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Modelling and monitoring the sediment trapping efficiency and sediment dynamics of the Burdekin Falls Dam, Queensland, Australia

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Abstract: The Burdekin River, Queensland, Australia drains a catchment area of ~130,000 km^2 and contributes approximately 30% of the total sediment supplied (~ 3.8 t) to the Great Barrier Reef Lagoon from all Great Barrier Reef catchments. Much of this watershed (~115,000 km^2) drains into the Burdekin Falls Dam, the largest dam reservoir in Queensland (1,860 GL capacity; 224 km^2 surface area; average depth 8.3 m). Current SedNet and ANNEX modelling (a sediment and nutrient transport process model) of the Burdekin catchment suggests that the Burdekin Falls Dam (BFD) is a very efficient trap for sediment and particulate matter. However, some field studies have suggested a much lower trapping efficiency. Improved knowledge of the amount of sediment trapped by the Burdekin Falls Dam is crucial for stakeholders managing sediment loads to the Great Barrier Reef Lagoon. The SedNet model is used to assist the identification and prioritisation of areas for remedial works within the catchment. If the Burdekin Falls Dam traps the high amounts of suspended sediment as predicted by the SedNet model then works can essentially be prioritised in the catchment area below the dam, a much smaller area (15,000 km^2).

A monitoring program was conducted over three wet seasons to estimate the trapping efficiency of the Burdekin Falls Dam and its variability over different flow events. We measured suspended sediment concentrations and particle size distribution in the Burdekin dam overflow and also in the large river catchments upstream and downstream of the dam to calculate sediment loads and examine sediment dynamics operating in the dam. We found that in moderate to large flow events, the Burdekin Falls Dam traps approximately 60% (±10%) of suspended sediment while in smaller flows the trapping efficiency is much higher (~80-90%). The results also show that the Upper Burdekin River arm of the catchment consistently contributes a large proportion of suspended sediments (>77%) delivered to the Burdekin Falls Dam even with the larger flows that occurred in the Cape and Belyando-Suttor catchments in the 2007/08 water year. Therefore we believe that the SedNet model is overestimating the sediment trapping efficiency of the Burdekin Falls Dam due to the trapping algorithm which is unsuitable for the Burdekin catchment area. Conversely, our calculations of sediment trapping appear to be higher than the estimates deduced from other field studies. Particle size distribution data show that the coarser sediment fraction >20 µm typically does not pass through the Burdekin Falls Dam.

Keywords: *Burdekin Falls Dam, sediment trapping, Burdekin River, sediment loads*

1. INTRODUCTION

The estimated total sediment flux to the Great Barrier Reef (GBR), Australia has increased by 4-5 fold since the arrival of Europeans ~150 years ago (Brodie et al., 2003; Furnas, 2003; McCulloch et al., 2003). This has caused detrimental effects on the ecological health of the GBR systems (e.g. Fabricius et al., 2005). Therefore, the management of sediment runoff is a key goal within the Reef Water Quality Protection Plan (Anon, 2003). Of the waterways within the GBR catchment area, the Burdekin River contributes the largest amount of suspended sediment to the GBR lagoon with an average annual export of 3.8 million tonnes, or approximately 30% of the total sediment supply to the GBR (Furnas, 2003). In large, above average flow events such as the 2007/08 water year, the Burdekin River alone exported a total of 12.3 million tonnes of suspended sediment (Bainbridge et al., 2008). Therefore, the management of soil erosion in the Burdekin River catchment is a key goal for natural resource managers, although it is unclear where remedial works should be prioritised within this large catchment area (130,000 km^2).

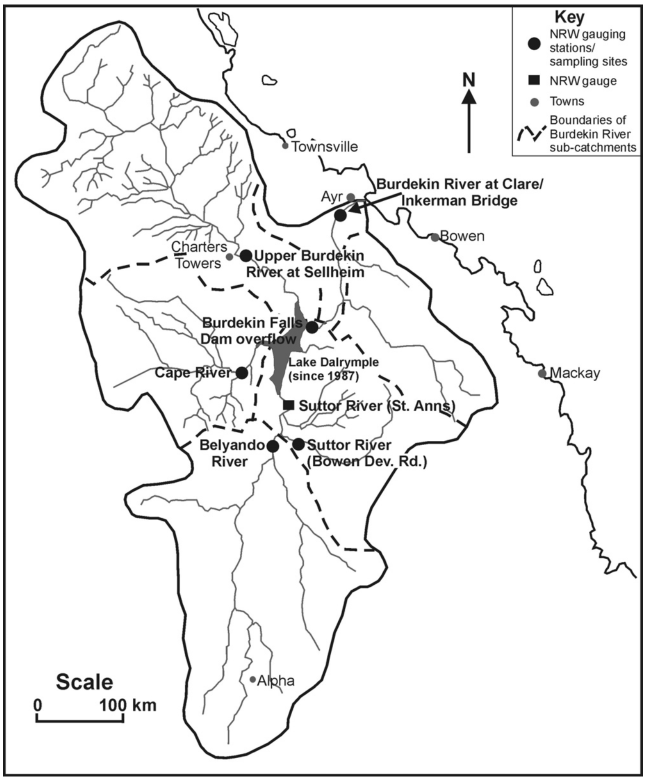

Figure 1. Burdekin River catchment showing sampling sites.

Current SedNet and ANNEX modelling of the Burdekin catchment suggests that the Burdekin Falls Dam (BFD), a large reservoir (1.86 million ML capacity) which is fed by much of the Burdekin watershed (~115,000 km^2), is a very efficient trap for sediment and particulate matter (Fentie et al., 2006; Post et al., 2006). The latest models estimate that the BFD traps 77-82% of suspended sediment, and 79% of particulate nitrogen and phosphorus, with negligible trapping of dissolved materials (Fentie et al., 2006; Post et al., 2006). As much of the remedial work undertaken in the catchment is targeted at reducing bulk suspended sediment loads to the GBR, works above the dam would not be undertaken for this purpose if the current dam trapping models are accurate. However, field studies using sediment traps, water column/bottom profiling and water sampling within the dam reservoir during flow events do not support this high trapping efficiency (Faithful and Griffiths, 2000). It is critical to have an accurate estimate of trapping within the BFD. Here we present suspended sediment load data from a three year monitoring program in the Burdekin River catchment to quantify the sediment trapping efficiency of the BFD. The three year dataset provides insights into the dam trapping efficiency over small (2005/06), average (2006/07) and large (2007/08) flow events. Particle size data of suspended sediments collected during these events also provide insights into the sediment dynamics operating within this system.

2. BACKGROUND

The Burdekin River catchment is located within the Dry Tropics of north Queensland. The tropics of northern Australia are renowned for highly variable seasonal and annual rainfall linked to the El Niño Southern Oscillation, tropical lows/cyclones and monsoonal activity (Lough, 2001). This extreme variability is highlighted by the historical daily, annual and event discharge records of the Burdekin River. On average, over 80% of the freshwater discharged from the Burdekin River at the Home Hill (1922-1957) and Clare (1950-current) gauging stations (NRW gauge no. 120001, 120006) occurs during high flow events (Lewis et al., 2006). This percentage is similar within the sub-catchments of the Burdekin Region. The majority of sediments and nutrients are also transported through Burdekin River waterways during these high flow events (see Lewis et al., 2006). Therefore, an event-focused approach to water quality monitoring is required to quantify the transport of sediments and nutrients in the waterways of the Burdekin River catchment.

The BFD (Fig. 1) was constructed in 1987 largely to facilitate irrigation requirements for sugar cane and cropping in the lower Burdekin region and also to supply water to coal mines within the Bowen Basin to the south (Faithful and Griffiths, 2000). The dam, with a full capacity of 1.86 million ML, is the largest reservoir in the State of Queensland (Faithful and Griffiths, 2000). The dam has a surface area of 224 km^2 (at capacity) and an average depth of 8.3 m (max depth of 40 m). Despite its relatively large capacity, the dam is fed by a considerable upstream catchment area (~115,000 km^2) and has overflowed in every wet season since construction (with one exception: see Faithful and Griffiths, 2000). Four major tributaries of the Burdekin River unite just upstream of the BFD including the Burdekin River from the north, the Cape River from the west and the Suttor and Belyando Rivers from the south. Queensland Department of Natural Resources and Water gauging stations measure stream flow on these tributaries and are located in close vicinity of major roads which cross these rivers, thereby providing optimal monitoring sites. The measurement of suspended sediment concentrations during flow events at these sites enables the calculation of loads to estimate the supply of suspended sediment into the BFD reservoir (Lake Dalrymple).

Field studies within Lake Dalrymple show that a turbid mid-flow layer develops during flow events due to the thermal stratification between the upper and lower water columns within the reservoir (Faithful and Griffiths, 2000; M. Cooper, unpublished data). This finding, accompanied by data from sediment traps (J. Faithful, unpublished data) suggests that the majority of sediments are transported through the dam in average to large flow events. However, measurements of suspended sediments upstream and downstream of the dam to calculate sediment loads have not been undertaken and so a quantitative estimation of trapping within Lake Dalrymple has not previously been performed.

Estimates of average suspended sediment export from the Burdekin River alone range between 2.4 and 9.0 million tonnes (see Lewis et al., 2006), although some of these estimates were calculated prior to the construction of the BFD and would not have considered its sediment retention capacity. The influence of dams and reservoirs on sediment supply in the GBR catchments is an important consideration and may significantly reduce total sediment export (e.g. Pringle, 1991).

3. METHODS

3.1. Sample collection

Suspended sediment samples were collected over three wet seasons (2005/06, 2006/07 and 2007/08) from the Burdekin River at Sellheim (flow gauge no. 120002C), Cape River at Gregory Developmental Road (flow gauge no. 120302B), Belyando River at Gregory Developmental Road (flow gauge no. 120301B), Suttor River at Bowen Developmental Road (flow gauge no. 120310A) and the BFD overflow (SunWater flow gauge) (Fig. 1). As the Suttor River at Bowen Developmental Road gauge did not become operational until the 2006/07 wet season, we have used the downstream Suttor River at St Anns (no. 120303A; minus the Belyando River gauge) to estimate the total discharge (and thus suspended sediment load) for the Suttor River arm.

A total of 362 samples were collected and analysed for total suspended solids (TSS) throughout the three monitored wet seasons including 37 samples from Burdekin River at Sellheim, 44 samples from the Cape River, 53 samples from the Belyando River, 44 samples from the Suttor River and 184 samples from the BFD overflow. This total does not include selected duplicate samples for precision estimates and inter-laboratory comparisons. Surface water 'grab' samples (top 50 cm of water column) were collected with a bucket and rope following rainfall events which triggered significant stream flow. Where possible, samples were collected over the rising, peak and falling stages of the flow hydrograph. Samples were collected from the centre of the channel flow where possible, and if samples were collected from the edge, every effort was made to ensure samples were collected from the main flow, away from the backwash at the riverbank. The samples were then well mixed with a stirring rod before being sub-sampled into 1L containers. The samples were refrigerated and transported on ice to the laboratories for analysis.

In addition, many samples from each site were analysed for particle size distribution to examine the potential for size-specific deposition within Lake Dalrymple and the river channel downstream. Particle size samples were selected to best capture the flow hydrograph over the rising, peak and falling stages. A total of 110 water samples were analysed from the sites over the three monitored wet seasons: 21 samples from Burdekin River at Sellheim, 16 samples from the Cape River, 19 samples from the Belyando River, 17 samples from the Suttor River and 37 samples from the BFD overflow.

3.2. Analytical methods

TSS analysis was performed at the Australian Centre for Tropical Freshwater Research laboratory at James Cook University (JCU), Townsville and at the Queensland Department of Natural Resources and Water laboratory, Brisbane. Samples of known volume were filtered through pre-weighed GF/C glass fibre filter papers with a nominal pore size of 1.2 µm. The filter and retained matter were dried to constant weight at 105°C. TSS (in mg/L) was calculated by dividing the mass of the retained matter (in mg) by the volume of sample filtered (in L). Selected TSS samples were duplicated to assess the repeatability of the analysis. Duplicate determinations were, on average, within 10% of each other. Duplicate samples were also analysed by separate laboratories to ensure consistency. These samples were typically within 10%.

Particle sizing was conducted on selected water samples using a Malvern Mastersizer 2000 at the School of Earth and Environmental Sciences, JCU. Each sample was analysed at least twice and a mean was taken.

3.3. Load calculations

The collection of TSS samples near the locations of the gauging stations allows for the calculation of the mass or load of TSS exported through the sampled point of the waterway. The highest concentrations of suspended sediments typically occur during the rising limb of the flow hydrograph before concentrations become diluted with increasing discharge volume or with decreasing flow. Therefore it is critical to sample all stages of the flow to obtain reliable load estimates. The continuous time series flow data from the stream-flow gauging stations and point source water quality data were entered into the BROLGA database, a software program designed by the Queensland Department of Natural Resources and Water, which calculates loads using linear interpolation. The linear interpolation technique is considered the most suitable to estimate catchment loads given the available input data (Letcher et al., 1999; Lewis et al., 2007). In some cases in the 2005/06 and 2006/07 water years, the ‘full’ hydrograph event was not sampled at some of the sites and ‘tie down’ concentrations were added to capture the total flow range over these events. Concentrations were deduced by using the best estimate possible with the available data. We estimate that the uncertainty of the load data to be generally within ±20%, although fewer samples collected from the Belyando and Suttor Rivers in the 2005/06 water year may increase the uncertainty to ±50% in these cases. These estimated uncertainties have been used to calculate the error range in dam trapping (Table 1).

Table 1. Summary of load data and sediment trapping estimates for the BFD and delivered to the coast at Clare

Year	2005/06	2006/07	2007/08
Dam overflow discharge (ML)	1,400,000	5,100,000	1,670,000
Upper Burdekin sediment load (tonnes)	1,760,000	2,800,000	4,700,000
Cape River sediment load (tonnes)	30,000	180,000	320,000
Belyando River sediment load (tonnes)	120,000	90,000	230,000
Suttor River sediment load (tonnes)	130,000	100,000	280,000
Other estimated sediment load	10,000	30,000	140,000
Sediment load inflow waters (tonnes)	2,050,000	3,200,000	5,670,000
Sediment load overflow waters (tonnes)	240,000	1,200,000	2,400,000
Sediment trapping (%)	88 ± 2%	62 ± 7%	58 ± 9%
Burdekin River sediment load end of catchment (tonnes)	500,000	6,140,000	12,300,000
Sediment contribution of dam overflow to end of catchment (%)	48%	20%	20%

Approximately 9% (~10,000 km^2) of the catchment area above the BFD is ungauged and includes waterways such as Sellheim River, Kirk River and Elphinstone Creek. Monitoring data from the Kirk River and Elphinstone Creek were used to estimate the suspended sediment event mean concentration for this catchment area. The flow contribution for this catchment area was estimated by developing a water budget using the BFD overflow data coupled with the measured capacity of the dam prior to the event flows.

4. RESULTS

4.1. Sediment load budgets

For the catchments above the BFD, all streams had below average flows in the 2005/06 water year. In the 2006/07 water year, the Burdekin River at Sellheim and Cape Rivers had average flows while the Suttor and Belyando Rivers had below average flows. All contributing rivers had above average flows in the 2007/08 water year.

Our measurements suggest that the sediment trapping efficiency of the BFD was 88% in 2005/06, 62.5% in 2006/07 and 58% in 2007/08 (Table 1). The higher trapping efficiency in the 2005/06 water year is a product of relatively small catchment flows and also due to a lower dam water level prior to the onset of this wet season. The consistency in the trapping efficiency estimates in 2006/07 and 2007/08 of ~60% (± 10%) suggest that this is probably more reflective of an 'average' trapping estimate. Therefore, we suggest that SedNet models are currently overestimating the trapping efficiency of the BFD, using the trapping efficiency of 77-82%. Indeed, if the latest SedNet model incorporated 60% dam trapping then the average annual export of 3.5 million tonnes (Kinsey-Henderson et al., 2007 using model of Post et al., 2006; note original estimate 2.6 million tonnes) is close to the estimate of Furnas (2003: 3.8 million tonnes) and also to the loads calculated over 9 years of monitoring data (4.6 million tonnes: Bainbridge et al., 2008). In addition, the data show that the suspended sediment contribution from the dam overflow to the end-of-catchment was 48%, 20% and 20% for the 2005/06, 2006/07 and 2007/08 water years, respectively (Table 1).

4.2. Particle size analysis

The particle size results show high variability across the flow hydrograph for the upstream rivers and also the BFD overflow. This result suggests that different sources of suspended sediment are being transported from different lithologies/catchment areas during flow events. All four major river arms upstream of the BFD drain considerable catchment areas and also contain several different rock/soil types. We note that the PSD of the outflow waters reflects the PSD of inflows entering the reservoir up to several days earlier. Figure 2 shows the particle size distribution (PSD) of sediments entering and leaving the reservoir on 9 February 2007 and is representative of the qualitative impact of the dam on sediment transport seen in other events. During the February 2007 event, approximately 75% of the inflow was from the Upper Burdekin River at Sellheim and it is apparent that the coarser sediments (> 20 µm) generally do not pass downstream of the dam.

Generally, the dominant particle size fraction measured at all sites was in the fine to medium silt range, particularly when the distributions were unimodal (4 to 25 µm), although a finer clay fraction was also evident in all samples especially when a bimodal pattern was apparent. Previously it was thought that most of the 'fine-grained' particles were derived from the southern Belyando and Suttor River arms of the Burdekin (Faithful and Griffiths, 2000), however, our data show that similarly fine particles can also be derived from the Upper Burdekin River at Sellheim and Cape Rivers (Fig. 2).

The high variability in the PSD occurring over single flow events in all streams (i.e. change from unimodal to bimodal distribution) suggests that different sources of sediments are being eroded in the catchment areas and reflect the different 'parcels' of water passing through the catchment over time. Further study is required to determine the origin of the bimodal particle size distribution.

5. DISCUSSION AND CONCLUSIONS

The sediment trapping algorithm within the SedNet model is based on a well-established relationship between trapping efficiency and the ratio of reservoir capacity to annual inflow for 'normal ponded reservoirs' which receive runoff that is more evenly distributed throughout the year than is the case for the Burdekin River (Brune, 1953). This algorithm predicts that ~80% of suspended sediment should be trapped by the BFD. Our measurements indicate that the BFD trapping efficiency is about 20% less, i.e. approximately 60% of sediment delivered during normal floods is trapped by the dam. We believe the algorithm used in SedNet may not be appropriate for the BFD, which experiences strong thermal stratification and highly episodic flows and therefore shorter residence times than is typically the case for temperate reservoirs (see Faithful and Griffiths, 2000).

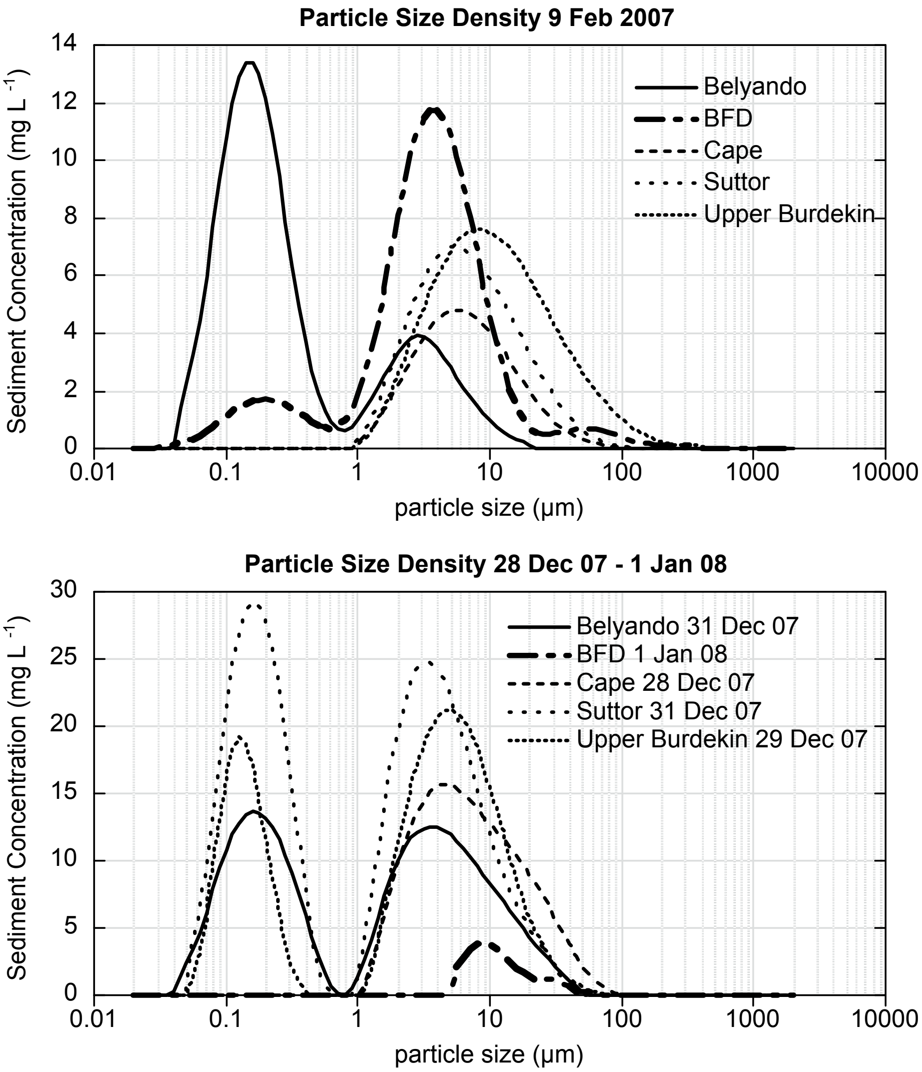

Figure 2. Particle size distribution (PSD) of suspended sediment in inflowing rivers and passing over Burdekin Falls Dam (BFD) on 9 Feb 07 (top) and during event from 28 Dec 07 - 1 Jan 08 (bottom).

In contrast, suggestions that most suspended sediments would pass over the dam spillway based on physical measurements of turbidity and water column temperature appear to have underestimated the trapping efficiency of the BFD. The turbid mid-flow layer that develops in Lake Dalrymple during event flows (Faithful and Griffiths, 2000) may only rarely reach the surface waters and pass over the dam. In fact, during the large flows of the 2007/08 water year, the surface TSS concentrations measured across Lake Dalrymple were close to the TSS concentration collected in the dam overflow waters. In addition, stratification in Lake Dalrymple was not observed during the moderate flows in 2004/05 (M. Cooper, unpublished data).

Our data also show that the vast majority (~80%) of the suspended sediment load delivered to the BFD is derived from the Upper Burdekin River arm (Table 1). This finding supports the results of Cooper et al. (2006) who, using trace element and isotopic tracing methods, found that the bottom sediments within Lake Dalrymple were from the Upper Burdekin River. Therefore, any on-ground management within the catchment intended to reduce 'bulk' suspended sediment delivery to the dam should focus on the Upper Burdekin River catchment area. Importantly, this study (Table 1) indicates that, in large flows, the majority (80%) of the total suspended sediment load exported from the Burdekin River (Inkerman Bridge; end-of-catchment) is sourced from the catchment area below the BFD. This area below the dam only comprises 10% of the total Burdekin catchment area. Although additional data are required to support these results, based on the current findings, remedial works to reduce the 'bulk' suspended sediment load exported from the Burdekin River should focus on the catchment area below the dam. However, we note that this assertion only relates to the management of the 'bulk' suspended sediment supply and not to specific sediments which may travel further in the marine environment (i.e. types of clays) and thus may be more ecologically important.

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REFERENCES

Anon. (2003), Reef Water Quality Protection Plan; for catchments adjacent to the Great Barrier Reef World Heritage Area, Queensland Department of Premier and Cabinet, Brisbane.

Bainbridge, Z., Lewis, S., Davis, A., Brodie, J. (2008), *Event-based community water quality monitoring in the Burdekin Dry Tropics Region: 2007-2008 wet season update*, ACTFR Report 08/19, JCU, Townsville.

Brodie, J. McKergow, L.A. Prosser, I.P. Furnas, M. Hughes, A.O. Hunter, H. (2003), *Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area*. ACTFR Report 03/11, JCU, Townsville.

Brune, G.M. (1953), *Trap efficiency of reservoirs*. Transactions of the American Geophysical Union, 34, 407-418.

Cooper, M., Shields, G., Faithful, J., Zhao, J. (2006), Using Sr/Nd isotopic ratios to define sediment sources in the Burdekin Falls Dam, Queensland, Australia. *Geochimica et Cosmochimica Acta*, 70, A112.

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

Fentie, B., Duncan, I., Cogle, A.L., Sherman, B., Read, A., Chen, Y., Brodie, J. (2006), *6. Sediment and nutrient modelling in the Burdekin Basin*, in: Cogle, A.L., Carroll, C., Sherman, B.S. The use of SedNet and ANNEX models to guide GBR catchment sediment and nutrient target setting. Department of Natural Resources, Mines and Water.

Faithful, J.W., Griffiths, D.J. (2000), Turbid flow through a tropical reservoir (Lake Dalrymple, Queensland, Australia): responses to a summer storm event, *Lakes and Reservoirs: Research and Management*, 5, 231-247.

Furnas, M. (2003), *Catchments and corals: terrestrial runoff to the Great Barrier Reef*, Australian Institute of Marine Science, 334 pp.

Kinsey-Henderson, A., Sherman, B., Bartley, R. (2007), *Improved SedNet modelling of grazing lands in the Burdekin catchment*, CSIRO Land and Water Science Report 63/07.

Letcher, R.A. Jakeman, A.J. Merritt, W.S. McKee, L.J. Eyre, B.D. Baginska, B. (1999), *Review of techniques to estimate catchment exports*, Environmental Protection Authority Technical Report, EPA, Sydney. ISBN: 0731327098.

Lewis, S., Brodie, J., Ledee, E., Alewijnse, M. (2006), The spatial extent of delivery of terrestrial materials from the Burdekin Region in the Great Barrier Reef lagoon, ACTFR Report 06/02, JCU, Townsville.

Lewis, S.E., Bainbridge, Z.T., Brodie, J.E. (2007), *A review of load tools available for calculating pollutant exports to the Great Barrier Reef lagoon: A case study of varying catchment areas*, in: Oxley, L., Kulasiri, D. MODSIM 2007 International Congress on Modelling and Simulation, 2396-2402.

Lough, J.M. (2001), *Climate variability and change on the Great Barrier Reef*, in: Wolanski, E. Oceanographic processes of coral reefs – physical and biological links in the Great Barrier Reef, 269-300.

McCulloch, M.T., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D. (2003), Coral record of increased sediment flux to the inner Great Barrier Reef, *Nature*, 421, 727-730.

Post, D., Bartley, R., Corfield, J., et al. (2006), *Sustainable grazing for a healthy Burdekin catchment*, CSIRO Land and Water Science Report 62/06, 220 pp.

Pringle, A.W. (1991), Fluvial sediment supply to the north-east Queensland coast, Australia, *Australian Geographical Studies*, 29, 114-138.