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Key Points:

- Catchment sediment budgets should incorporate sediment particle size
- Large reservoir influences clay and fine silt transport in a tropical catchment
- Annual sediment loads highly variable in seasonally dry tropical rivers

Supporting Information:

- Readme
- Bainbridge et al Auxiliary Material

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Fine-suspended sediment and water budgets for a large, seasonally dry tropical catchment: Burdekin River catchment, Queensland, Australia

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Abstract The Burdekin River catchment ($\sim$130,400 km^2) is a seasonally dry tropical catchment located in north-east Queensland, Australia. It is the single largest source of suspended sediment to the Great Barrier Reef (GBR). Fine sediments are a threat to ecosystems on the GBR where they contribute to elevated turbidity (reduced light), sedimentation stress, and potential impacts from the associated nutrients. Suspended sediment data collected over a 5 year period were used to construct a catchment-wide sediment source and transport budget. The Bowen River tributary was identified as the major source of end-of-river suspended sediment export, yielding an average of 530 t km^{-2} yr^{-1} during the study period. Sediment trapping within a large reservoir (1.86 million ML) and the preferential transport of clays and fine silts downstream of the structure were also examined. The data reveal that the highest clay and fine silt loads—which are of most interest to environmental managers of the GBR—are not always sourced from areas that yield the largest total suspended sediment load (i.e., all size fractions). Our results demonstrate the importance of incorporating particle size into catchment sediment budget studies undertaken to inform management decisions to reduce downstream turbidity and sedimentation. Our data on sediment source, reservoir influence, and subcatchment and catchment yields will improve understandings of sediment dynamics in other tropical catchments, particularly those located in seasonally wet-dry tropical savannah/semiarid climates. The influence of climatic variability (e.g., drought/wetter periods) on annual sediment loads within large seasonally dry tropical catchments is also demonstrated by our data.

1. Introduction

Sediment budgets provide a structured framework for representing river catchment sediment sources, storage, and yields [*Dunne and Leopold* 1978; *Walling and Collins*, 2008], and provide an effective communication tool for natural resource managers to understand sediment loads and transport [*Slaymaker*, 2003]. In particular, catchment-scale sediment budgets have been applied to identify changes in catchment sediment loads and sources associated with anthropogenically modified land use, including both increases in loads driven by elevated erosion associated with land clearing, agriculture, and mining as well as declines in sediment load downstream of depositional areas such as reservoirs [*Syvitski*, 2003; *Walling*, 2006]. Although this approach is commonly adopted (see reviews by *Walling and Collins* [2008] and *Koiter et al*. [2013]), there have been few sediment-budget studies from tropical catchments (see reviews by *Nagle et al*. [1999] and *Tooth* [2000]). Further, detailed investigations on the transport of specific sediment-size fractions within tropical catchments are rare [e.g., *Verbist et al*., 2010]. This study addresses this knowledge gap by quantifying suspended sediment sources and yields for a large seasonally dry tropical river catchment with high interannual and intra-annual streamflow variability associated with the arrival and strength of the summer monsoon. We focused on the finer clay and silt sediment fractions (<16 μm) that are most likely to reach the downstream receiving environment, the Great Barrier Reef (GBR) lagoon, located on the north-eastern coast of Australia [*Bainbridge et al*., 2012].

The influence of anthropogenically increased sediment delivery on inshore GBR turbidity and resuspension regimes has been debated over the past few decades. Some studies suggest that turbidity levels on the

GBR have remained constant over thousands of years due to the availability of abundant terrigenous sediment along the GBR's inner shelf [*Larcombe et al*., 1995; *Orpin and Ridd*, 2012]. In contrast, recent evidence suggests a strong link between increased inshore turbidity and higher sediment yields to the GBR from streams draining coastal catchments that have been modified by European settlement [*Fabricius et al*., 2013, 2014]. Increased turbidity associated with river plumes and subsequent dry season resuspension events may directly impact GBR coral and seagrass communities by reducing light available for photosynthesis [*Fabricius*, 2005; *Collier et al.,* 2012]. When accompanied by high sedimentation rates, smothering may also occur [*Weber et al*., 2006]. Reduced vigor of coral communities affected by elevated turbidity and sedimentation can also result in increased macroalgal cover [*De'ath and Fabricius*, 2010] and more frequent coral disease outbreaks [*Haapkyla et al*., 2011]. Further, the clay and fine silt-sized sediment particles are easily resuspended [*Browne et al*., 2012; *Davies-Colley and Smith*, 2001], and have the greatest effect on corals in the form of increased and persistent turbidity regimes and sedimentation of organic-rich flocs [*Bainbridge et al*., 2012; *Fabricius*, 2005; *Humphrey et al*., 2008; *Weber et al*., 2006].

The focus of this study, the Burdekin River catchment ($\sim$130, 400 km^2) has an annual average discharge of 9.18 million ML (range: 0.25–54.03 million ML) over a 91 year gauge record to 2012 (1921–2012) [*Department of Environment and Resource Management*, 2012]. The Burdekin contributes the highest suspended sediment load to the GBR ($\sim$30% of total) of all the coastal catchments, exporting an average of 3.93 million tonnes of suspended sediment annually, corresponding to an average area yield of 30 t km^{-2} yr^{-1} (1986–2010) [*Kuhnert et al*., 2012]. Historical records from inshore coral cores influenced by Burdekin River discharge and recent catchment modeling efforts suggest that annual sediment export is five to eight times higher than pre-European loads [*McCulloch et al*., 2003; *Kroon et al*., 2012]. Although low compared to tropical rivers globally (see discussion), this marked increase in export since European settlement ($\sim$1850) threatens the sensitive ecosystems of the GBR, making efforts to reduce sediment runoff from the Burdekin catchment a management priority [*Bartley et al*., 2014]. To inform targeted and effective management of sediment erosion within the Burdekin, catchment-wide sediment source and transport annual budgets were constructed using empirical field data collected at key river network locations between 2005 and 2010. The contributions of clay (<4 μm), fine silt (4–16 μm), and coarse (>16 μm) sediment fractions were quantified to isolate sediment sources at a relatively coarse "sub-catchment" scale before "hot-spot" tributaries were identified and specific environmental drivers for erosion were investigated. This study builds on sediment trapping estimates of a large reservoir within the catchment reported in *Lewis et al*. [2013], and quantifies the significant influence this impoundment has on downstream sediment transport and end-of-river export. This study reveals that the highest loads of the finer sediment fraction (i.e., clay and fine silt), which are of most interest from a management perspective are not necessarily derived from areas yielding the highest total suspended sediment load, and highlights how climate variability influences sediment loads; for example, elevated loads are typically transported by run-off events following prolonged drought. This study demonstrates that sediment budgets incorporating sediment particle-size fractions are far more useful to managers seeking to reduce fine sediment export and inshore turbidity than the traditional "yield-only" approach.

2. Study Area

The Burdekin River catchment is located within the seasonally dry tropics of north-eastern Australia (Figure 1). It is the second largest catchment draining into the GBR lagoon. The Burdekin catchment includes five major subcatchments: the Upper Burdekin River; the Cape River; the Belyando River; the Suttor River; and the Lower Burdekin (Figure 1). All but the Lower Burdekin subcatchment drain into Lake Dalrymple—an artificial lake impounded behind the Burdekin Falls Dam (BFD). Although Lake Dalrymple has a capacity of 1.86 million ML, the dam has overflowed every wet season but one since its construction was completed in 1987 [*Faithful and Griffiths*, 2000], indicating the enormous run-off from this large catchment (capacity to inflow ratio = 0.24). The Bowen River is the only major tributary that discharges directly into the Burdekin River downstream of the BFD, comprising $\sim$50% of the Lower Burdekin subcatchment area. In this study, we focused on the gauged Bowen River subcatchment where streamflow can be gauged relatively accurately, which is not possible for the broader (ungauged) Lower Burdekin area.

The coastal mountain ranges that enclose the eastern margins of the Bowen and Upper Burdekin Rivers have peaks rising to 750–1070 m and are steeply sloped, vegetated with rainforest, and receive the highest mean annual rainfall (up to 2370 mm yr^{-1}) across the Burdekin (Figure 2). Steep mountain ranges reaching

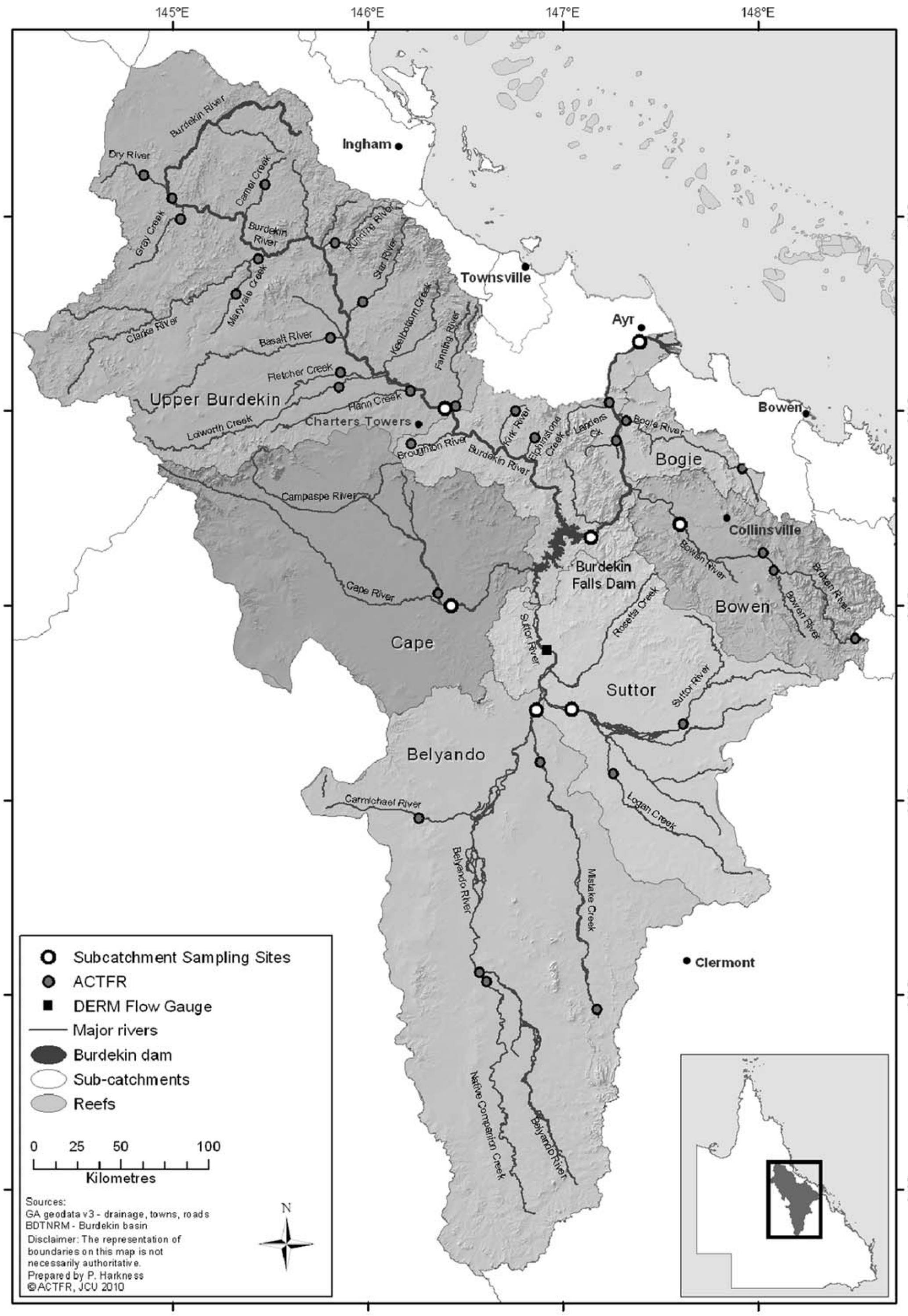

Figure 1. Burdekin River catchment map indicating the five major subcatchment areas (Upper Burdekin, Cape, Belyando, Suttor, and Bowen Rivers) and flow gauge/sediment sample locations, as well as the Burdekin Falls Dam and end-of-river (near Ayr) gauged sample locations, all represented as white circles. The location of the ungauged minor tributary sample sites are also displayed as gray circles across the catchment.

900 m in height also form the western boundary of the Upper Burdekin, with large areas within this subcatchment strongly undulating, draining into an incised river channel lined with inactive terraces and high upper banks. Eucalypt savannah woodlands dominate the Upper Burdekin subcatchment. The Bowen

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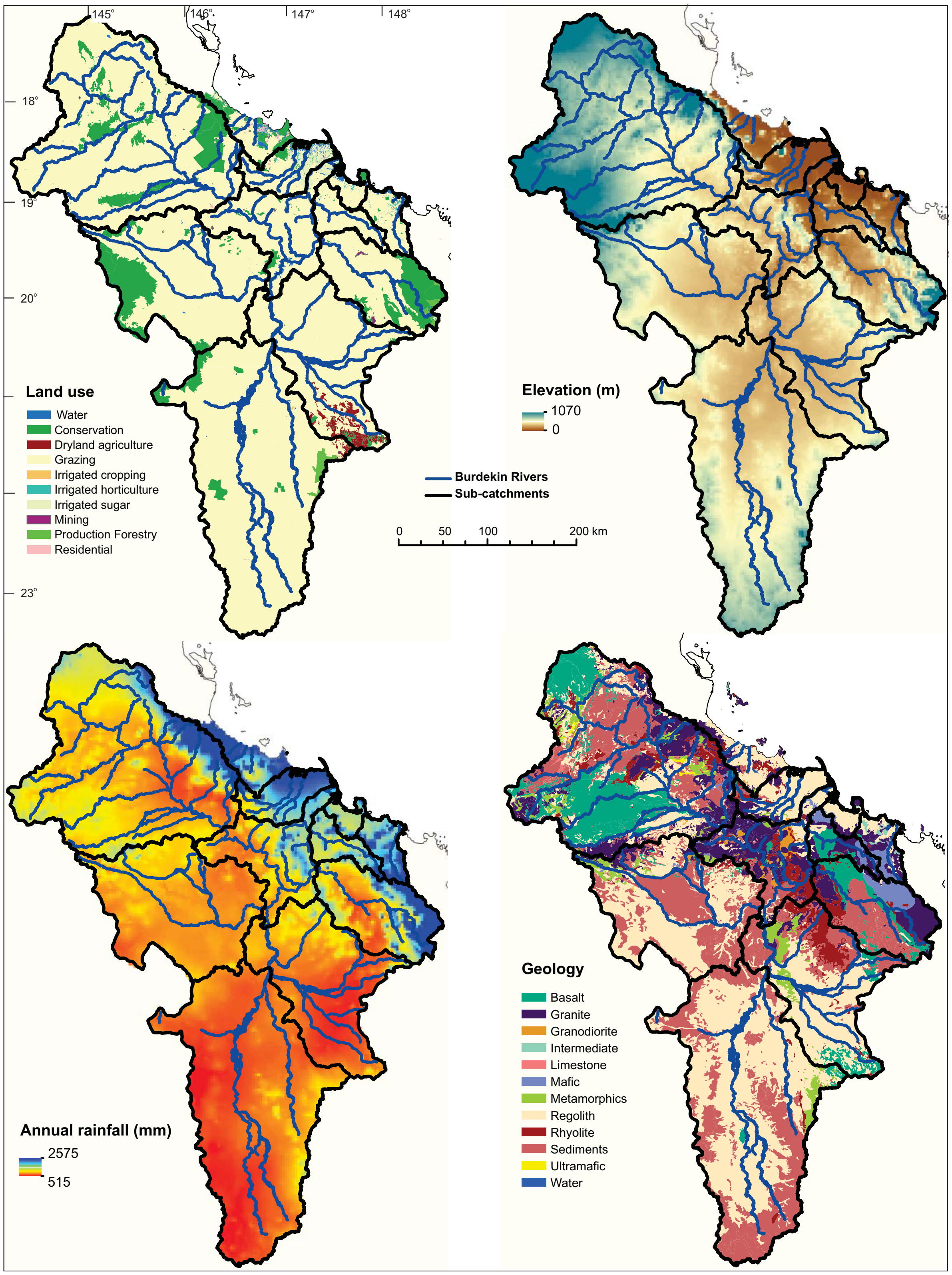

Figure 2. Burdekin River land use, elevation, annual average rainfall, and geology.

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Table 1. Gauged Sample Site Locations and Total Suspended Sediment (TSS) and Particle-Size Analysis (PSA) Data Collection Summary

				PSA Subset	
Sample Site	Gauge Station/Location	Water Years Sampled	# TSS Samples	# Samples	Water Years
Upper Burdekin River (Sellheim)	120002C: Burdekin River at Sellheim	2005/2006–2009/2010	75	32	2005/2006–2008/2009
Cape River	120302B: Cape River at Gregory Dev. Rd.	2005/2006–2009/2010	173	24	2005/2006–2008/2009
Belyando River	120301B: Belyando River at Gregory Dev. Rd.	2005/2006–2009/2010	155	21	2005/2006–2008/2009
Suttor River	[a]120310A: Suttor River at Bowen Dev. Rd.	2005/2006–2009/2010	117	22	2005/2006–2008/2009
Burdekin Falls Dam Overflow (capturing above sites)	120015A: Burdekin River at Hydro Site	2005/2006–2009/2010	348	50	2005/2006–2008/2009
Bowen (Myuna)	120205A: Bowen River at Myuna	2005/2006–2007/2008	140[b]	110	2006/2007–2008/2009
Burdekin River –Inkerman (end-of-catchment)	120006B: Burdekin River at Clare (immediately upstream of Inkerman bridge)	2005/2006–2009/2010	227[b]	12	2006/2007; 2008/2009 only[c]

[a]120310A gauge was installed after the 2005/2006 wet season. Streamflow for this site for the 2005/2006 water year was calculated by subtracting the Belyando River gauge (120301B) data from the downstream Suttor River (St Anns) gauge (120303A).

[b]Individual water year load calculations by the LRE utilize any available preceding wet season TSS data (i.e., develops a site specific TSS concentration/streamflow relationship), which included 40 additional samples from 2002/2003 to 2004/2005 for the Bowen (Myuna) site and an additional 465 samples from 1986/1987 to 2004/2005 for the Burdekin River (Inkerman) site [*Kuhnert et al.* 2012].

[c]Burdekin River (Inkerman) data were collected by a different authority and not available for PSA. Opportunistic sample collection by the authors at this site during peak flood conditions was conducted specifically for the purposes of PSA.

subcatchment is also characterized by low undulating hills and steeper ridges in the upper catchment, and an incised valley system through volcanic hills [*Roth et al*., 2002]. Volcanic and sedimentary rock types dominate these two subcatchments (Figure 2). Extensive areas of erodible "Goldfields" red duplex soils, black and red basaltic soils, and sodic duplex soils occur in the Upper Burdekin. Red-brown earths, yellow soils, granite/sandstone-derived gravely/sandy soils, and black earths cover large areas of the Bowen River catchment [*Roth et al*., 2002]. In comparison, the inland western subcatchments (the Cape, Belyando, and Suttor Rivers) drain gently undulating lowlands and alluvial plains, with wide multithreaded rivers, and with lower maximum elevations (300–450 m) located along the western boundary of the Cape and Belyando Rivers. Eucalypts, acacias (Brigalow Belt), and grasslands dominate these drier subcatchments, with average annual rainfall below 700 mm yr^{-1} (Figure 2). Remnant sedimentary basins and cracking clay soils form the dominant rock and soil types within these subcatchments, with gray/brown clays and red/yellow earths also widespread in the Belyando and Suttor subcatchments [*Roth et al*., 2002]. Cattle grazing across eucalypt savannah woodlands is the dominant (>90%) land use in the Burdekin catchment. More details about this region can be found in *Roth et al*. [2002] and the regional natural resource management body, North Queensland Dry Tropics website (www.nqdrytropics.com.au).

The majority of the catchment is classified as a "hot semi-arid" climate (BSh) under the Köppen-Gieger classification scheme [*Peel et al*., 2007], although the interannual and intra-annual rainfall and river flood variability of northern Australia is more pronounced than for other semiarid climates across the globe [see *Petheram et al*., 2008]. Annual rainfall variability is "moderate" to "moderate-high" across the Burdekin according to the Australian Bureau of Meteorology's "index of variability," representing the 10th and 90th percentiles over average rainfall (www.bom.gov.au/climate/averages/maps.shtml). Rainfall is strongly seasonal, with >80% of annual rainfall and river discharge occurring during the wet season months December to April [*Lewis et al*., 2006; *Lough*, 2007]. Mean annual rainfall also varies greatly across the catchment, ranging from >1500 mm yr^{-1} in the "tropical wet and dry" Upper Burdekin coastal ranges (north-eastern corner, Figure 2) to 500 mm yr^{-1} in the driest south-west corner of the Belyando subcatchment (Figure 2). This range is the largest for any watershed along the Australian east coast [*Rustomji et al*., 2009]. Locally this region is defined as "seasonally-dry tropical," a definition that we also adopt. Because of the seasonally dry tropical climate most streams within the Burdekin catchment are ephemeral, and streamflow predominately occurs as "flood events" where flows rapidly rise when fed by wet season rainfalls. Negligible flows typically occur during the dry season (May–November). Wetter water years often result from monsoonal and cyclonic events, which are strongly modulated by El Niño—Southern Oscillation cycles [*Rustomji et al*., 2009]. This climatic variability significantly influences sediment runoff generation and transport each wet season; for example, drought-breaking floods carrying high-suspended sediment loads [*Mitchell and Furnas*, 1996; *Amos et al*., 2004]. This variability in annual Burdekin River suspended sediment export is captured in export measurements recorded between 1986 and 2010 that range from 0.004 to 15.74 (mean=3.93, SD=0.41) million tonnes per annum [*Kuhnert et al*., 2012].

3. Methodology

3.1. Suspended Sediment Sample Collection

River water samples were collected from existing streamflow gauge locations draining the five major subcatchments of the Burdekin River (Upper Burdekin, Cape, Belyando, and Suttor Rivers, as well as the Bowen River to represent the otherwise ungauged Lower Burdekin subcatchment), the outflow of the Burdekin Falls Dam and the end-of-river freshwater discharge point during streamflow events over five consecutive water years (1 Oct to 30 Sept; 2005/2006–2009/2010). Site details, locations, and data history for each site are presented in Table 1 and shown in Figure 1; time series plots of streamflow hydrographs and concentration data are provided in supporting information FS01. Surface water "grab" samples (top 0.5 m of water column) were collected at these sites during flood conditions with a bucket and rope. Where possible, samples were collected over the rising, peak and falling stages of the streamflow hydrograph over multiple streamflow events that occurred each wet season. Samples were collected from the center of the channel flow where possible, and were well mixed with a stirring rod before being subsampled into prerinsed 1 L polypropylene bottles. Samples were kept on ice prior to laboratory refrigerated storage and subsequent analysis. These water samples were used to measure total suspended solids (TSS) concentrations and to calculate fine suspended sediment loads for the streamflow conditions at each site for each year sampled. We only examined the washload fractions because the delivery of fine sediments to the GBR is the focus of this study [see *Bainbridge et al*., 2012].

To increase the spatial density of data, a network of trained landholders was established to collect water samples at ungauged minor tributaries, many of which become inaccessible to external visitors during floods. Twenty-four sites were established, located as close to the bottom of each tributary catchment area as possible, at sites safely accessible to the landholder during floods (see Figure 1). Between 2004 and 2011, volunteers collected 460 water samples from the 24 sites over rising, peak and falling stages of streamflow events (supporting information Table A1). Samples collected by the volunteer network were kept refrigerated until analyzed.

3.2. Laboratory Analysis

3.2.1. Total Suspended Solids Analysis

TSS analysis was performed at the TropWATER Laboratory, James Cook University (JCU), Townsville and at the Queensland Department of Science, Information Technology, Innovation, and the Arts (DSITIA) laboratory in Brisbane using standard techniques. TSS (in mg L^{-1}) was measured gravimetrically by weighing the fraction remaining on a preweighed Whatman GF/C filter (nominally 1.2 μm pore size), dried at 103–105°C for 24 h, after vacuum filtration of a measured volume of sample (Method 2540D) [*American Public Health Association*, 2005]. We note there is a tendency for this method to underestimate the "true" suspended sediment concentration (SSC) particularly where abundant (i.e., $>$ 25%) sand particles are present [see *Gray et al*., 2000].

3.2.2. Sediment Particle-Size Analysis

A subset of water samples collected from the rising, peak and falling stages of the flood hydrograph for each of the gauged sampling sites were selected for particle-size analysis. Samples were selected from four of the study water years (2005/2006–2008/2009) where available and include a total of 274 samples. See Table 1 for site specific sample numbers and water years represented. These samples were processed from either an additional 1 L bottle collected during streamflow events, or a subsample of the original water sample. Particle-size distributions for the water samples were determined using a Malvern Mastersizer 2000, a laser diffraction particle-size analyser with a lens range of 0.02–2000 µm. The parameterization methodology of *Sperazza et al*. [2004] was applied, and all data presented are the mean of three measurement runs. Sediments were classified as one of three size classes based on the Udden-Wentworth sediment grain size scale [*Leeder*, 1982]: (1) clay ($<$ 3.9 µm); (2) very fine and fine silt (3.9–15.6 µm; hereafter referred to as fine silt); and (3) coarse silt and sand (15.6–2000 µm; hereafter referred to as coarse sediment).

3.3. Sediment Load Calculations

Streamflow and corresponding TSS data from each of the gauged locations were entered into a regression style "Loads Regression Estimator" (LRE) model developed by *Kuhnert et al*. [2012] to predict suspended sediment loads (in tonnes) with estimates of error for each subcatchment site and each water year. The LRE uses a generalized additive model (GAM) to incorporate key hydrological processes consisting of:

Table 2. Catchment-Specific Suspended Sediment Yield Contributions (tonnes km^{-2} yr^{-1}) and Mean Annual Concentration (MAC) (mg L^{-1}) During the Five Monitored Water Years (2005–2010). Sample Size for Each Site/Water Year is Shown in Italics

		Sediment Yield (t km^{-2} yr^{-1}) and Sample Size (*n*) for Each Water Year											
Major Subcatchment	Upstream Area (km^2)	2005/2006	*n*	2006/2007	*n*	2007/2008	*n*	2008/2009	*n*	2009/2010	*n*	Mean	MAC Range 2005–2010 (mg L^{-1})
Upper Burdekin	36,140	60	*12*	85	*14*	130	*15*	415	*26*	47	*8*	147	680–795
Cape	15,860	2	*7*	12	*8*	32	*30*	30	*13*	10	*115*	17	205–360
Belyando	35,055	5	*12*	4	*9*	6	*33*	3	*8*	5	*93*	5	55–650
Suttor	10,870	9	*4*	9	*7*	65	*35*	13	*8*	21	*63*	23	120–370
Burdekin Falls Dam Overflow (capturing above catchments)	114,260	3	*31*	15	*55*	27	*97*	43	*102*	4	*63*	18	81–260
Bowen	7,110	35	*49*	370	*48*	1035[a]	*43*	670[a]	*0*	540[a]	*0*	530	1780–3600
Burdekin River (end-of-catchment)	129,600	7	*23*	55	*52*	115	*53*	85	*52*	19	*47*	56	320–730

[a]Note lower confidence in the Bowen River loads (and therefore sediment yields) in the latter years with wide CV related to lack of monitoring data in these wet seasons.

1. linear and quadratic terms for streamflow;
2. the concept of higher TSS concentrations during a "first flush" and the characterization of TSS concentrations on the rise and fall of an event;
3. a discounted flow term that captures historical flows and the exhaustion of sediment supply over the flow period.

The addition of terms such as a rising-falling limb and flow discounting strengthen the predictive capability of the model, as clearly demonstrated by the improved explanatory power achieved by shifting from a simple rating curve style approach to the LRE model that includes these additional terms (supporting information Table A2). The discounting flow term provided the greatest increase in the explanatory power of the model, contributing 25–40% of deviance explained for each site. Additional terms (vegetation ground cover and ratio of flow from above and below the BFD [*Kuhnert et al*., 2012]) were included in the LRE model for the end-of-river (Inkerman) site to accommodate its size and complexity. These terms were not relevant to the subcatchment sites.

The LRE characterizes the loads through a regression modeling relationship for each site that takes into account concentration data collected over multiple water years, with the capacity to predict loads for years that have limited data. We have higher confidence in the loads calculated for well-sampled water years, with associated uncertainty ranges <5–10%. In this regard, preceding wet season TSS data sets from the Bowen River (Myuna; 2002/2003–2004/2005, 40 samples) and Burdekin River (Inkerman; 1986/1987–2004/2005, 465 samples) were utilized in the calculation of sediment loads for the water years included in this study. Importantly, the number of samples collected in our study increased throughout the monitoring program (Table 2), which coincided with larger streamflow events (see FS01), with the LRE (GAM) model developing a strong relationship for each site (with the exception of the Bowen River: see discussion). This, in turn, allowed reasonable confidence in the loads to be generated for the Belyando and Suttor subcatchments of the Burdekin despite limited sampling carried out in the 2005/2006 water year, further highlighting the benefits of applying the LRE model [*Kuhnert et al*., 2012]. The method can detect changes in annual sediment loadings due to catchment condition as the LRE model can characterize the pattern in TSS concentration using the relationship with flow and additional model explanatory terms such as seasonal/annual changes in ground cover over the entire timeframe for modelling [see *Kuhnert et al*., 2012].

The LRE model quantifies the uncertainty in the load estimate, which is reported in this paper as 80% confidence intervals [*Kuhnert et al*. 2012]. This envelope takes into account uncertainty and variability in TSS concentrations associated with the surface grab sampling field method (i.e., variations in TSS concentrations across the stream profile, subsampling), errors associated with the laboratory analysis, as well as potential errors associated with opportunistic stream gauge positioning and sampling error. See *Kuhnert et al*. [2012] for further detail on the LRE, including input data used to quantify the two errors in flow.

3.4. Catchment-Wide Discharge and Sediment Load Budgets

Catchment-wide discharge and sediment load budgets were constructed for each of the five monitored water years using streamflow and suspended sediment load data from the gauged study sites. The four gauged subcatchment sites upstream of the BFD (Upper Burdekin, Cape, Belyando, and Suttor Rivers) were used to determine individual subcatchment discharge and sediment load contributions into the dam for each water year. The ungauged Lower Burdekin subcatchment annual contributions to end-of-river export were then calculated by subtracting the BFD overflow from the Burdekin River (Inkerman) site. Contributions from the Bowen River (Myuna) site are represented within the Lower Burdekin contribution. Measurements of uncertainty for each of the sediment loads are represented as 80% confidence intervals in parenthesis after each load. Annual dam trapping estimates calculated in *Lewis et al*. [2013] have also been included within the sediment load budgets. LRE measured uncertainties in annual dam trapping estimates are also reported in parentheses, as 80% confidence intervals. Long-term mean annual discharge based on all available recorded flow years at each gauge, and a 5 year mean sediment load for each site calculated over the study period are also provided.

3.4.1. Clay, Fine Silt, and Coarse Sediment Load Budget

As sediment particle-size data were available over the first four water years (2005–2009), an additional sediment load budget was constructed using 4 year averaged sediment load contributions from each of the seven gauged sites including the proportions of clay, fine silt, and coarse sediment. This 4 year averaged budget is not summative and does not represent a complete mass balance from subcatchment source to export. However, this 4 year period covers a range of rainfall and hydrological regimes, with particle-size class contributions from each site relatively similar from year to year, particularly the ratio of the clay/fine silt component to the coarse sediment fraction (data not shown). Therefore, we contend these data are representative of longer term sediment particle-size trends within this catchment.

Clay, fine silt, and coarse sediment loads were calculated for each of these sites by the following process: (1) linear interpolation was used to calculate daily particle-size distribution for days lacking sample data provided data existed prior to and following each interpolated day; (2) the daily suspended sediment load calculated by the LRE tool was multiplied by the corresponding particle-size distribution data for that day, and then each day was summed for each water year (2005/2006 to 2008/2009); (3) these size-fractioned loadings were then scaled-up to represent each full water year using the total annual suspended sediment load for any "flow/load" period outside of the sample collection dates and (4) the clay, fine silt, and coarse sediment load fractions were then calculated for each site, as a sediment load weighted mean of the four water years. The numbers of available particle-size samples for each site are displayed in Table 1. The Bowen River (Myuna) site had a number of days where multiple samples were collected during a 24 h period. In this case, particle-size distribution data for these samples were averaged for that day.

3.4.2. Minor Tributary Volunteer Network Sites

Available TSS data for each of the ungauged minor tributary volunteer network sites were averaged over all discrete flood events and water years where water samples were collected to determine a mean TSS concentration per site. The number of wet seasons monitored for each site varied from each location depending on the occurrence of flood events in any given wet season (i.e., wetter versus drier years) and the availability of the landholder to collect samples during such events (see supporting information Table A1). Load-based mean annual concentrations (MAC) for each of the end-of-subcatchment gauged sites from 2005 to 2010 were also calculated for context with the ungauged minor tributary volunteer network sites located within these subcatchments. A Burdekin-wide mean TSS concentration was also calculated using compiled TSS data from all Burdekin minor tributary and gauged subcatchment locations.

3.5. Sources of Error

Although the sampling techniques applied capture the clay and fine silt sediment fractions of interest in this study, the collection of water samples at the surface may miss the sand fraction transported as suspended, bed and saltation load, resulting in underestimates of this fraction. In an attempt to quantify uncertainties in field collection and laboratory analysis, experimental cross-section transect samples were collected at each gauged site (e.g., triplicate water samples collected at the left bank, center, and right bank of each stream channel). These data confirmed that the surface of each river was laterally well-mixed in relation to TSS concentrations, providing confidence in the surface grab sampling approach and the laboratory methodology; on average, each individual set of triplicate TSS samples were within 10% (RSD). Further statistical analysis of the data show the variation in TSS concentrations across the stream profiles was not significant (see supporting information section). This variability in TSS concentration measured through our stream profiles has been incorporated into the LRE model, and contributes to the uncertainty in each load estimate. *Belperio* [1979] showed the clay and fine silt fractions were well mixed through the water column during flood flows in the Burdekin River, which further confirm the robustness of our sampling approach for the clay and silt fractions; however, we acknowledge that the grab sampling technique may result in the sand-sized fraction being significantly underestimated.

4. Results

4.1. Catchment-Wide Discharge and Sediment Load Budgets

4.1.1. Subcatchment Contributions to Total Catchment Discharge

Two of the largest discharge years on the 91 year record at the end-of-river stream gauge occurred during this study, including the 2007/2008 (27.5 million ML, sixth largest) and 2008/2009 (29.4 million ML, fourth largest) water years. In both water years catchment discharge exceeded three times the mean annual discharge (see Figure 3a). During the 2007/2008 water year, streamflow in all major subcatchments far exceeded mean annual discharge, including 6.2 million ML and 5.9 million ML from the Upper Burdekin and Suttor subcatchments above the BFD, respectively, and an estimated 9.5 million ML from the ungauged Lower Burdekin (Figure 3b). Overflow from the BFD (18 million ML) dominated end-of-river discharge, with minimal retention of water from the subcatchments above the BFD.

Streamflow from the Upper Burdekin subcatchment dominated total Burdekin River discharge volume for the 2008/2009 water year, with a near-record 20 million ML (Figure 3b). Approximately 35% of the total annual discharge during 2008/2009 occurred in the 6 days following Tropical Cyclone Ellie's path through the upper catchment, and 90% of all discharge in the 2008/2009 water year occurred during the two wet season months January and February, 2009 (Bureau of Meteorology, www.bom.gov.au/cyclone/history/index.shtm). The Cape (2.30 million ML) and Bowen (1.38 million ML) Rivers also experienced above average discharge in 2008/2009 (Figure 3b). Similarly to 2007/2008, end-of-river discharge was dominated by the catchments above the BFD. Discharge in the 2006/2007 and 2009/2010 water years were comparable to average annual discharge volumes (Figure 3a). The 2005/2006 water year was well below average across the entire Burdekin catchment, with an annual discharge of just 2.2 million ML. The BFD was well below capacity at the start of this wet season due to drought, allowing around 40% of inflow from upstream subcatchments to be captured (Figure 3a).

4.1.2. Subcatchment Contributions to Total Catchment Sediment Export

Application of the LRE model indicates that the Upper Burdekin subcatchment was the source of between 76 and 95% of suspended sediment influx to the BFD over each water year from 2005/2006 to 2009/2010 (Figure 3). In comparison, the Cape, Belyando, and Suttor subcatchments each contributed between just 1 and 11% of the suspended sediment loads delivered to the dam during each of the monitored water years. Suspended sediment trapping within the BFD ranged from 50 to 85% over the five water years, with the highest trapping occurring in 2005/2006 (85%) and 2009/2010 (82%) [*Lewis et al*., 2013]. In both of these years, similar sediment load inputs and export from the dam occurred (Figure 3). During the 5 year study period, the Lower Burdekin subcatchment area contributed 55–82% to the end-of-river suspended sediment export. The bulk of this sediment was derived from the Bowen River (7110 km^2 at Myuna gauge), which includes approximately 50% of the total Lower Burdekin subcatchment area (Figure 3).

4.2. Subcatchment Annual Sediment Yields

The Bowen River had the largest annual sediment yield of all Burdekin subcatchments when sediment loads were normalized to catchment area, with a mean annual yield of 530 t km^{-2} yr^{-1} over the five water years (Table 2). The mean annual sediment yield from the Upper Burdekin subcatchment, five times the size of the Bowen subcatchment, was 147 t km^{-2} yr^{-1}; with the highest yield (415 t km^{-2} yr^{-1}) occurring during the above average 2008/2009 water year. Sediment yields from the Cape, Belyando, and Suttor subcatchments were markedly lower, with the study period means ranging between 5 and 23 t km^{-2} yr^{-1} (Table 2). An exception occurred in the Suttor subcatchment during the wet 2007/2008 water year which resulted in a sediment yield of 65 t km^{-2} yr^{-1}.

4.3. Minor Tributary Hot-Spot Sources

Site-averaged TSS concentrations over the study period ranged from 115 to 4075 mg L^{-1} across the minor tributary volunteer network sites, providing a reliable indication of sediment source or hot spot areas to

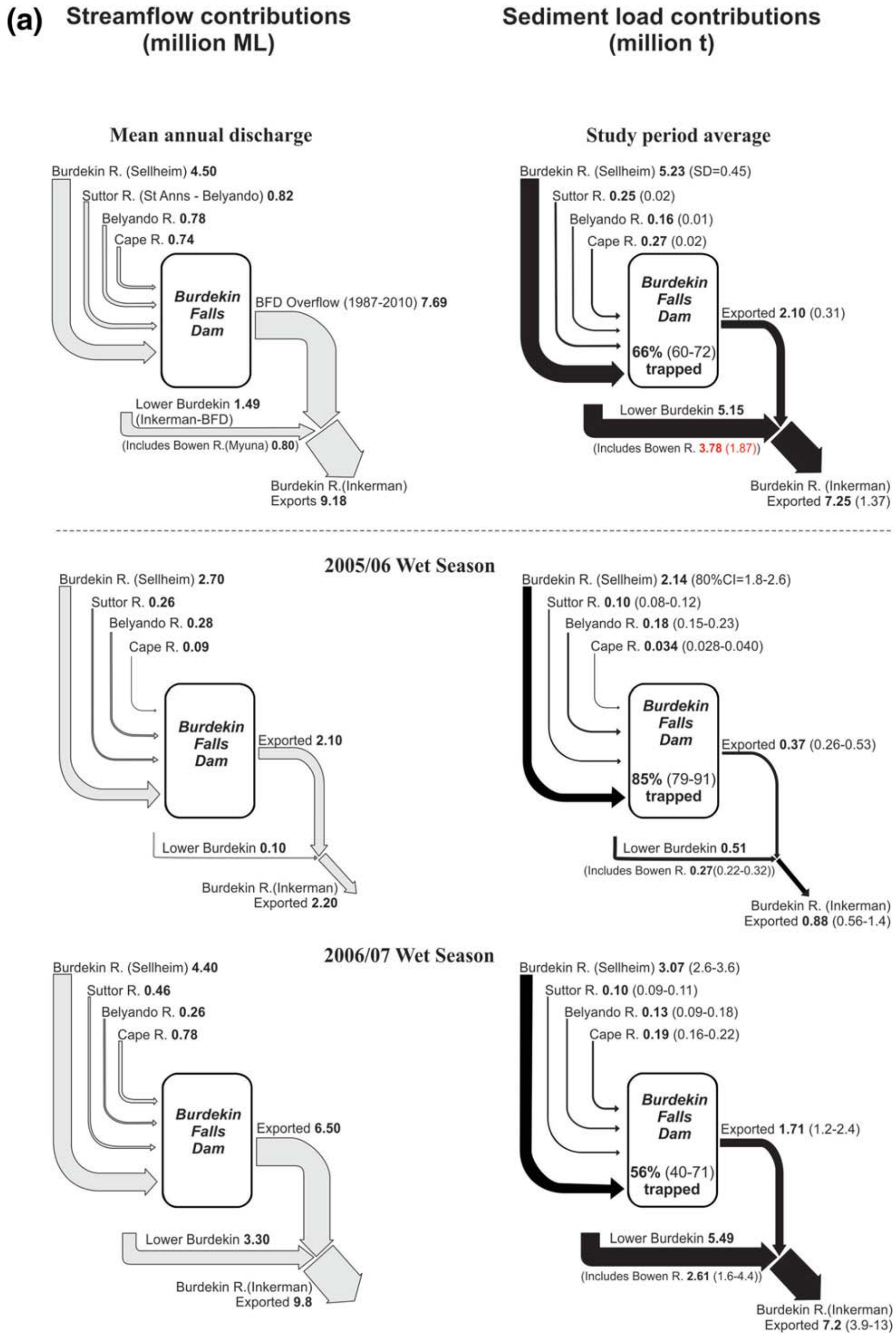

Figure 3. (a and b) Streamflow (left) and suspended sediment (right) budgets for the Burdekin River catchment over five monitored water years 2005/2006 to 2009/2010. Arrows represent the respective contributions from each of the Burdekin River major subcatchments, the Burdekin Falls Dam spillway, Lower Burdekin (includes a contribution from the gauged Bowen River), and end-of-river export (Inkerman), where the width of each arrow indicates contribution size. Each load estimate in million tonnes is accompanied by 80% confidence intervals as a measure of uncertainty. Four of the major subcatchments flow into the Burdekin Falls Dam, and an estimate of suspended sediment trapped within this reservoir is also represented (% trapped accompanied with 80% CI) for each water year, as reported in *Lewis et al*. [2013]. The Lower Burdekin subcatchment contribution is calculated by subtracting the BFD overflow discharge/sediment load from the end-of-catchment (Inkerman) discharge/sediment load. The Bowen River loads in the 2007/2008, 2008/2009, and 2009/2010 water years have low confidence due to a lack of monitoring data available for this site in the latter years. Mean annual discharge (long-term based on available flow data at each gauge) and a 5 year mean sediment load (including SD in brackets) for each site over the study period are also shown.

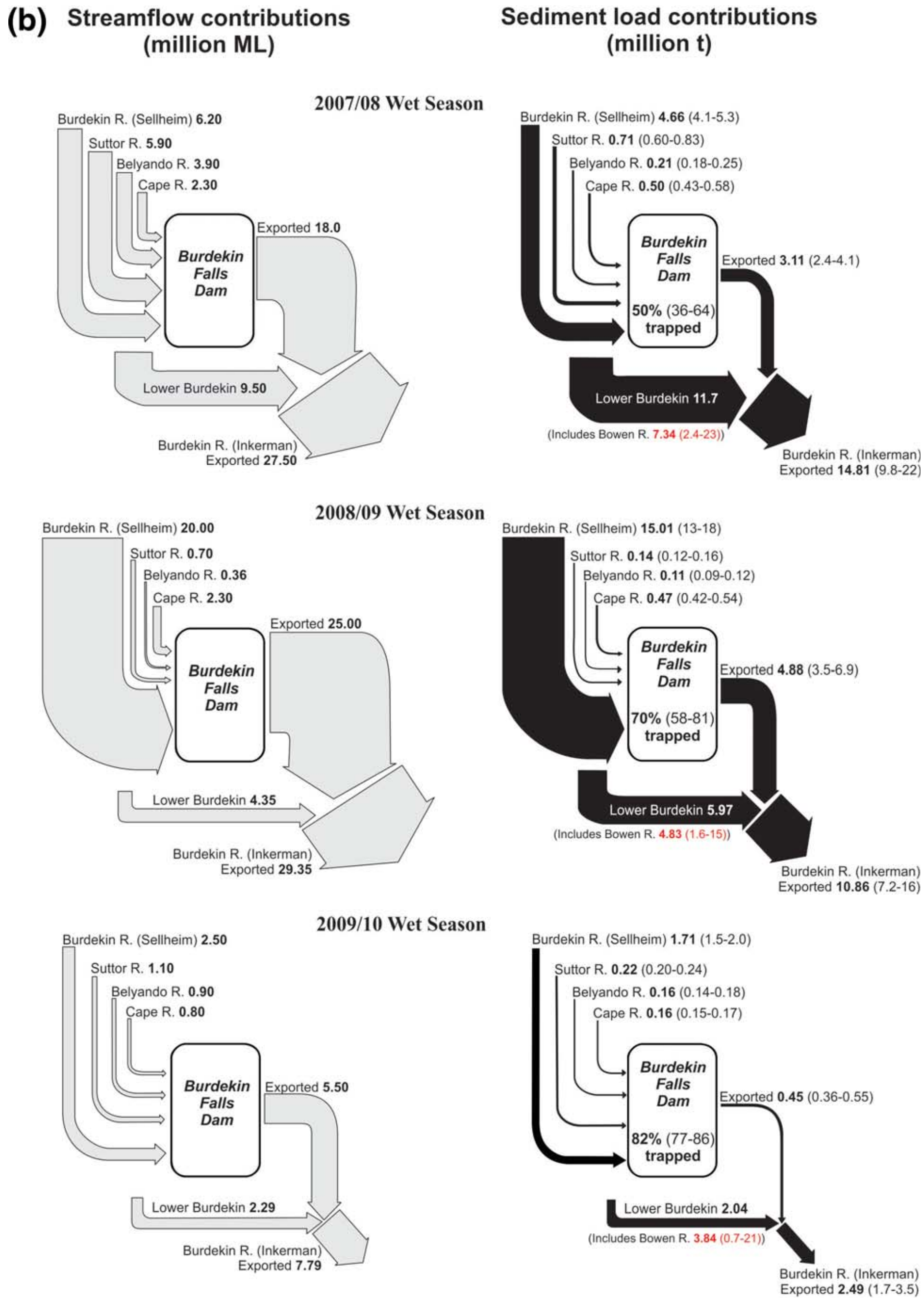

Figure 3. (continued)

target remedial efforts (Figure 5). The tributaries with the highest mean TSS concentrations were observed within the Upper Burdekin and Bowen subcatchments, reflecting the large sediment load contributions from these two subcatchments (subsection 4.1). The Dry River and Camel Creek tributaries of the Upper Burdekin subcatchment had the highest average TSS concentrations across the entire Burdekin (3395 and 4075 mg L^{-1}, respectively) (Figure 5). These sites are located in the northern area of this subcatchment, and all monitored tributaries in this region had elevated TSS concentrations including Grey Creek (2465 mg L^{-1}) and the Clarke River (1230 mg L^{-1}); the Clarke River is the largest tributary ($\sim$6400 km^2) draining into the Upper Burdekin River (Figure 5). The other tributaries of the Upper Burdekin had much lower TSS concentrations, particularly Fletcher Creek (130 mg L^{-1}) within the basalt country and the two eastern tributaries that drain the wet coastal range, the Star and Running Rivers (210 and 235 mg L^{-1}, respectively). The 5 year

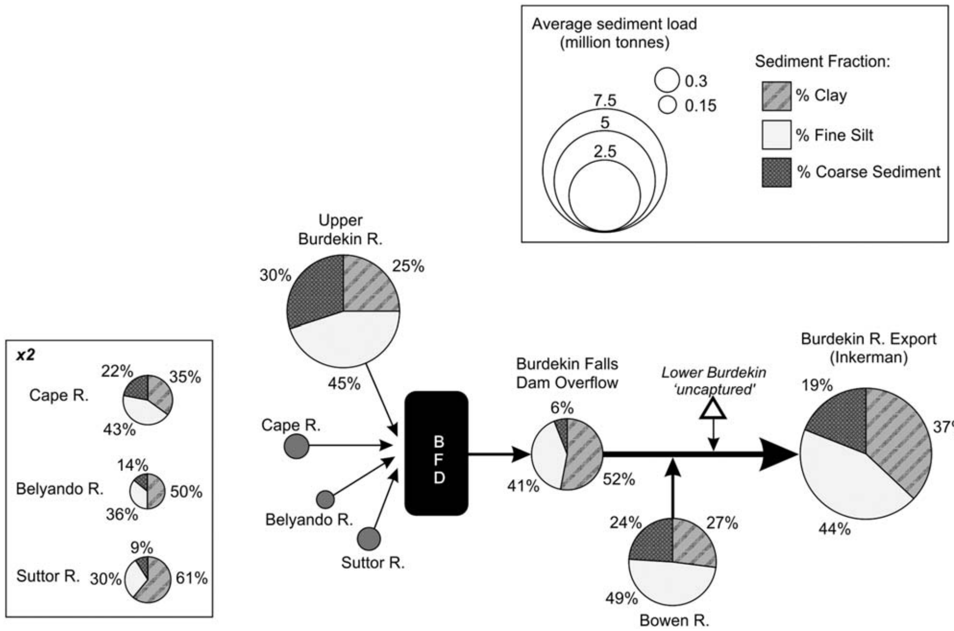

Figure 4. Four year (2005–2009) mean suspended sediment load contributions from each of the major subcatchments (Upper Burdekin= 6.22 million tonnes; Cape= 0.30 Mt; Belyando= 0.16 Mt; Suttor= 0.26 Mt, Bowen= 3.76 Mt), Burdekin Falls Dam (2.52 Mt), and end-of-river export (Inkerman= 8.44 Mt), with volume (million tonnes) represented by circle area. The proportions of clay, fine silt, and coarse sediment fractions contributed by each of these sites are also shown, within each circle. A triangle denotes an "uncaptured" sediment load (2.16 Mt) contributed to the end-of-river from the ungauged component of the Lower Burdekin subcatchment.

average mean annual concentration (MAC) for the Upper Burdekin (735 mg L^{-1}) was below the Burdekin-wide average of 980 mg L^{-1}.

In comparison, the Belyando, Suttor, and Cape River subcatchments all had lower end-of-catchment MAC's (335, 220, 245 mg L^{-1}, respectively), despite elevated TSS concentrations in some tributaries of the Belyando and Suttor subcatchments, including the Carmichael (1100 mg L^{-1}), upper Belyando (925 mg L^{-1}), and upper Suttor (850 mg L^{-1}) Rivers. All sites in the Bowen River tributary had elevated concentrations compared to the Burdekin-wide average, except for the small (36 km^2) rainforest headwater site on the upper Broken River (115 mg L^{-1}). The Little Bowen River had the highest average TSS concentration (3270 mg L^{-1}) within the Bowen. The gauged site (Myuna) had the highest 5 year average MAC of the five Burdekin subcatchments (2880 mg L^{-1}; Figure 5). The Bogie River, the second largest tributary of the Lower Burdekin had below average TSS concentrations at both upper (305 mg L^{-1}) and lower (510 mg L^{-1}) locations (Figure 5).

4.4. Clay, Fine Silt, and Coarse Sediment Load Budget

The clay and fine silt sediment fractions (<16 μm) dominated ($>70\%$) suspended sediment at all Burdekin subcatchment sites over the four water years (2005–2009) where sediment particle-size data were available (Figure 4). The Upper Burdekin subcatchment was the dominant (90%) source of all clay, fine silt, and coarse sediment fraction loads into the BFD (Figure 4). Minor sediment load contributions into the dam from the other three upstream subcatchments were dominated (78–91%) by the clay and fine silt fractions; with the clay-only component dominating the sediment fraction contributed by the Belyando (50%) and Suttor (61%) subcatchments (Figure 4). The efficiency with which different particle-size fractions are trapped within the BFD was considered by *Lewis et al*. [2013], but they did not directly report the specific trapping of the clay and fine silt-sized fractions. Our reanalysis of these data averaged over the four water years show that 31% of the clay, 66% of the fine silt, and 92% of the coarse sediment fractions were trapped by the BFD, with an overall average trapping efficiency of 66% (Figures 3 and 4). The BFD overflow and Bowen River subcatchment sites contributed a similar clay load of 1.32 and 1.03 million tonnes, respectively, to the end-of-river over the 4 year average (Figure 4). Export at the end-of-river was dominated (81%) by the clay and fine silt sediment fractions (Figure 4).

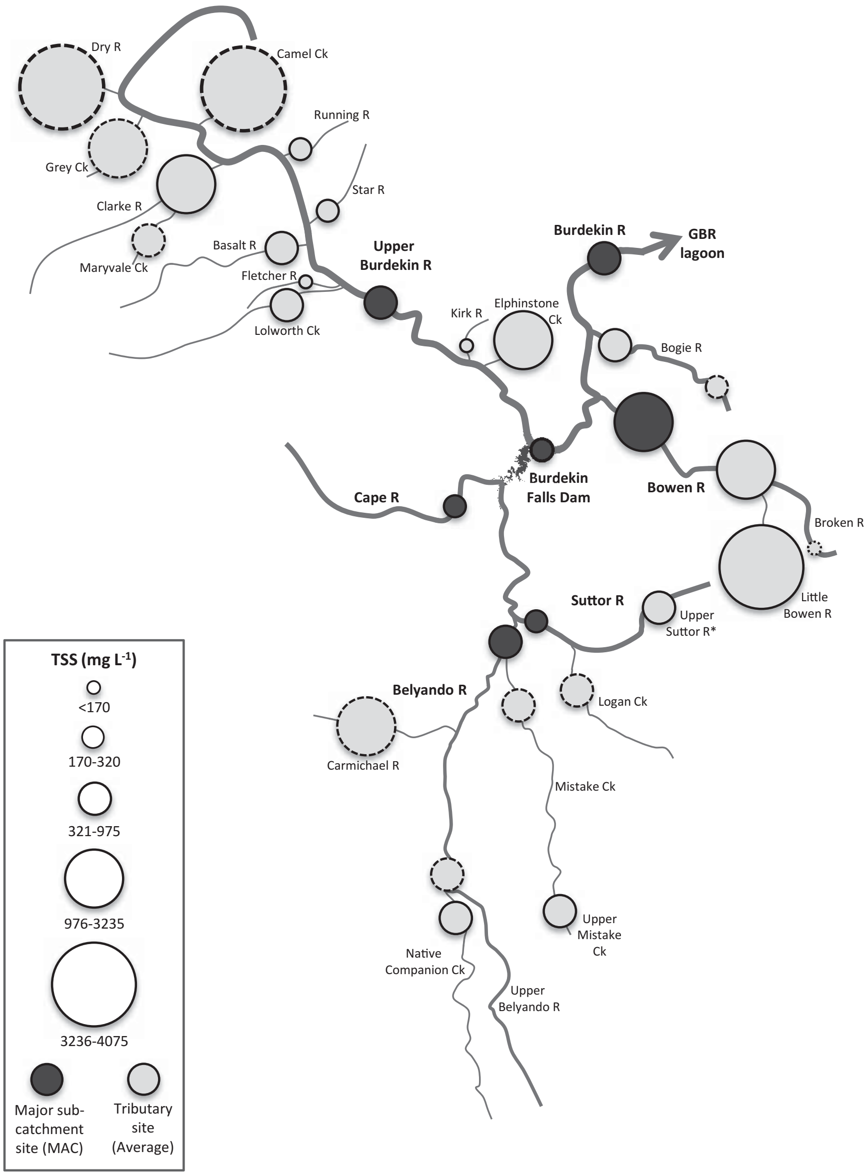

Figure 5. Average suspended sediment concentration (light gray circles) for each tributary network site across the Burdekin over seven water years (2004–2011) of data collection. Load-based mean annual concentrations (MAC) for the seven gauged sites (2005–2010) are also displayed for reference, shown as dark gray circles. Circle size represents the mean/MAC TSS concentration in mg L^{-1} for each site, with the sizing scale representing increasing TSS concentration based on percentiles (<10%, 10–30%, 30–70%, 70–90%, and >90%) of all site averages. Dotted circles indicate lower data confidence, with either <3 wet seasons monitored or <20 TSS samples collected in total. *Samples collected 2002–2003 to 2008/2009.

5. Discussion

5.1. Catchment-Wide Discharge and Sediment Load Budgets

The Upper Burdekin subcatchment was the dominant source of streamflow to the end-of-river over the five water years (Figure 3). *Roth et al*. [2002] calculated that the Upper Burdekin on average contributes 50% of total annual end-of-river discharge despite comprising only ~30% of the Burdekin catchment area, suggesting the flows measured in the study period are representative of longer term patterns. The study period captured below average, average, and above average discharge years in all Burdekin subcatchments (Figure 3). This included the largest gauged annual discharge recorded for the Belyando River (2007/2008; recurrence interval (RI) =58) and second largest for the Upper Burdekin (2008/2009; RI=33). Very little discharge from subcatchments upstream of the BFD was trapped in the reservoir during the study period, except for

2005/2006, when drought had reduced reservoir water levels to ~60% of capacity (Figure 3a). Otherwise the dam was almost full prior to each wet season; despite its considerable volume (1.86 ML), full capacity is <6% of the average annual inflow. BFD overflow waters were the primary source (i.e., 65–95%) to end-of-river discharge over the study period, with the remainder contributed from the Lower Burdekin subcatchment, including the Bowen River (Figure 3).

An important finding of this study is that the Upper Burdekin is the dominant sediment source to the BFD under all streamflow conditions, contributing 76–95% of the total sediment influx in each of the five water years studied. The Cape, Belyando, and Suttor subcatchments each contributed only 1–11% of the total sediment load into the dam in any water year during the study period (Figure 3). The contrast between the Upper Burdekin and these other subcatchments was greatest in the 2007/2008 water year when the Belyando and Suttor subcatchments combined contributed ~54% of total inflow into the dam due to above average events across their catchment areas, but contributed only 15% of the total sediment load (0.92 million tonnes) into the dam (Figure 3b). In comparison, the Upper Burdekin contributed 4.66 million tonnes, or 77% of the sediment load into the BFD, while contributing only ~33% of total inflow (Figure 3b). The BFD reservoir trapped an average of 66% (80% CI = 60–72) of annual suspended sediment influx over the five study years (Figure 3; *Lewis et al*., 2013]. The dominance of the Upper Burdekin subcatchment as a major sediment source to end-of-river export has been diminished by the construction of this reservoir and its sediment trapping efficiency. Assuming equal trapping of sediment within the reservoir contributed from all upstream subcatchments, the Upper Burdekin contributed ~14–43% to annual end-of-river sediment export during this study period. The Lower Burdekin subcatchment, including the Bowen River, is now the major sediment source, despite representing only 12% of the entire Burdekin catchment area (Figure 3). The Bowen River contribution to end-of-river sediment export ranged from 31–50% over the study period, representing 48–81% of the Lower Burdekin subcatchment contribution (Figure 3). However, these Bowen River contributions do not include the 2009/2010 water year due to a high uncertainty in the load estimate; high uncertainties for the Bowen River were also calculated for the 2007/2008 and 2008/2009 load estimates (see load estimates in red, Figure 3b). The high uncertainties result from a lack of TSS concentration data available during these above average discharge years and the difficulties developing discharge-TSS concentration relationships using TSS data collected only in below average and average water years. In particular, TSS data were not available for the largest streamflow event in the above average (RI=13) 2007/2008 water year (see supporting information FS01f). Uncertainties in the Bowen load outputs in this study highlight the importance of (1) prioritising critical water quality monitoring sites to inform management decision-making and (2) prioritizing the capture of larger discharge events in sampling regimes for more precise load calculations.

Our results demonstrate the importance of measured stream TSS concentration and flow data to accurately estimate loads and source areas of suspended sediment in comparison to catchment modeling-only studies. The study of *McKergow et al*. [2005] [see also *Brodie et al*., 2003] based on the SedNet model showed delivery of a large proportion of the suspended sediment from a small proportion of the catchment, although their findings were limited to an assessment of the entire GBR catchment area (i.e., no specific numerical data for the Burdekin catchment were presented). Furthermore inaccurate and unrealistic assumptions in the modeling approach at the time, such as overestimates of dam trapping [see *Lewis et al*., 2013] and underestimates of gully and stream bank erosion [see *Wilkinson et al*., 2013] are now known to have produced poor estimates of actual subcatchment spatial sources of suspended sediment. In contrast, our study using measured field data for suspended sediment and particle size provides far more accurate estimates which can be compared and used to calibrate recently improved modeling estimates using the Source Catchments model and updated versions of SedNet [*Wilkinson et al*., 2014].

5.2. Subcatchment Annual Sediment Yields: A Comparison With Other Tropical River Studies

End-of-river sediment yields for the Burdekin are low (<115 t km^{-2} yr^{-1}) when compared to published yields from other tropical catchments around the world (Table 3). Most catchment studies across the tropical belt have been conducted in wet tropical rainforest (*Af*), monsoon (*Am*), and savannah (*Aw*) climates [*Peel et al*., 2007] within South America and South-East Asia, where annual rainfall typically exceeds 2000 mm y^{-1} and yields exceed 500 t km^2 yr^{-1} (Table 3). Although the Burdekin catchment is defined largely as semiarid (*Bsh*), it is the higher rainfall and steeper terrain of the coastal areas (*Aw* and *Cwa*) that are the primary hydrological drivers of this catchment; climatic conditions that position it somewhere

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Table 3. Comparison of Burdekin Sediment Yields (Bold Type) With Other Tropical River Sediment Studies

Wet or Dry Tropical Climate	Köppen Climate Classification [*Peel et al.*, 2007]	Mean Annual Rainfall (mm yr^{-1})	Study Location	River	Study Reference	Upstream Catchment Area (km^2)	Dominant Land Use	Average Annual Sediment Load (Million tonnes yr^{-1})	Annual Sediment Load for Study Period (Mt)	Sediment Yield (t km^{-2} y^{-1})
Wet	*Af* Tropical rainforest	3200	Ecuador/Peru, South America	Napo River, Amazon basin	*Laraque et al.* [2009]	26,860/100 520	Forest	-	26,860 km^2: 22.6 Mt (2002–2005) 100 520 km^2: 46 Mt (2004/2005)	463–998
Wet	*Af, Am, Aw* Tropical rainforest, monsoon, savannah	2050 (basin-wide mean variation 1200–3100)	Columbia, South America	Magdalena River, Andes	*Restrepo and Kjerfve* [2000]	257,440	Agriculture, forest	143.9 Mt yr^{-1} (1975–1995)	-	560
Wet	*Af* Tropical rainforest	2500	Indonesia, SE Asia	Upper Way Besai catchment, West-Lambung, Sumatra	*Verbist et al.* [2010]	6.7–360	Coffee, forest, paddy rice	-	-	110–1730
Wet	*Am* Tropical monsoon climate	2765	Borneo, SE Asia	Baru catchment	*Chappell et al.* [2004]	0.44	Forest, selective logging	-	0.00026 Mt (12 months to 30 Jun 1996)	592
Wet/Dry	*Aw* Tropical savannah (wet and dry)	2125–2700	Indonesia, SE Asia	Upper Konto catchment, East Java	*Rijsdijk* [2005]	233	Natural forest, agroforestry (steep area), intensive agriculture, rice (lower parts)	-	0.29 Mt (average of 1988–1989) *includes bed load	1,200
Wet/Dry	*Cwa* Humid Subtropical	1600	Vietnam, SE Asia	Red River watershed, China, Laos, Vietnam	*Ha Dang et al.* [2010]	169,000	Forestry/natural forest, agriculture	90 Mt yr^{-1}	24–200 Mt (1960–2008)	600
Wet/Dry	*Aw* tropical savannah (wet and dry)	800–1360	India (draining east into Bay of Bengal)	Eight tropical (Peninsular) river basins	*Panda et al.* [2011]	35,000–313,000	Agriculture, forest	1.5–170 Mt yr^{-1} (1986 - 2006)	-	17–704
Wet/Dry	*Aw* tropical savannah; *BSh* Hot semi-arid	250–3500	Kenya, Africa	Multiple catchments, southern Kenya	*Dunne* [1979]	<2,000	Forest, rangeland, agriculture	-	-	20–200
Dry	*BSh* Hot semiarid	600	Ethiopian highlands, Africa	May Zeg-zeg, Tigray, north Ethiopia	*Nyssen et al.* [2009]	1.87	Agriculture, exclosure, rangeland, grassland	-	0.00036 Mt (2006)	190
Dry	**Predominately *BSh* Hot semiarid, coastal areas *Aw/Cwa***	**500–2500**	**Australia**	**Burdekin River, north Queensland**	***This study; Kuhnert et al.*, [2012]**	**133,400**	**Grazing**	**3.93 Mt yr^{-1}**	**0.88–14.81 Mt (range 2005–2010 water years)**	**7–114**
Dry	*BSh* Hot semiarid	630 (basin-wide mean variation 530–2000)	Australia	Fitzroy River, neighboring basin	*Packett et al.* [2009]	142,600	Grazing, dryland cropping	-	0.03–4.24 Mt (range 1994–1998 and 2002–2008)	0.23–30

between these wet tropical climates and the more temperate semiarid or "dryland" regions [see *Tooth*, 2000]. Indeed, sediment yields from the Bowen River reflect its wet coastal location, particularly in 2006/2007, 2007/2008 and 2008/2009 where mean annual discharge (0.80 million ML) was well exceeded (1.03, 2.49, and 1.38 million ML, respectively). Bowen sediment yields (370–1035 t km^{-2} yr^{-1}) in these years are comparable with rates generated in much wetter tropical rainforest studies of the Andes [*Restrepo and Kjerfve*, 2000] and NW Amazon basin [*Laraque et al*., 2009] in South America, and Borneo [*Chappell et al*., 2004] and northern Vietnam [*Ha Dang et al*., 2010] in South-East Asia (Table 3). In contrast, sediment yields generated from all other Burdekin subcatchments and the end-of-river are more comparable to those generated in north-eastern Africa and India [*Dunne*, 1979; *Nyssen et al*., 2009; *Panda et al*., 2011], where wet-dry tropical conditions also prevail (i.e., high variability, rare but extreme runoff events). Thus data generated in this study and the sediment budget approach utilized might be most applicable for use in such climatic regions, where limited sediment sourcing and yield studies have been conducted.

5.3. Minor Tributary Hot-Spot Sources

Across the Burdekin subcatchments variations in sediment load contributions are driven by their varied topography, geology, rainfall, and vegetation. The Upper Burdekin and Bowen subcatchments have steep terrain, with highly incised river channels (>18 m channel depths) that are highly efficient in streamflow and sediment transport [*Fielding and Alexander*, 1996; *Roth et al*., 2002]. The tributaries with the highest average TSS concentrations are located within these two subcatchments, including the north-western region of the Upper Burdekin, a relatively steep landscape hosting old sedimentary rock deposits prone to erosion. Tributaries monitored in this region include the Dry and Clarke Rivers, and Camel and Grey Creeks (Figure 5). The Little Bowen River was also identified as a hot-spot within the Bowen River subcatchment, with large areas of exposed soils and gullying, also containing old sedimentary rock deposits, and TSS concentrations peaking >10, 000 mg L^{-1} in both 2006/2007 and 2008/2009. Recent sediment tracing by *Wilkinson et al*. [2013] also identifies the Little Bowen River as a major sediment source, together with large areas of gully erosion immediately upstream of the Myuna gauge. Tributaries within both the Bowen (Broken River) and Upper Burdekin (Star and Running Rivers) subcatchments with coastal rainforest headwaters contribute considerable streamflow to the end of each subcatchment, but have low sediment concentrations compared to other tributaries within these subcatchments (Figure 5). For example, the Star and Running Rivers contributed ~30% of Upper Burdekin discharge in the 2005/2006 water year, but only ~3% of the total sediment load exported by this subcatchment. The tributaries draining these wetter coastal catchments are naturally forested with different geology types to the western tributaries of the Upper Burdekin and Bowen subcatchments which are less densely vegetated and widely composed of weathered and erodible lithologies (Figure 2).

In contrast, the south-western Cape, Belyando, and Suttor subcatchments have low relief, expansive anastomosing floodplains (overbank flooding at gauged site depths of 8, 8, and 4.5 m, respectively), less stream power for entraining coarser material, and greater opportunity for sediment deposition before it is exported from these subcatchments. Thus, although the steeper headwater tributaries within these western subcatchments produce high sediment concentrations (e.g., Carmichael and upper Suttor Rivers), mean end of subcatchment yields remain low (<23 t km^{-2} yr^{-1}) compared to the Upper Burdekin (147 t km^{-2} yr^{-1}) and Bowen (530 t km^{-2} yr^{-1}) subcatchments (Table 2), both of which have greater sediment availability and transportability.

5.4. Clay, Fine Silt, and Coarse Sediment Load Budget

Suspended sediment loads exported by all Burdekin subcatchment sites were dominated by the clay (<4 μm) and fine silt (4–16 μm) sediment fractions over the four water years 2005/2006 to 2008/2009 (Figure 4). As noted in the methods, the coarser sand fraction may be underestimated in our results. Clay, fine silt, and coarse sediment loads into the BFD were all dominated by the Upper Burdekin subcatchment, including 4.35 million tonnes of clay and fine silt per year on average over this 4 year period. In comparison, the Cape, Belyando, and Suttor subcatchments combined contributed an average of 0.60 million tonnes of clay and fine silt per year (Figure 4). Although the BFD traps an average of 66% of incoming sediment and considerably reduces sediment delivery to the end-of-river from these four upstream subcatchments, it is the coarser sediment fraction that is preferentially trapped. As a result, the clay-sized fraction dominates all sediment carried over the dam spillway [Figure 4; *Lewis et al*., 2013]. While the Bowen River was a much larger source of suspended sediment loads to the end-of-river when compared to the BFD source, the mean particle size specific loads over this period reflect the increasing proportional importance of the BFD source with respect to the contribution of fines to the end-of-river. Indeed the proportional contribution from the Bowen River to BFD source reduces from 1.5:1.0 for the bulk sediment fraction (3.76 and 2.52 million tonnes from the Bowen River and BFD sources, respectively), to 1.2:1.0 when the combined clay and fine silt fractions are considered (i.e., 2.86 and 2.36 million tonnes, respectively) and further to 0.8:1.0 when the clay-only fraction is considered (1.03 and 1.32 million tonnes, respectively). However, the clay-only sediment yield from the smaller Bowen River tributary (145 t km^{-2} yr^{-1}) is 10-fold higher compared to the BFD overflow source (11 t km^{2} yr^{-1}).

Despite the influence of the BFD in reducing sediment export from the sizable upstream catchment area, and the increased importance of the Lower Burdekin subcatchment area as the major sediment source, management efforts targeting the finer sediment fractions still need to consider this large source area above the BFD. Further geochemical and clay mineralogy tracing analyses may also highlight the relative importance of apparent minor sediment sources such as the Belyando and Suttor Rivers, which contribute almost exclusively the clay and fine silt fractions (86% and 91%, respectively, Figure 4). Waterholes within these two subcatchments are constantly turbid [*Burrows et al*., 2007], and fine dispersible clay particles are known to be contributed to the BFD by the Suttor arm [*Fleming and Loofs*, 1991], with the reservoir often remaining turbid long after flood conditions recede (*Z. T. Bainbridge,* personal observation, 2005-2010; *Fleming and Loofs*, 1991; *Griffiths and Faithful*, 1996]. Such tracing may discriminate these dispersive clay types from other potential clay sources across the Burdekin and determine which clay mineral types are preferentially transported through the catchment and further into the adjacent marine environment. A further research gap is the quantification of the relative contributions of suspended clays washed as surface runoff into tributaries compared to those yielded from lower in the soil profile by gully and stream bank erosion; this quantification will help to further target erosion management efforts. Recent research has identified these subsurface erosion processes as major sediment sources in the larger Australian tropical catchments, including the Burdekin, under current climatic and land management conditions (see reviews by *Caitcheon et al*. [2012] and *Bartley et al*. [2014]).

5.5. Burdekin River Discharge and Sediment Export to the GBR Lagoon

Above average discharge across the Burdekin subcatchments in the 2007/2008 and 2008/2009 water years resulted in total Burdekin discharge to the GBR lagoon that were three times the mean annual discharge, and are ranked as the sixth (2007/2008) and fourth (2008/2009) largest years on record (Figure 3b). These wetter years were followed by the third largest discharge year on record in 2010/2011 (34.8 million ML), which saw an extended period of river discharge into the GBR lagoon for $\sim$200 days [*Bainbridge et al*., 2012]. This study has fallen within a “wet cycle” in the longer term interdecadal cycling of wet and dry conditions in the Burdekin, where rainfall and streamflow trends coincide with the Pacific Decadal Oscillation [*Lough*, 2007]. The current wet conditions followed a period of drought in the mid late 1990’s/early 2000’s and preceding wetter cycles in the 1950’s, 1970’s and the late 1980’s/early1990’s. Reconstructed streamflow using coral luminescence showed an increase in the cyclic variability of rainfall and streamflow in the 20th century, as well as the extent of both wet and dry conditions [*Lough*, 2007]. The tight cluster of very wet years highlighted in this study are projected to occur more regularly as climate change progresses [*Lough*, 2007], increasing the frequency and volume of terrestrial sediment discharged to the inshore GBR.

As part of a broader research effort focused on managing Burdekin River export to the GBR lagoon, *Kuhnert et al*. [2012] calculated annual Burdekin suspended sediment export using the Loads Regression Estimator (LRE) on 24 years of available suspended sediment data (1986–2010). This data analysis incorporated key controlling features of Burdekin sediment export including covariates representing (1) ratio of streamflow sourced from above the BFD, and (2) annual dry season vegetation ground cover figures, representing the influence of cover on sediment erosion [*Kuhnert et al*., 2012]. Using these explanatory terms, they were able to produce an average load of 3.93 (80% CI=3.41–4.45) million tonnes, with tight uncertainty bounds representing errors associated with the input data, thus providing resource managers with our current best estimate of present day Burdekin sediment export. When compared to this study period, three of the five water years far exceeded this long-term average, including 7.2 million tonnes in 2006/2007, 14.81 million tonnes in 2007/2008, and 10.86 million tonnes in 2008/2009 (Figure 3), illustrating the variability of suspended sediment export from this river catchment and the influence of wetter climatic cycles.

The influence of drought breaking years and sediment supply availability on Burdekin River annual suspended sediment export has also been highlighted in this study. For instance, end-of-river export was ~30% greater in 2007/2008 than 2008/2009, despite both water years having discharges of similar volumes; 27.50 and 29.35 million ML, respectively. The earlier year had a larger sediment contribution from the catchment area below dam, with higher sediment yields per unit area (Table 2). The Burdekin has been described as a supply-limited catchment [*Amos et al*., 2004] and given that above average discharge occurred across the entire catchment in 2007/2008 (Figure 3), it is also likely there was a depletion in available sediment supply for runoff in the subsequent year. Previous studies have highlighted the increased sediment loads delivered during drought-breaking floods [*Mitchell and Furnas*, 1996; *McCulloch et al*., 2003; *Amos et al*., 2004], which was also observed in this study with a drought breaking flood year in 2006/2007 which followed a series of relatively dry years, including 2005/2006 (Figure 3). Total discharge in the 2006/2007 and 2009/2010 water years were similar to average annual discharge, however, the sediment load exported in 2006/2007 (7.2 million tonnes) was double the annual average and three times greater than the sediment load exported in 2009/2010 (2.49 million tonnes; Figure 3). The 2009/2010 sediment load also reflects the depleted sediment supply after the two record flood years, and improved ground cover across the entire catchment resulting from this wetter period, which results in decreased soil loss [*Bartley et al*., 2014]. Indeed *Kuhnert et al*. [2012] found a significant decrease in sediment loads at the end-of-river site as ground cover increases.

5.6. Implications for Great Barrier Reef Management

The Upper Burdekin and Bowen River subcatchments have the highest suspended sediment yields of all Burdekin subcatchments and were the major sediment sources during this study. Their wetter coastal locations, steeper topography, and weathered geology result in high streamflow and sediment transport efficiency. The Upper Burdekin is the major source of discharge to both the BFD and end-of-river, and the dominant source of all sediment fractions (i.e., clay, fine silt and coarse sediment) into the BFD. The BFD reservoir is an efficient sediment trap, and has reduced the suspended sediment load supplied from the large upstream catchment area (88% of the entire catchment) to end-of-river export, including the Upper Burdekin source. The reservoir has also influenced the sediment-size fractions transported from this upstream catchment area, with the finer clay fraction now dominating all sediment exported over the dam spillway to the river mouth and adjacent GBR lagoon. This study identified the Bowen River as the major source of end-of-river suspended sediment export. This catchment has a comparatively small upstream area and the highest sediment yields (mean of 530 t km^{-2} yr^{-1}) across the Burdekin, providing a clear focus area for management efforts aimed at reducing the export of all sediment-size fractions. However, our findings show that similar load contributions of both the clay and fine silt fractions were delivered from the two major source areas: the Bowen River and the BFD overflow. Targeted source area remediation of the clay and fine silt sediment fractions of increased ecological importance should first be confined to the Bowen River tributary if assessed on a per unit area contribution; however, we caution further investigation into the geochemical and clay mineralogy characteristics of these different clay/fine silt sources, and their subsequent transport in and likely impact on the marine environment is required. The sediment sourcing, reservoir influence on sediment-size transport, and yield data generated across the Burdekin has broader application in other dry tropical river catchments, particularly those located in wet-dry tropical savannah climates. This study also highlights the importance of incorporating sediment particle size into catchment sediment budget studies where management goals are aimed at reducing downstream turbidity and sedimentation on marine ecosystems such as seagrass and coral reef ecosystems.

The influence of this terrigenous fine sediment within the GBR has been recently highlighted by *Fabricius et al*. [2014], who correlated increased inshore turbidity with rainfall and runoff events from GBR Rivers such as the Burdekin. Finer sediment particles, often with an attached organic component once in the marine environment, are easily resuspended and transported along the GBR shelf (Orpin et al., 1999; Wolanski et al., 2008; Webster and Ford, 2010; *Brodie et al*., 2012] and are the most harmful sediment type to GBR receiving ecosystems such as corals [*Fabricius and Wolanski*, 2000; *Weber et al*., 2006; *Humphrey et al*., 2008], seagrass and other associated communities such as reef fish [*Wenger and McCormick*, 2013]. The combined influence of increased fine sediment particles with decreased salinity (i.e., synergistic effects on coral fertilization; see *Humphrey et al*., 2008] during extended flood plume conditions in above average Burdekin discharge years also requires further investigation. While our study and *Bainbridge et al.*'s [2012] Burdekin flood plume research show a clear partitioning of sediment fractions through the BFD and into the marine environment, there is still a need to delineate the marine areas of most risk to the increased sediment loads delivered from the Burdekin River [*Bartley et al.*, 2014]. For example, coral reefs that have developed and thrived in naturally turbid areas such as Paluma Shoals and Middle Reef [*Browne et al.*, 2013; *Perry et al.*, 2012] are unlikely to be as adversely affected by increased sediment loadings as clear water reefs, such as off Pelorus Island where elevated sediment inputs and associated increased turbidity are argued to have negatively affected coral reefs [*Roff et al.*, 2013].

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