy Basin sub-catchments from the development of sediment rating curves and estimated that these catchments contributed about 60% of the Fitzroy Basin sediment load. However, Packett et al. (2009) showed that the Connors sub-catchment contributes about 50% of the long-term average total flow from the Fitzroy River as it lies in the wetter area of the basin (Figure 1). Importantly, this catchment also drives the hydrology of the Fitzroy River during very large to extreme events, which in turn dominates the freshwater volumes that reach the Keppel Islands and about 90% of the suspended sediment particle size is < 10 µm (Packett et al. 2009). In fact, the latest Source Catchments modelling suggest that the Connors (Isaacs sub-catchment) and Dawson catchments are the highest contributors of the annual average export of 'fine' sediment (i.e. <63 µm) and particulate nutrients from the Fitzroy Basin due to the higher rainfall and run-off in these areas (Dougall et al. 2014).

The Fairbairn Dam would capture most of the Nogoa River discharge and would trap virtually all the sediment delivered above its catchment area in most years (i.e. when the dam does not overflow); interestingly the dam did not overflow in 2003 and 2004 when the tracing in the Fitzroy flood events was conducted (C. Dougall pers comm., 13/7/2015). In moderate to large flow events where the dam overflows, large amounts of very fine sediment (< 16 µm) could be transported past the dam. Importantly, it is these moderate to large events that also deliver the suspended sediment to the outer Keppel Islands and beyond where it has the capacity to reduce photic depth and so this area may still provide an important source. Overall there is an apparent discrepancy in the potential sources of the suspended sediment that reaches the Keppel Islands and influence photic depth with the geochemical tracing data indicating a basaltic soil source (likely from the Nogoa/Comet) while other monitoring (suspended sediment and flow volume) data and modelling outputs suggest a greater influence from the Connors sub-catchment. In fact, the Isaac sub-catchment also contains basaltic soils as well as highly erodible sedimentary soils (in Bee Creek) (C. Dougall pers comm. 13/7/2015). Black soils are also used for intensive cropping on the floodplains of the Dawson River and Callide Creek, the Mackenzie, Isaacs, Connors and Fitzroy rivers. The area cropped on floodplains is less extensive than the broadacre dryland regions of the Nogoa and Comet sub-catchments. However, lands used for cropping on floodplains are often well connected hydrologically to the major streams and the delivery ratio of sediments in run-off can be high compared to broadacre cropping.

In conclusion, tracing data suggest that the very fine (<20 µm) sediment derived from basalt sources from lands used for intensive cropping are preferentially transported through the Fitzroy Basin and into the GBR lagoon. Substantial areas of the Nogoa and Comet sub-catchments are used for irrigated and dryland cropping. In addition, there are less extensive areas of black soils on the floodplains of most rivers and major creeks in the Fitzroy Basin. However, other monitoring and modelling data suggest that the majority of the long-term annual fine sediment load from the Fitzroy Basin to the GBR originates from high volume events from the Connors and Dawson sub-catchments. These larger volumes allow the freshwater plume to travel greater distances in the marine environment and reach the fringing reefs of the Keppels and further offshore. It would appear from current knowledge that depending on the location and type of rain event both cropping and grazing lands can supply fine sediments to plumes that reach corals in the GBR lagoon. There is a need to conduct field monitoring and tracing research on the sediments that reach the reefs in the Keppel Bay in order to fill current knowledge gaps regarding Fitzroy Basin sediment sources.

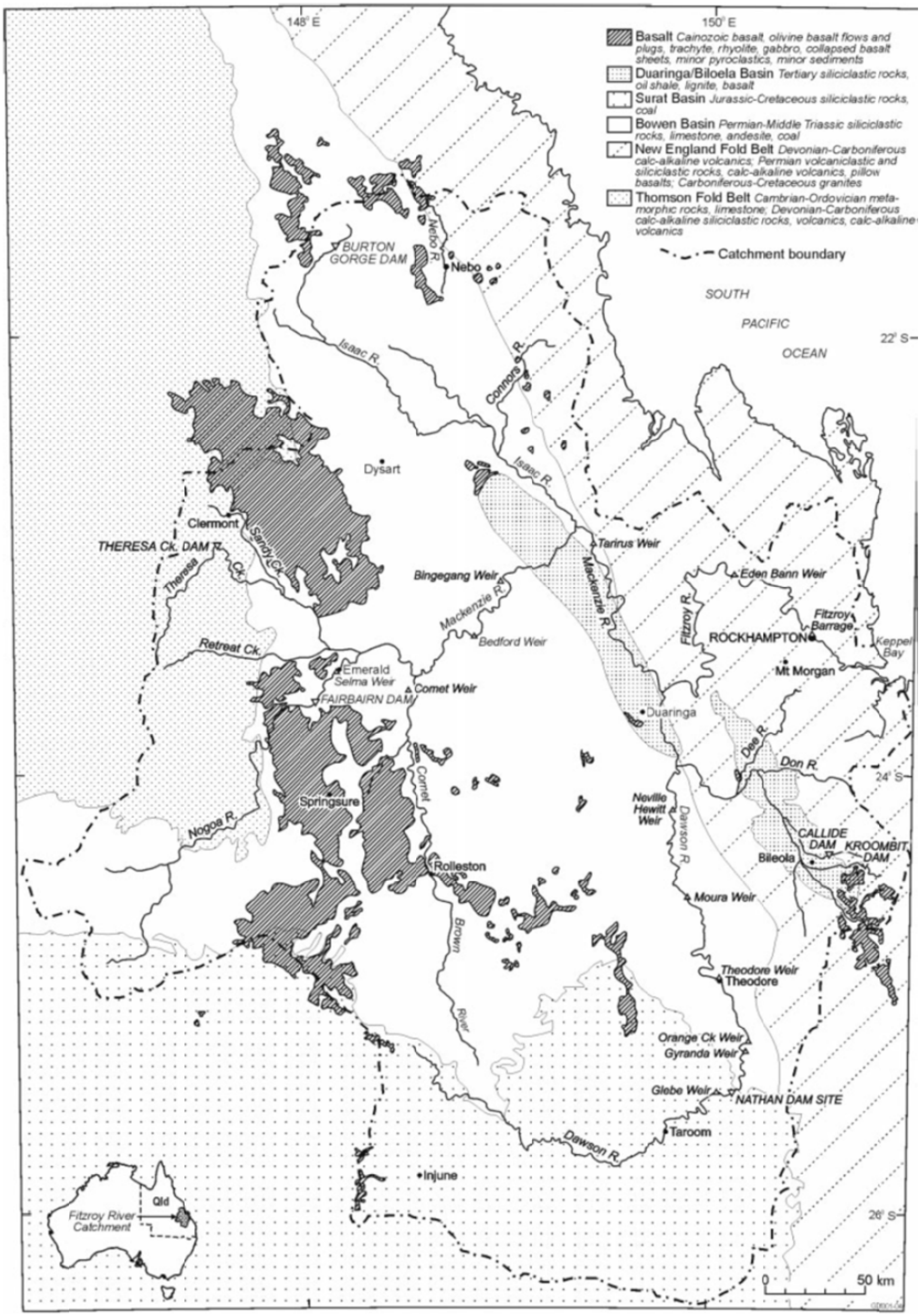

Figure 10. Geology of the Fitzroy River catchment area (from Douglas et al. 2006a).

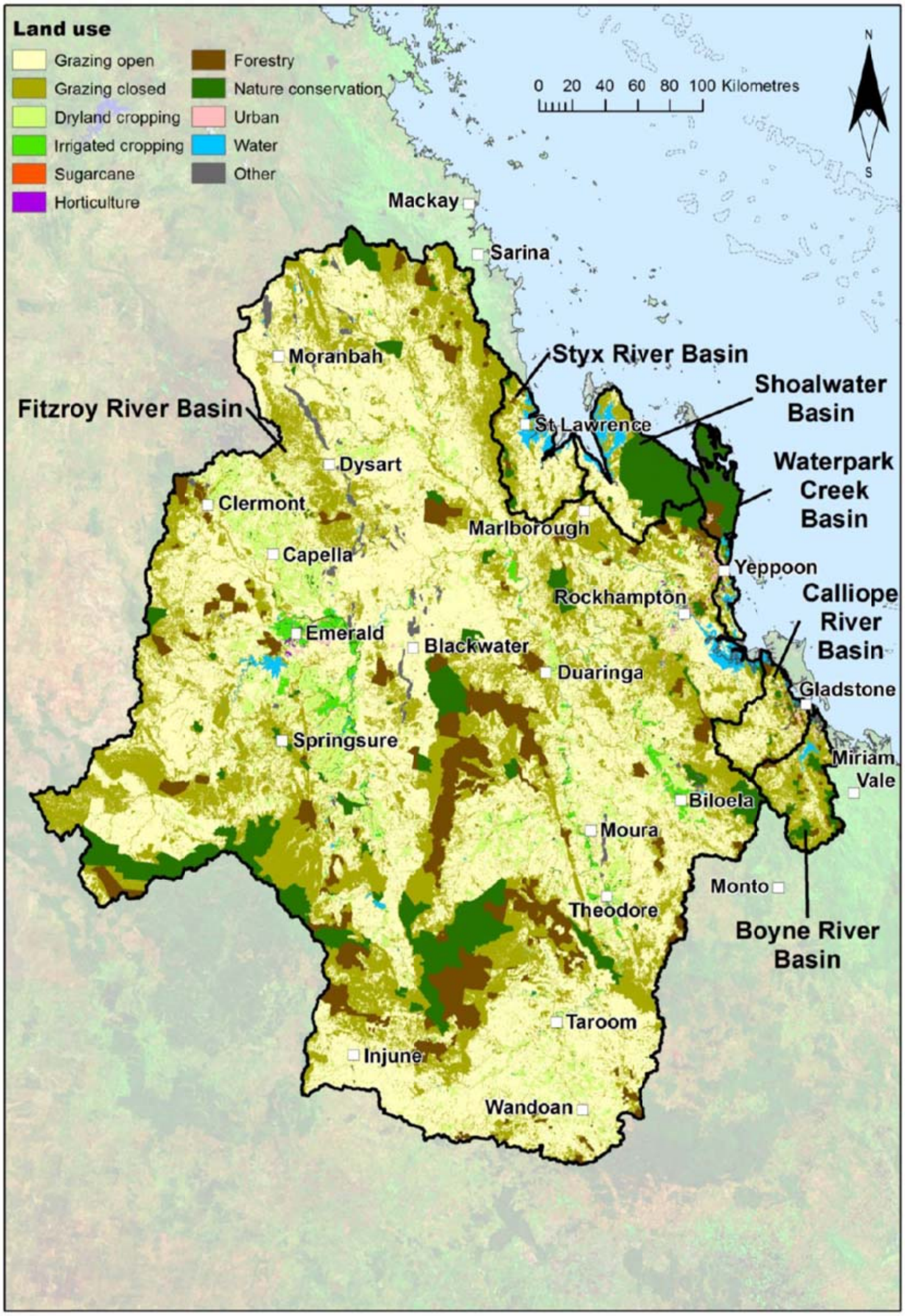

Figure 11. Land use map of the Fitzroy Basin (from Dougall et al. 2014).

5. What are the key erosion processes that release the priority sediment to the rivers and have erosion rates in the Fitzroy catchment changed over time?

Sediment tracing research within the Theresa Creek sub-catchment highlights that two distinct sources of erosion were contributing the most sediment to Theresa Creek including: 1) Sheetwash (hillslope) and rill erosion from basalt soil cropping lands and; 2) Gully headcut and sidewall channel erosion from non-basalt sources (i.e. likely Thompson Fold Belt) (Hughes et al. 2009). The gully/channel erosion was thought to have largely initiated (or amplified) in the late 19th Century, coinciding with the introduction and expansion of sheep and cattle in the catchment area, although gully erosion sediment supply appeared to reduce during the mid-20th Century (Hughes et al. 2010). Gully erosion risk mapping has also been performed for Theresa Creek, Nogoa and Comet sub-catchments (Eustace et al. 2011). The basalt erosion was thought to have largely increased from the mid-20th Century coinciding with the development of cropping lands over the fertile basaltic soils (Hughes et al. 2009). There are no similar tracing studies that have been conducted on the Nogoa or Comet rivers sub-catchments, although these findings from Theresa Creek are likely to be broadly transferable to these sub-catchments.

While the statistical analysis of Yu et al. (2013) suggested little changes in the sediment loads from the Fitzroy Basin since the 1960s, other evidence suggest large changes have occurred since the clearing of the Brigalow lands. This includes large changes in hydrology within the catchments since the Brigalow clearing where Thornton et al. (2007; also Cowie et al. 2007) showed that run-off at the Brigalow Catchment Study effectively doubled after clearing of Brigalow forest. On a broader sub-catchment scale, modelling suggested that run-off in the Comet River had increased by 40% after the Brigalow clearing (Siriwardena et al. 2006). Furthermore, intensive agriculture lands have much higher erosion rates than grazing lands (Packett et al. 2009) where rates for conventional tillage practices have been measured at 4 $t.ha^{-1}$ (Carroll et al. 1997) and zero-till cropping systems with contour bays at 1.2-1.7 $t.ha^{-1}$ (Murphy et al. 2013). These measurements were from cropping sites in the Theresa Creek catchment and the rates were much higher than those measured for well managed/good condition grazing lands (0.1 $t.ha^{-1}$) (Murphy et al. 2013). In comparison, grazing lands in poor condition (scalded, rilled, gullied) in the Nogoa can produce erosion rates of 30 $t.ha^{-1}$ (Silburn et al. 2011) and localised coal mining areas can produce erosion rates in excess of 70 $t.ha^{-1}$ on bare soils (Carroll et al. 2010). Sediment transport from mining was also examined by Lucas et al. (2010) but they only considered the influence on bed load (i.e. sand) transport and have no real application for the GBR. Experience with managing run-off and sediment losses in grazing lands have also been more positive in the Fitzroy (Silburn et al. 2011; Waters 2004) than in the Burdekin (Bartley et al. 2014).

Studies in other countries have shown that riparian damage from cattle can deliver substantial loads of sediments to streams (Trimble & Mendel 1995; Trimble 1994). Preliminary results from a study into bank erosion suggest that fine sediments contributed in-stream by cattle damage to riparian areas may be more significant than previously thought (Packett & Dougall, unpublished data). This study is finding that cattle ramps cut into the banks of first- to third-order streams are numerous and widespread in grazing lands in the Fitzroy Basin. The soil lost directly to the stream from the ramps will primarily be subsoils, a process observation that agrees with current sediment tracing data from the Burdekin Basin. Based on the available data, surface erosion from cropping lands on basalt soils, gully and scald erosion, and cattle damage to riparian areas in grazing lands should be the priority focus of management in the Fitzroy Basin.

In conclusion sheet-wash erosion in the cultivated basaltic soils, gully and scald erosion, and stream bank damage from cattle ramps and trials in grazing lands should be the priority for management of sediment erosion in the Fitzroy River catchment area. The latest modelling suggests that the Connors and Dawson catchments contribute the highest loads of fine sediment (i.e. 63 µm, although monitoring in the Connors suggest a large proportion is <10 µm). The geochemical tracing data suggest that basalt sources in the Comet and Nogoa catchments should also be a priority for management.

6. Overall summary and conclusions

A review of the available information suggests that land use change in the Fitzroy Basin has resulted in an increase of water, sediment and nutrient loads to the GBR lagoon compared to pre-development conditions. From a reef health perspective, the increases in discharge and particulate constituents have a negative impact on coral reefs and seagrass meadows by increasing turbidity and reducing light penetration. Multiple lines of evidence show that mainly very fine sediments with particulate-bound nutrients such as nitrogen and phosphorus are transported in moderate to large flood plumes from the Fitzroy Basin into the GBR lagoon. Investments aimed at reducing the impacts of flood run-off should therefore target land use management that results in a reduction of fine sediment transport to the ocean. Sediment tracing and constituent load monitoring studies suggest that intensive agriculture such as cropping on basalt derived soils is a major contributor of fine sediment in flood waters from the Fitzroy Basin. In addition, there is monitoring and modelling data to suggest that grazing lands in high rainfall regions (Connors and Dawson sub-catchments) contribute the largest long-term annual average loads of fine sediment and particulate nutrients to the coast. Large flood plumes from widespread heavy rainfall can transport fine sediment from cropping and grazing lands well out into Keppel Bay and beyond. There is currently a lack of tracing data regarding the origin of fine sediment that reduces photic depth in the southern GBR lagoon and plume monitoring studies are needed to fill this knowledge gap.

The process of soil erosion and transport from cropping lands is well documented and best management practices have been described. The management of cropping areas to reduce sediment flux to streams during run-off events is the most well understood and because cropping occurs on a limited area, it is spatially easier to manage than the large areas used for grazing. Best management practice on cultivated basaltic soils is therefore considered a priority to reduce fine sediment contributions from broadacre and floodplain cropping.

Improved management of grazing lands to reduce sediment supply from gully and scald erosion should also be a priority. The area of land used for grazing in the Fitzroy Basin is very large compared to the area used for cropping and will be far more difficult to manage via remedial on-ground works aimed at reducing soil erosion. However, the available data suggest that strategic management via lower stocking rates should allow grazing lands to recover or at least prevent further increases in soil loss. Preliminary findings of a study looking at stream bank erosion suggest that cattle ramps on minor streams may be a larger contributor of fine sediment than previously thought. There is a need to quantify this contribution and explore scenarios to reduce cattle impact on stream banks via off-stream watering, fencing or other means.

From a reef perspective, the large flood plumes that travel well out to sea from the mouth of the Fitzroy River and carry loads of sediment and attached nutrients mainly originate from steep parts of the basin close to the coast. Areas like the Dawson and Connors sub-catchments have regions where the western slopes of high ranges can produce large volumes of run-off. The north-eastern region of the Connors River sub-catchment generates a substantial percentage of the total annual average volume of fresh water that flows to the estuary. In addition, the region contributes reliable base flow for downstream users such as the residents of Rockhampton and the Capricorn Coast. This region also regularly produces high discharge annual flood events of relatively high quality water that result in large flood plumes. Maintaining or improving the condition of this region should be considered a high priority. Any deterioration in land condition due to intensive agriculture or over-stocking would result in a decrease in water quality for downstream users and an increase in fine sediment and nutrient loads to the GBR lagoon.

In summary, it would appear from the information at hand that soil erosion from both cropping and grazing lands in the Fitzroy Basin contributes very fine sediments that are periodically transported into Keppel Bay. Long-term rainfall and river discharge data indicate that the regions that contribute the highest discharge, and therefore the largest flood plumes, are mainly used for cattle grazing. Monitoring and modelling data suggest that these regions contribute the highest long-term annual load of fine sediment to the GBR lagoon compared to areas used for cropping. This is primarily due to the large volumes of water with lower concentrations of sediments from grazing lands compared to the lower volumes of water and higher concentrations of sediments from cropping lands. Therefore the pattern is that in most years there will be minor to moderate flood plumes from grazing lands with low sediment concentrations, fewer years where there are similar plumes with high sediment concentrations from cropping lands and occasionally (once every 15 to 20 years) very large flood plumes with relatively low sediment concentrations from mainly grazing lands.

El Niño and La Niña periods will also affect the types of floods and periods between major flood events; however, there are sufficient data available to suggest that the pattern is maintained in regards to the origin and relative contribution of fine sediment from cropping and grazing lands. From a future research perspective, there is an urgent need to quantify the contribution that cattle trails and ramps make to the supply of in-stream fine sediment and nutrients, and to conduct field monitoring of the sediment that reaches corals and seagrasses to assist with tracing knowledge.

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