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Refining fine sediment source identification through integration of spatial modelling, concentration monitoring and source tracing: A case study in the Great Barrier Reef catchments

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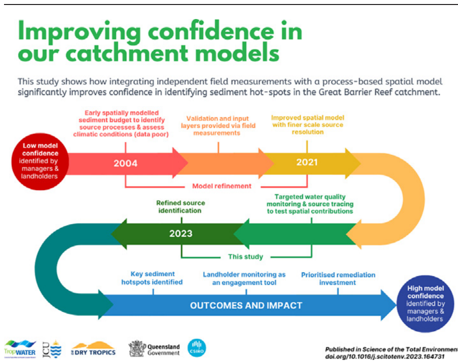
HIGHLIGHTS

- Water quality monitoring and sediment source tracing constrain spatial models.
- Improved confidence in spatial representation of erosion and associated supply
- Integrating multiple lines of evidence improves the basis for catchment management.
- The Little Bowen River catchment is a dominant contributor to GBR sediment loads.
- Landholder monitoring is a low cost and key engagement tool to improve management.

GRAPHICAL ABSTRACT



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ABSTRACT

Excess fine sediment delivery is a major contributor to the declining health of the Great Barrier Reef and identifying the dominant source areas of fine sediment has been critical to prioritising erosion remediation programs. The Bowen River catchment within the Burdekin Basin has been recognised as a major contributor and hence received considerable research investment over the last two decades. This study adopts a novel approach to integrate three independently derived sediment budgets produced from a catchment scale sediment budget model (Dynamic SedNet), targeted tributary water quality monitoring and geochemical sediment source tracing to refine and map the sediment source zones within the Bowen catchment. A four year study of water quality monitoring combined with modelled discharge estimates and geochemical source tracing both identified that the Little Bowen River and Rosella Creek were the largest sources of sediment in the Bowen River catchment. Both data sets contradicted initial synoptic sediment budget model predictions due to inadequate representation of hillslope and gully erosion. Recent improvements in model inputs have resulted in predictions that are consistent with the field data and are of finer resolution within the identified source areas. Priorities for further investigation of erosion processes are also revealed. Examining the benefits and limitations of each method indicates that these are complimentary methods which can effectively be

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used as multiple lines of evidence. An integrated dataset such as this provides a higher level of certainty in the prediction of fine sediment sources than a single line of evidence dataset or model. The use of high quality, integrated datasets to inform catchment management prioritisation will provide greater confidence for decision makers when investing in catchment management.

1. Introduction

Against the backdrop of increasing anthropogenic pressures and changing climate, worldwide, aquatic ecosystems are adversely affected by elevated sediment and associated particulate nutrient loads. Considerable resources are being spent to reduce these impacts (e.g. Bernhardt et al., 2005; Nkonya et al., 2016; Risk, 2014; Sartori et al., 2019). Understanding the spatial patterns and processes of sediment supply form core parts of these efforts (e.g. Nyssen et al., 2004; Wolflin, 2008; Deng et al., 2012; Griffiths and Topping, 2017). Despite the growing range of tools practitioners have at their disposal, including spatial modelling, water quality monitoring and sediment tracing (i.e. McCloskey et al., 2021; Collins and Walling, 2004; Collins et al., 2020), identifying the specific sediment sources that impact aquatic ecosystems can be challenging. Individually these methods all have limitations related to parameterisation/validation issues (modelling), spatial and temporal coverage (monitoring and tracing) and issues associated with multiple (including unidentified) sediment sources and their transport mechanism through the catchment. One approach to identify and address these limitations is to integrate the information from across these multiple lines of evidence (Sherriff et al., 2019) to ultimately produce a highly robust spatial sediment budget.

The sediment budget concept has been a central organising principle within the discipline of geomorphology since at least the 1970s (Dietrich and Dunne, 1978; Dunne and Leopold, 1978). In essence, a sediment budget provides a method of accounting for sediment inputs and outputs through a drainage network. It enables the identification of the primary source of sediment and its key transport mechanisms, and when the budget has high confidence, it facilitates improved targeting of erosion control remediation work (Wilkinson et al., 2009). Despite the wide application of sediment budgets that have informed catchment management efforts around the world, less attention has been paid to understanding the veracity of the outputs developed from multiple independent methods. Indeed, the aforementioned limitations of the individual approaches to construct sediment budgets may result in high uncertainty which could lead to poorly targeted management interventions. The production of multiple independently derived sediment budgets offers the novel opportunity to compare, contrast and synthesise the results, leading to higher confidence in sediment source identification.

Here we test the approach of integrating information from multiple lines of evidence to assess spatial patterns in sediment sources in the Bowen and Bogie River catchments from north-eastern Australia. These catchments (Fig. 1 inset) have been identified as major contributors to the sediment load derived from the Burdekin River, the largest individual contributor of sediment export to the Great Barrier Reef (GBR) lagoon. The Burdekin Basin has an estimated average annual fine sediment (<20 μm) load of 3.3 million tonnes, contributing nearly 40 % of the total load exported (~8.5 Mt) from all GBR catchments (McCloskey et al., 2021). Modelling and sub-basin scale monitoring in the Burdekin Basin (130,000 km^2 area) reveal that the majority (60 %) of the fine sediment load is delivered from the comparatively smaller area (15,200 km^2) below the Burdekin Falls Dam, which includes the Bowen and Bogie catchments (Bainbridge et al., 2014; McCloskey et al., 2021) (Fig. 1 inset). The Reef 2050 Water Quality Improvement Plan proposed a 30 % reduction (2.69 Mt) target in the anthropogenic fine sediment load delivered from the Burdekin River (State of Queensland, 2018). To achieve this load reduction, the Queensland State and the Australian Federal Governments, with support from the Great Barrier Reef Foundation, have invested in excess of AU$50 million for landscape remediation and catchment repair within the Bowen and Bogie catchments since 2016. To date, identifying specific areas for remediation has been constrained by conflicts in findings between investigations of the sediment sources within the Bowen and Bogie catchments. For example, earlier modelling outputs suggested a large contribution of fine sediment came from the Broken River (Fig. 1) delivered via hillslope erosion (Bartley et al., 2004; Dougall et al., 2014), whereas monitoring and tracing data identified this tributary as a minor source (Wilkinson et al., 2013; Bainbridge et al., 2014).

This paper first reviews the evolution of spatial modelling and earlier sediment source and erosion process research within the Bowen and Broken River catchments. Second, we present new monitoring and tracing data that refines our understanding of sediment contributions from tributaries within these catchments. Third, we examine the benefits and limitations of the different methods and explore how water quality monitoring, sediment tracing and spatial models can be utilised as a multiple lines of evidence approach to refine sediment budgets for the prioritisation of catchment remediation efforts. The results of this study are then discussed in the context of considerable remediation investment in the GBR catchments, as well as for other parts of the globe.

2. Bowen and Bogie catchments

The influence of the Burdekin River discharge on the ecosystem health of the GBR has been widely investigated both in the context of spatial and temporal changes in terrestrial runoff (McCulloch et al., 2003; Lewis et al., 2007, 2014, 2018; Lough et al., 2015; Lambert et al., 2021; D'Olivo and McCulloch, 2022) and as a ‘ridge-to-reef’ case study linking back to the catchment sources, delivery and management (Bartley et al., 2014a; Bainbridge et al., 2018a, 2021). Collectively, this research has identified that fine sediment <20 μm in size (‘fine sediment’) is the most ecologically detrimental (and bioavailable) sediment fraction that travels the furthest into the GBR lagoon (Bainbridge et al., 2012, 2018a, 2021; Garzon-Garcia et al., 2021). Consequently this paper focuses on this fine sediment fraction. Sediment budgets have identified the Bowen and Bogie catchments as the dominant contributors of fine sediment to the end-of-basin (Bainbridge et al., 2014, 2016; Bartley et al., 2015). Catchment modelling has also identified them as having the largest area-specific fine sediment contribution to the GBR of the 50 catchments which drain to the GBR coast (McCloskey et al., 2021), being six times the average contribution across the region. As a result, significant investment in erosion control has been targeted to the Bowen and Bogie catchments (Fig. 1) and improved understanding of spatial patterns in sediment sources remains a priority.

Detailed descriptions of the Bowen and Bogie catchments are provided by Roth et al. (2002), Wilkinson et al. (2013) and Bainbridge et al. (2014). Together, these two coastal catchments cover 11,720 km^2 and, in their headwaters, contain mountain ranges with 550 m (above sea level) peaks in the Bogie, and up to 1170 m in the rugged Broken catchment (Fig. 2). Volcanic (felsic/mafic) and sedimentary rock types dominate these catchments (Fig. 2). The rugged terrain of the Broken River headwaters receives the highest average wet season (November to April) rainfall (1430 mm/yr), and the highlands contain conservation status rainforest (13 % of this catchment). Rainfall steadily decreases towards the western boundary of the Bowen catchment, where the wet season average rainfall is only ~380 mm/yr. Gully density is lowest in the Broken River catchment and increases towards the west. The Bowen catchment is characterised by steeper ridges in the upper catchment, and an incised valley system through volcanic hills (Roth et al., 2002). The main land use within the region is cattle

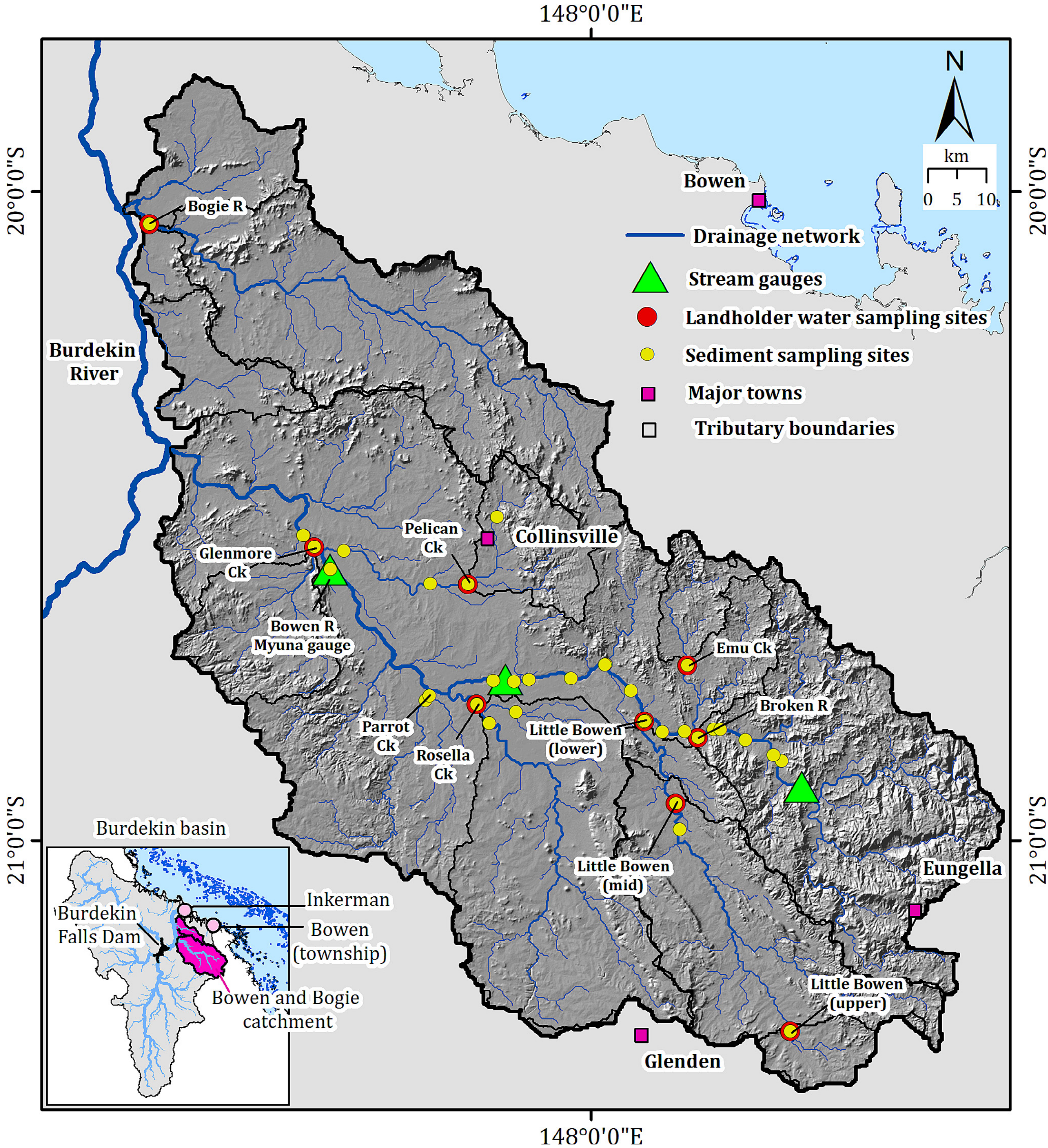

Fig. 1. Map of the Bowen and Bogie catchment area showing the location of the landholder water quality tributary monitoring sites (red circles), additional sediment tracing site locations (yellow circles), and Queensland Government stream gauges along the Broken and Bowen Rivers (green triangles). Inset figure shows the location of the Bowen and Bogie catchments and the Burdekin Falls Dam within the Burdekin basin, Queensland, Australia.

grazing on eucalypt savannah woodlands, with pockets of active mining, and the rural town of Collinsville (Pop. ~3000) in the central region.

The Bowen River has a mean-annual discharge of ~1000 Gigalitres (at the Myuna gauge site), with the Broken River (Sugarloaf gauge) tributary supplying the majority (~70 %) of the measured flow. By comparison, the Little Bowen River tributary lies to the west of the Broken tributary where runoff (~90 mm a^{-1}) is on average much lower, supplying ~13 % of flow (Fig. 1). Despite its relatively large area (1425 km^2), the Rosella Creek tributary contributes ~10 % of the flow, and downstream of the Myuna gauge, Glenmore Creek and the other areas contribute the remaining 10 % of flow.

3. Sediment budgets

In the following sub-sections, we describe *three methods* used to develop sediment budgets for the Bowen and Bogie catchments. First, we summarise the various spatial sediment source modelling approaches that have been applied to the catchment and present the current Dynamic SedNet

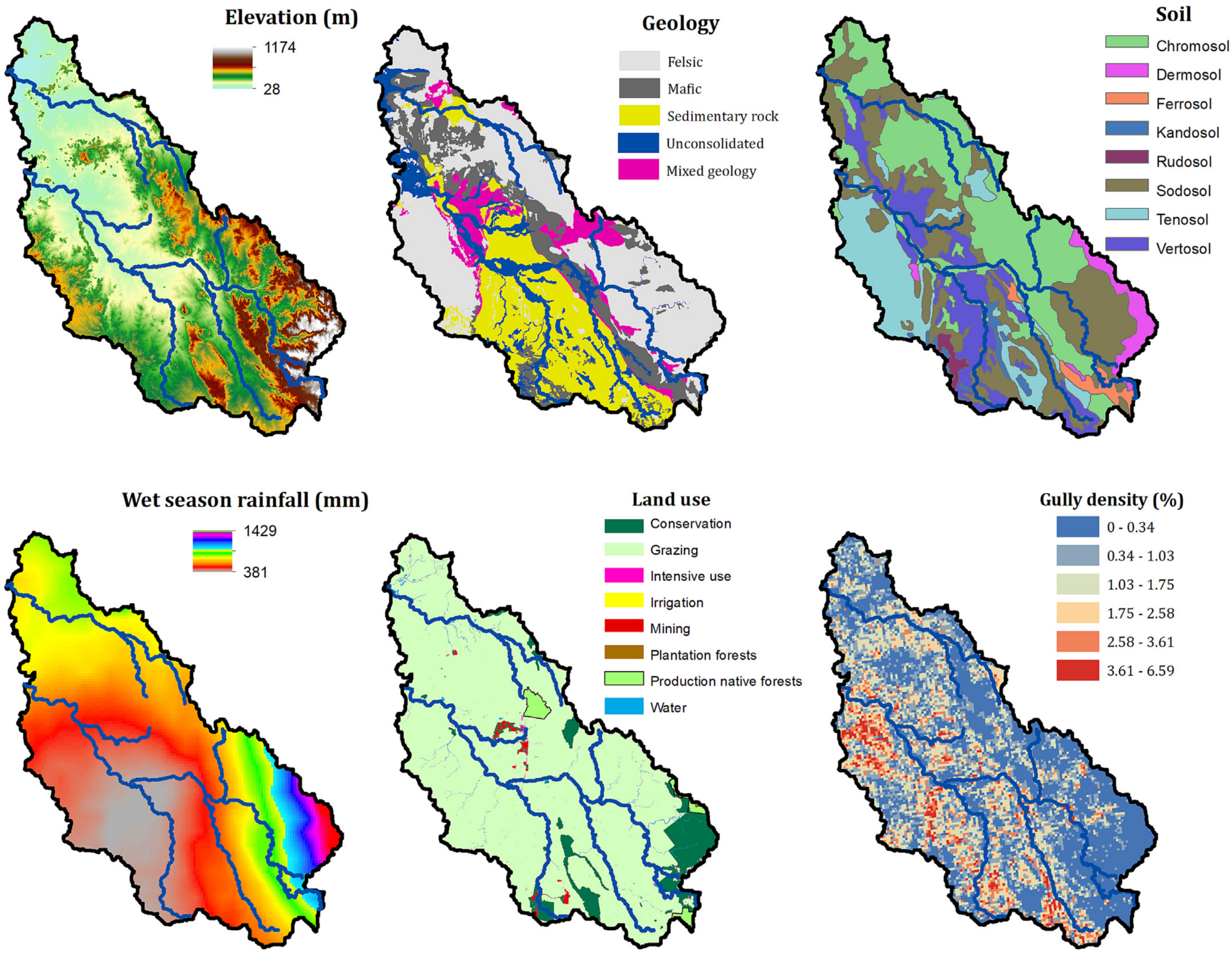

Fig. 2. Spatial distribution of elevation, geology, soil, average wet season rainfall, land use and gully density in the Bowen and Bogie catchment.
Sources: SILO, Geoscience Australia, QLD_Gully_erosion_density_1km supplied by S.Darr, Qld Department of Environment and Science.

modelled sediment budget (*Part A*). It should be noted that this budget incorporates erosion process and catchment source learnings derived from earlier water quality and geochemical tracing studies (details below). We then present new tributary-based water quality monitoring (*Part B*) and sediment geochemical data (*Part C*) and use these new data to develop independent sediment budgets to test the current model-derived sediment budget.

3.1. Part A: sediment source modelling

Over the past three decades, techniques used for simulating sediment loads exported from the Burdekin basin have become more sophisticated, refined and process-based. Earlier catchment modelling approaches included sediment rating curves, and the incorporation of land use factors to account for increasing yields (e.g. Moss et al., 1992; Neil and Yu, 1996; Neil et al., 2002; Furnas, 2003). More recently, the Sediment River Network Model (SedNet) has been developed and refined to improve the physical representations of surface runoff, gully and streambank erosion. The SedNet model developed for the Australian Government's National Land and Water Resources Audit (Prosser et al., 2001) is a process based physical model. It constructs a sediment budget of a river network and identifies the major sources, stores and loads of sediment and nutrients. In the model the river network is divided into a series of links which are the basic units of calculation for the sediment budget (Fig. 3). A link is the stretch of river

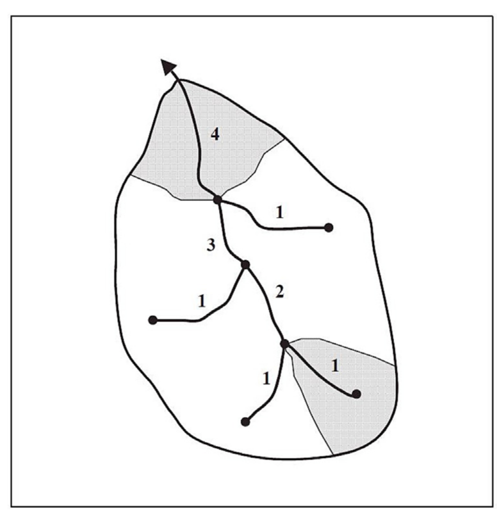

Fig. 3. A river network showing links, nodes, Shreve magnitude of each link (Shreve, 1966) and internal catchment area of a magnitude one and a magnitude four link.
Source: Prosser et al. (2001).

between adjacent stream junctions (or nodes; each link has an internal sub-catchment), which is the catchment area added to the link between its upper and lower nodes. Sediment inputs to each link are determined from the contribution of hillslope, gully (sub-soil) and riverbank erosion, and from upstream tributaries.

Within the SedNet modelling framework, hillslope erosion is estimated from the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) multiplied by a sediment delivery factor (typically 0.05), gully erosion from an estimate of gully density and volume, and bank erosion from an equation incorporating stream power, presence of erodible soil and riparian vegetation cover (Wilkinson et al., 2009). Detailed spatial input datasets (i.e. ground cover, soil types) have progressively constrained the Burdekin SedNet model (Suppl. Table 1). A major model development incorporating a daily time step approach (Dynamic SedNet module) - a shift from average annual outputs - saw considerable improvements in temporal and spatial resolution, including the ability for climate and management practice change scenario modelling (Ellis and Searle, 2014; Dougall et al., 2014; Wilkinson et al., 2014). Importantly, in earlier model iterations, only end-of-basin measured sediment load data were available to calibrate modelled loads (Furnas, 2003; Amos et al., 2004). However, more recently independent monitoring and research conducted within the basin has provided valuable data to further constrain the model, including a sediment trapping algorithm for the Burdekin Falls Dam (Lewis et al., 2013), basin-wide sediment budgets developed from water quality measurements, hydrological data, geochemical sediment tracing and pre-development erosion rates (Kuhnert et al., 2012; Wilkinson et al., 2013; Croke et al., 2015; Bainbridge et al., 2014, 2016; Furuichi et al., 2016; Mariotti et al., 2021). The current GBR Dynamic SedNet modelling platform is based on five-yearly review cycles, which include a major update at the end of each phase to incorporate new research findings and other improvements to model parameterisation (McCloskey et al., 2021; see also Suppl. Table 1).

Model refinements over the past two decades have led to finer spatial resolution outputs and improved sediment erosion hot-spot identification, as shown across the two sub-catchment sediment generation maps presented in Fig. 4a. For the Burdekin basin these refinements in resolution have resulted in modelled average sub-catchment area reducing from approx. 390 km^2 down to 80 km^2. Whilst fine sediment export (~1.3 Mt/y) from the Bowen catchment remained unchanged over model iterations (Fig. 4b) largely due to being benchmarked to specific monitoring sites, predicted surface (hillslope) erosion contributions reduced from 72 % in the early model (Bartley et al., 2004) to only 9 % in the current model (McCloskey et al., 2021). Sediment radionuclide tracing investigations identified sub-soil erosion processes (i.e. gully, streambank and bare areas) to be driving sediment supply within the catchment (Wilkinson et al., 2013, 2015; Hancock et al., 2014). These data combined with improved gully density mapping led to a significant shift in how the model represents erosion within the Bowen catchment. Data limitations in earlier RUSLE predictions (i.e. Bartley et al., 2004; Fentie et al., 2006) also led to an over-prediction of sediment supply from the south-eastern headwaters (Broken River), largely due to the cover factor (C-factor), which has been improved over time from a static value to the current model which incorporates four seasonal grids (30 × 30 m) per year using satellite-based

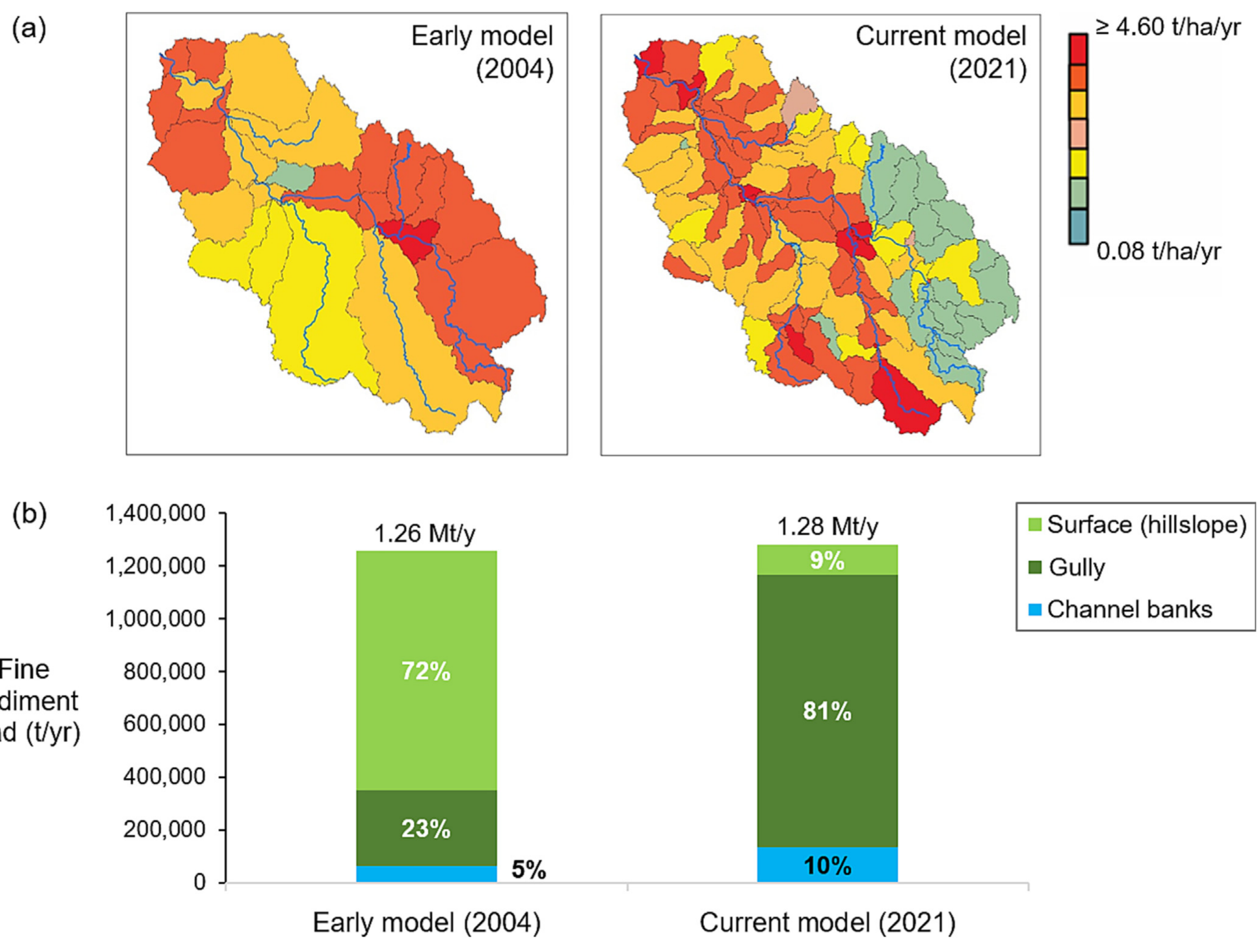

Fig. 4. (a) Bowen River fine sediment supply (t/ha/yr) by tributary link as predicted by the early SedNet (Bartley et al., 2004) and current Dynamic SedNet (McCloskey et al., 2021) models. (b) Model comparison of predicted Bowen fine sediment loads delivered to the Burdekin River, including the spatially modelled erosion source contributions to each of these loads.

fractional ground cover (refer to Supp. Table 1 and see also McCloskey et al., 2021). Subsequent spatial analysis that integrated tributary-based water quality and sediment tracing research, as well as higher resolution gully density mapping (Darr and Pringle, 2017) have shown that the upper Bowen tributaries supply the most sediment (Fig. 4a). In the current model, the Broken River contributes only 12 % of sediment supply (112,100 t/yr) to the downstream Bowen River (Myuna) gauge site, whilst the Little Bowen River and Rosella Creek tributaries collectively contribute 56 % (463,200 t/yr) of the sediment load, from ~40 % of the catchment area (Table 1).

3.2. Part B: tributary water quality monitoring

3.2.1. Site locations, water sample collection and sample numbers

A network of nine tributary water sampling sites was established across the Bowen and Bogie catchments in collaboration with local landholders and the local natural resource management organisation (Fig. 1). Sites were selected based on changes in rainfall, slope, lithology and vegetation, and in consultation with the Dynamic SedNet modelling team. Due to considerable access restraints some identified tributaries remained uncaptured. Multiple water samples were collected during each runoff event over four wet seasons (November to April) from 2018/2019 to 2021/2022. The landholders were trained to collect surface 'grab' samples (top 0.5 m of water column) directly into pre-rinsed 1 L polypropylene bottles from as close to the centre of the stream channel as possible (Bainbridge et al., 2018b; DES, 2018). In particular, landholders were requested to collect samples that targeted the rising (ideally 2–3 samples), peak (1 sample) and falling (2–3 samples) stages of runoff events so that the variability of concentrations could be well captured over the hydrograph. Once collected, each sample was placed in the fridge and then transported cold to the laboratory.

The 2018/2019 wet season experienced above-average rainfall (Table 2). During this period, a total of 109 water samples were collected across the nine sites. Runoff events sampled at each site ranged from one to four with samples collected across the flow hydrograph (rising, peak and falling stages) to capture the changing suspended sediment concentrations. Rainfall for the subsequent 2019/2020, 2020/2021 and 2021/2022 wet seasons were below average. In total 95 samples were collected across seven of the sites during this three-year period, with one to five discrete flow events being sampled each wet season.

The Broken River, Pelican Creek, Bogie River and Little Bowen River (lower) sites were the best represented. Sample numbers range from 37 to 78 across these sites, with sampling adequately capturing hydrograph profiles (i.e. often 4–10 samples per hydrograph capturing all stages) and multiple flow events over the four wet seasons (Table 2). The least represented sites included the typically drier western tributaries (i.e. Rosella and Glenmore Creeks) that received limited rainfall and associated runoff events over the sampling period, providing limited opportunity for sample collection.

3.2.2. Laboratory analysis

Total suspended solids (TSS) samples (in mg/L) were measured gravimetrically by weighing the fraction remaining on a pre-weighed Whatman Grade 934AH filter (nominally 1.5 μm pore size), that was dried at 103–105 °C for 24 h, after vacuum filtration of a measured volume of sample (APHA, 2012 Method 2540D). This method is consistent with the Queensland Government's state-wide GBR Catchment Loads Monitoring Program, allowing comparison with the longer-term Bowen River (Myuna) site TSS data. As noted in Bainbridge et al. (2014), 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).

Sediment grain size analysis was conducted on a sub-set of collected 1 L samples, using the Malvern Mastersizer 3000 and the settings described in Bainbridge et al. (2021) section 2.4.1 (without organic content removal).

Table 1
Independent sediment budgets for the Bowen and Bogie catchments, comparing tributary fine sediment contributions to the Bowen River (Myuna) gauge site (bolded site). Additionally, sampled Bowen tributaries downstream of the Myuna gauge, and the Bogie River catchment are also included. Sediment budgets are based on the current Dynamic SedNet model (McCloskey et al., 2021) from *Part A*, tributary suspended sediment concentration data (using Dynamic SedNet model discharge) from *Part B*, and sediment tracing source attribution from *Part C*. Empty cells represent data gaps, contributing tributaries of the Broken River are identified in italiacs.

Tributary/sub-catchment		Catchment area (km^2)	Modelled discharge (ML)	Modelled discharge contribution to Myuna (%)	Monitored suspended sediment concentration data using modelled flow (except Myuna = LRE output)				Sediment tracing source attribution		Dynamic SedNet model (1986–2014)		
					# wet seasons (# samples)	Fine sediment load (t) (±SE)	Load contribution to Myuna	t/ha/yr	# wet seasons (# samples)	Load contribution to Myuna (% ± SE)	Fine sediment load (t)	Load contribution to Myuna	t/ha/yr
	Broken River (Urannah gauge)	*1118*	*477,400*	*(47 %)*							42,000		
Broken River	*Emu Ck tributary*	*199*	*18,020*	*(2 %)*	*2 (11)*	1550 (±29 %)		0.08			8200		0.4
	Broken R (Sugarloaf)	2248	677,600	66 %	*4 (78)*	18,000 (±17 %)	1 %	0.08	*2 (8)*	16 ± 10 %	112,100	13 %	0.5
Little Bowen River (lower)		1462	128,000	13 %	*7 (37)*	488,800 (±14 %)	27 %	3.3	*4 (22)*	50 ± 20 %	282,300	34 %	1.9
Rosella Creek		1425	88,630	9 %	*2 (6)*	250,000[b] (±50 %)	14 %	1.8	*3 (5)*	33 ± 24 %	180,900	22 %	1.3
Parrot Creek		569	30,510	3 %					*1 (2)*	~1 %	64,700	8 %	1.1
Other not-captured (e.g. *East, Flagstone, Ten Mile*)		*1370*	*99,060*	*9 %*							*199,200*	*24 %*	
Bowen River (Myuna)		**7074**	**1,023,800**[a]	**100**	*15 (584)*	**1,804,300**[c]	**(100)**[d]	**2.6**	*4 (14)*	**100**	**839,200**	**100**	
Other tributary contributions to Burdekin end-of-basin below the Myuna gauged catchment area:													
Pelican Creek		610	60,225		*4 (38)*	71,600 (±14 %)		1.2			74,800		1.2
Glenmore Creek		470	93,065		*1 (10)*	31,250[b] (±27 %)		0.7			52,600		1.1
Bogie River		1740	445,000		*7 (46)*	197,400 (±12 %)		1.1			117,000		0.7

[a] The 60-year flow gauge record for Myuna is 866,000 ML.
[b] Based on ≤10 samples, or only one year of sample collection.
[c] Suppl. Section Table A2.
[d] Not all catchment area is represented in this budget.

Table 2
Annual wet season rainfall (mm), number of water samples collected and number of events sampled (in brackets) for each monitored tributary site. Mean rainfall received across each site's upstream catchment area was calculated using data extracted from SILO monthly rainfall grids.
Source: SILO Long Paddock; Jeffrey et al. (2001).

			Little Bowen River			Rosella Creek	Pelican Creek	Glen-more Creek	Bogie River (lower)	Emu Creek	Broken River	Total # samples/ wet season
			Upper	Mid	Lower							
Current sampling	2018/19	Rainfall	783	820	791	551	704	619	1046	1031	1442	
		# samples	11 (3)	8(2)	8 (3)	3 (1)	17 (4)	10 (3)	15 (4)	9 (3)	28 (5)	109
	2019/20	Rainfall	512	454	378	285	399	294	439	481	724	
		# samples			2 (2)		7 (2)		6 (3)	2 (1)	21 (5)	38
	2020/21	Rainfall	512	533	546	439	555	468	619	693	803	
		# samples			4 (3)	3 (2)	4 (2)		1 (1)		4 (1)	16
	2021/22	Rainfall	643	667	659	573	582	507	541	683	881	
		# samples			6 (3)		10 (4)				25 (4)	41
Earlier sampling	2005/06	Rainfall							482			
		# samples							3 (2)			3
	2006/07	Rainfall			583				531			
		# samples			5 (2)				7 (3)			12
	2007/08	Rainfall			1002				933			
		# samples			5 (2)				8 (2)			13
	2008/09	Rainfall			809				1007			
		# samples			7 (2)				6 (2)			13

3.2.3. Sediment load calculations

In the absence of river gauge flow data, fine sediment loads for each of the nine monitored tributary sites have been estimated using site average measured suspended sediment concentration and corresponding average annual site discharge generated by the GBR Dynamic SedNet model, which integrates the eWater Source hydrological model and a Dynamic SedNet plugin (McCloskey et al., 2021). The modelled average annual discharge represents a 28-year climatic period from 1986, which is calibrated with available streamflow gauges and rigorously updated during each five year model review (McCloskey et al., 2021; Zhang et al., 2013). Partial uncertainty for each load was calculated using the sediment concentration data and is represented as the standard error. The reported uncertainty does not incorporate error associated with field sampling, or with using a long-term average annual flow value (which is dominated by five of the 28 water years). Site average upstream sediment yields were then calculated by dividing each load by the respective upstream catchment area.

To complete the monitoring-based sediment budget, an average annual suspended sediment load was calculated for the Bowen River (Myuna gauge) site, using longer-term water quality monitoring data (Supp. Section A). This is the most downstream gauge on the Bowen River, capturing 75 % of the catchment area. The Loads Regression Estimator (LRE) tool (Kuhnert et al., 2012) was used to calculate annual sediment loads for 19 consecutive water years (1st Oct – 30th Sept) 2002/2003 to 2020/2021. Data were collated from historic and current monitoring programs (Suppl. Table A1); with water sampling conducted over 15 of these 19 wet seasons. Annual load error estimates (80 % confidence intervals) that incorporate errors in flow are also included (Suppl. Table A2).

3.2.4. Water quality monitoring results

Earlier samples collected across the 2005/2006 to 2008/2009 wet seasons at the Bogie and Little Bowen (lower) River sites (Bainbridge et al., 2014, 2016) have also been incorporated into this study (Table 2). These data extend the sampling for these two sites to seven water years and include sampling of a wetter climatic period.

Boxplots summarising all suspended sediment (SS) concentration data (mg/L) collected for each site are shown in Fig. 5a. The plots show the minimum, first quartile, median, third quartile and maximum concentrations. Site average concentrations (blue text in plot) were highest in the Little Bowen tributary sites (>3800 mg/L), which also had the greatest concentration range, with maximum concentrations occurring during the rise and peak flow stages. During the largest flow event sampled at Rosella Creek, SS concentrations rose to 9000 mg/L, indicating the sediment loss potential of this tributary when large or intense storm events occur. Sediment concentrations measured in the Little Bowen and Rosella Creek tributaries are considerably higher than any other site measured across the broader Burdekin and other GBR Basins (Bainbridge et al., 2014, 2016). The sampled creeks draining into the lower Bowen reaches (Pelican and Glenmore Creeks) had mean SS concentrations ranging from 335 to 1190 mg/L (Fig. 5a). In contrast, the significantly lower site mean (25 ± 41 mg/L) for the Broken River has remained consistent across the sampled wet seasons, with 78 samples collected over 15 discrete flow events. The Bogie River site, now sampled over seven wet seasons ($n = 48$) had a mean SS concentration of 440 mg/L.

Fine sediment loads calculated for each monitored tributary reflect the large variability in our concentration data across sites (Table 1). The Little Bowen River and Rosella Creek sites are estimated to make the highest sediment contributions of 488,800 (±14 %) and 250,000 (±50 %) t/yr, respectively. The Bogie River is estimated to contribute 197,400 (±12 %) t/yr, whilst the contribution from the Broken River tributary (18,000 ± 17 % t/yr) is over an order of magnitude lower. The level of uncertainty reported for each of these monitored loads reflects both the number of samples and wet seasons captured for each site, and we caution that our calculations only consider the uncertainty in the concentration data (i.e. we are unable to account for the uncertainty of the flow data, or sediment exhaustion etc.). On-going sampling coupled with reliable measurements of flow will improve the confidence of these monitored loads over time.

Incorporating the upstream catchment area into this comparison of monitored tributaries, the Little Bowen River is identified as the highest fine sediment contributor per unit area (Fig. 5b). Monitoring data collected to date suggest this tributary contributes at least 3.3 t/ha/yr (330 t/km^2/yr). Rosella (1.8 t/ha/yr) and Pelican (1.2 t/ha/yr) Creeks are also identified as considerable sediment yielding tributaries. In contrast, the Broken tributary draining steep forested headwaters and receiving the highest wet season rainfall contributes the lowest fine sediment yield (0.08 t/ha/yr). The monitoring-based annual sediment load (1,804,300 t/yr) calculated for the Bowen River (Myuna) site is considerably higher than the Dynamic SedNet average annual load (839,200 t/yr), even though the SS concentration data has been collected over 15 water years, and the measured load calculations account for key hydrological processes (refer to Suppl. Section A).

Grain size analysis of collected water samples show suspended sediment from the Bowen catchment tributaries was dominated (64–90 %) by clay and very fine silt particles (i.e. the <20 μm fraction of most ecological relevance to GBR ecosystems). The coarser silt grains (20–63 μm) comprised 8–26 % of measured samples collected across the sites, and sand grains (>63 μm) comprised only 2–11 % (Fig. 5a). The sand component was highest in the Glenmore Creek and Little Bowen River (upper) sites, which may be related to flow velocity.

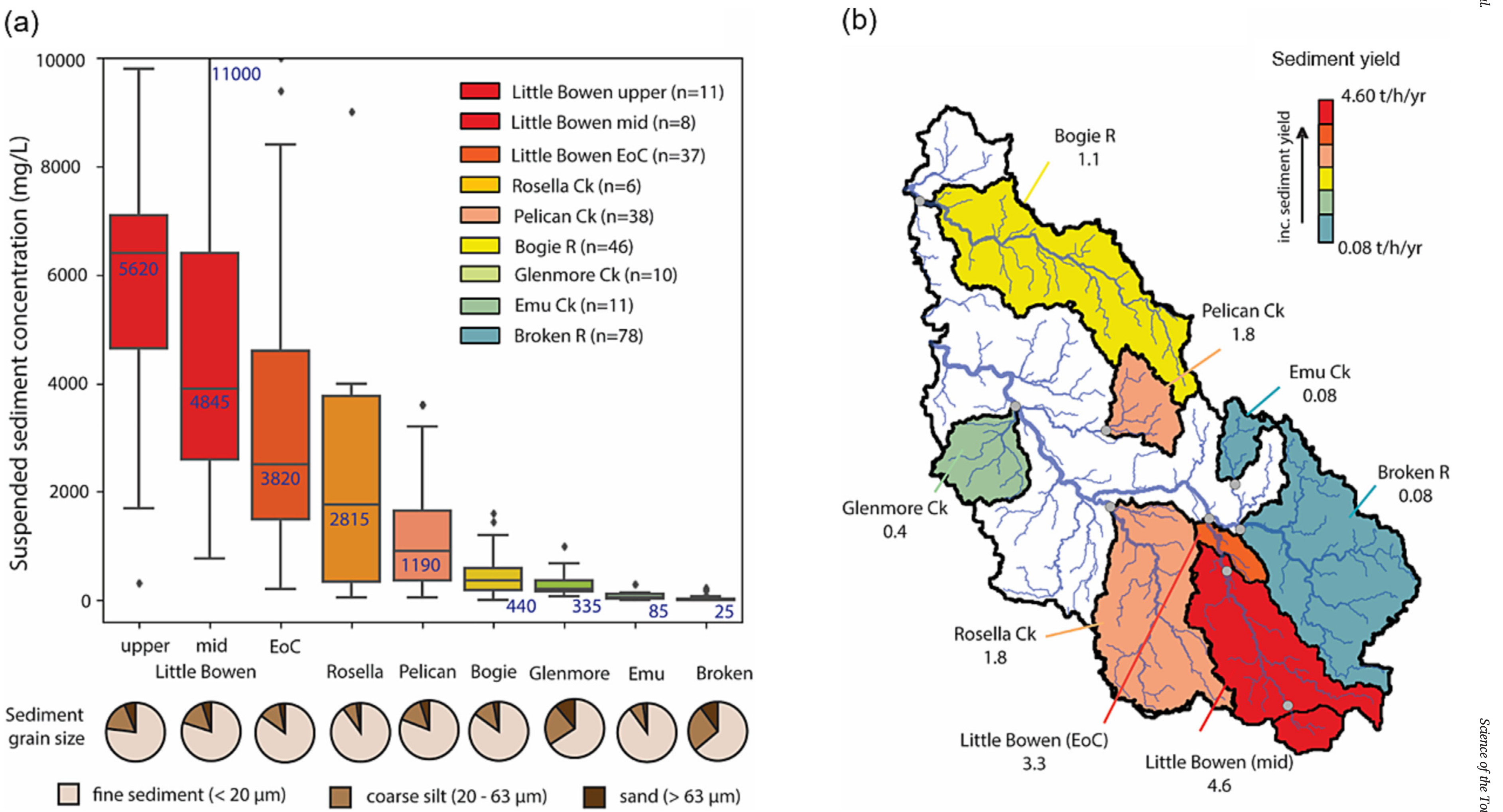

Fig. 5. (a) Boxplots arranged in order of increasing sediment yield highlight the range of suspended sediment concentrations (mg/L) measured across each of the sampled tributaries. All collected samples from the four sampled wet seasons (2018/2019 to 2021/2022) are included within each plot, with the median represented by the black line. Mean concentration values are provided in blue text (n = number of samples). Pie charts below the boxplots quantify the sediment grain size distribution measured at each site. The Little Bowen (lower) and Bogie River sites include additional data collected in earlier wet seasons (2005–2009; Bainbridge et al., 2014, 2016). (b) Spatial heatmap showing the sediment yield from each monitored Bowen and Bogie tributary. Note that sediment yield was not calculated for the upper Little Bowen tributary site due to small upstream catchment area.

3.3. Part C: geochemical sediment source tracing

Developing a sediment budget using sediment source tracing involves measuring sediment properties that are capable of distinguishing sediments derived from different areas of the catchment (Collins et al., 1998; Olley et al., 2001). The geochemical characteristics of eroded sediments are strongly influenced by those of the soils and ultimately the rock-types from which they are derived (Caitcheon et al., 2006). Different underlying parent rock materials often results in spatial sources with distinct geochemical compositions (Olley et al., 2001; Douglas et al., 2003). Sediments eroded from soils derived from a particular rock type often maintain these distinct geochemical properties during sediment generation and transport processes (Caitcheon et al., 2006; Hughes et al., 2009). Tracer concentrations are often strongly affected by both changes in particle size and organic matter (Laceby et al., 2017; Smith and Blake, 2014; Vale et al., 2022). These effects can be mitigated by using a narrow particle size range (He and Walling, 1996; Wilkinson et al., 2013) and determining the organic free concentrations (Olley et al., 2001).

A benefit of source tracing is less reliance on temporal variability provided that the tributary sediment samples are well-mixed and representative. Semi-arid catchments with severe erosion also produce plenty of perched sediment deposits following larger flow events, allowing material to be collected across the catchment post flow events to supplement within wet season suspended sediment sample collection. Most geochemical source tracing studies focus on smaller catchment areas than the Bowen River. This technique is more challenging to apply to larger catchments due to sediment fractionation, transformation and mixing processes that can occur within a large river network. To overcome these challenges, a systematic step-wise approach was conducted to confidently attribute sources at a tributary scale, and develop an independent sediment budget to compare with monitoring and spatial modelling data.

Here we use sediment source tracing in two ways:

i) Where samples were available from upstream and downstream of a tributary junction, we have used geochemistry to determine the relative contribution of the upstream tributaries to the downstream mix of sediments.
ii) Where sample numbers were limited, such as at the Burdekin end-of-basin at Inkerman ($n = 1$ *triplicated sample at peak flow*), downstream of the Burdekin-Bowen-Bogie junction, element concentrations were compared directly between the downstream sample and samples collected from upstream.

3.3.1. Sample compilation and laboratory analysis

A total of 96 tributary sediment samples were prepared:

Selected tributary suspended sediment samples were prepared for geochemical analysis ($n = 20$), with the <10 μm sediment fraction recovered using the settling method described in Bainbridge et al. (2016). In the instances where there was limited material in the discrete samples, these were combined to provide the desired mass for analysis. Seven additional suspended sediment samples collected over the 2016/2017 and 2018/2019 wet seasons (at 5 Bowen stream network sites; Fig. 1) were also utilised in this study (Garzon-Garcia et al., 2018). These samples were collected using time-integrated samplers (Phillips et al., 2000) which have been widely adopted in sediment tracing research (Collins et al., 2010; Walling et al., 2008; Furuichi et al., 2016). These samplers effectively trap a representative sample of suspended sediment with a particle size of <63 μm (Phillips et al., 2000) and capture an integrated sample over the period of inundation which include the rising and falling limbs of the flow hydrograph. Opportunistic surface water 'grab' samples were collected at the Burdekin River at Inkerman (i.e. end-of-basin site) at the peak of the March 2017 flood event; this discharge was almost exclusively sourced from the Bowen-Bogie River catchments below the Burdekin Falls Dam (BFD) and hence provides a direct end point to examine sediment source contributions for this event.

All <10 μm sediment samples were analysed at the Department of Environment and Science Chemistry Centre (Brisbane, Australia). Dried samples were fused with lithium metaborate flux at 975 °C and analysed on an Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) for the major element concentrations (Al, Ca, Cr, Fe, K, Mg, Mn, P, K, Na, Si, Ti, Zr and Zn) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) for the trace and rare earth element concentrations. These instruments are calibrated with certified commercial single- and multi-element standard solutions (9 for ICP-OES and 10 for ICP-MS).

Additional historic samples: these results were then combined with corresponding historical geochemical analysis of river sediment (<10 μm fraction) collected along the Bowen River stream network from 2007 to 2009 by Wilkinson et al. (2013) and Bainbridge et al. (2016), both during and following streamflow events (refer to Fig. 1 for site locations of geochemistry data). The reader is referred to those publications for their respective analytical methods. In brief, Wilkinson et al. (2013) collected suspended sediment ($n = 4$) and freshly deposited sediment ($n = 29$) samples along river bench and channels during and following flow events in the Bowen catchment. Bainbridge et al. (2016) performed laser ablation ICP-MS analysis (following Eggins, 2003) of suspended sediment ($n = 36$) samples collected across the Bowen and Bogie catchments.

The measured major element concentrations were converted to weight percent oxides and summed. The summed weights were then normalised to 100 % (i.e. exclude the loss on ignition). The same correction factors were then applied to the trace and rare earth element data.

3.3.2. Tributary junctions

3.3.2.1. Statistical analysis & mixing models. There were sufficient samples to determine tributary contributions to the downstream reaches at two locations in the Bowen catchment. Firstly, at the junction of the Broken River ($n = 8$) and Little Bowen River ($n = 24$) both contributing to the Upper Bowen River ($n = 19$). Secondly, the junction of Rosella ($n = 5$) and Parrot creeks ($n = 2$), with the Upper Bowen River ($n = 19$) all contributing sediment to the Bowen River at Myuna ($n = 14$).

To assess the degree to which each tributary source could be distinguished using the major and trace element geochemistry, the Mann-Whitney *U* test and linear discriminant analysis were used. For the Mann-Whitney U test, elements with a test statistic of *p*-value >0.05 were excluded from further consideration following Collins et al. (2010). Linear discriminant analysis was then applied to the remaining elements to identify the optimum combination that distinguished the source areas. The percentage of samples correctly classified by each individual element was then calculated. Starting with the individual element that provided the highest proportion of correctly classified samples, additional elements were added to the analysis and the proportion of source samples correctly classified were calculated. Parameters were added such that with each addition the number of samples correctly classified was maximised.

This suite of geochemical properties was then used in a mixing model to determine the relative contribution of each tributary to the downstream sediment through simultaneously minimising mixing model difference (MMD):

$$MMD = \sum_{i=1}^{n} \left| \left(C_i - \left(\sum_{s=1}^{m} P_s S_{si} \right) \right) / C_i \right| \quad (1)$$

where n is the number of elements included in the model determined by the above selection process; C_i is the distribution of the mixture sample geochemical property (i); m is the number of sources; P_s is proportion derived from that source. P_s is modelled as truncated normal distribution such that $0 \le P_s \le 1$, and the sum of all source proportions equals 1; and S_{si} is the distribution of element ($_i$) in source (Collins et al., 2010). To preserve element correlations in samples, the distributions to characterise each of the sources were determined by selecting from the measured values using a Monte Carlo approach (Hughes et al., 2009; Haddadchi et al., 2014).

The Goodness of Fit (GOF_1) was used to determine the average relative deviation of the modelled results from the measured data using the equation:

$$GOF_1 = 1 - \left(\frac{1}{n} * MMD\right) \quad (2)$$

where n equals the number of elements in Eq. (1) and MMD is the result of Eq. (1). GOF value of 1 indicates that modelled data perfectly match the geochemistry of the downstream samples. No weightings were used during the modelling process as they have been demonstrated to bias modelling results (Laceby and Olley, 2015).

3.3.2.2. Broken River and Little Bowen River. Of the 33 elements compared between the samples collected from the Broken River (n = 8 samples), and Little Bowen River (n = 24), 13 passed the Mann-Whitney U test, indicating that they could be used to discriminate between these two sources. Concentration biplots for a selection of these elements are shown in Fig. 6 for samples collected from these two tributaries and the sample set collected along the Upper Bowen River section downstream of the Little Bowen-Broken junction (i.e. upstream of the Rosella Creek confluence). Selected elements are plotted against thorium (Th), a stable element that behaves coherently during weathering, erosion and fluvial transport across the catchment (Olley and Murray, 1994). Of these elements Th, Sr, Ba and Ni provided the best discrimination between the two sources with 100 % of the samples being correctly classified back to their tributary catchments. This discrimination also reflects the distinctive geology (i.e. felsic vs mafic vs sedimentary) of these two sources (Fig. 2). The distributions of these four elements from each source and the downstream mixture were used in the distribution mixing model to estimate the contribution of the two tributaries to the downstream sediments. It's of note that one data point in the biplots for Sr and Eu plots outside the minimum bounding polygon defined by the tributary source data (sensu Smith et al., 2018). However, inclusion of this point in the model does not change the results.

Box plots and concentrations for Th, Sr, Ba and Ni for each of these sites are shown in Fig. 7; including the modelled distribution for comparison.

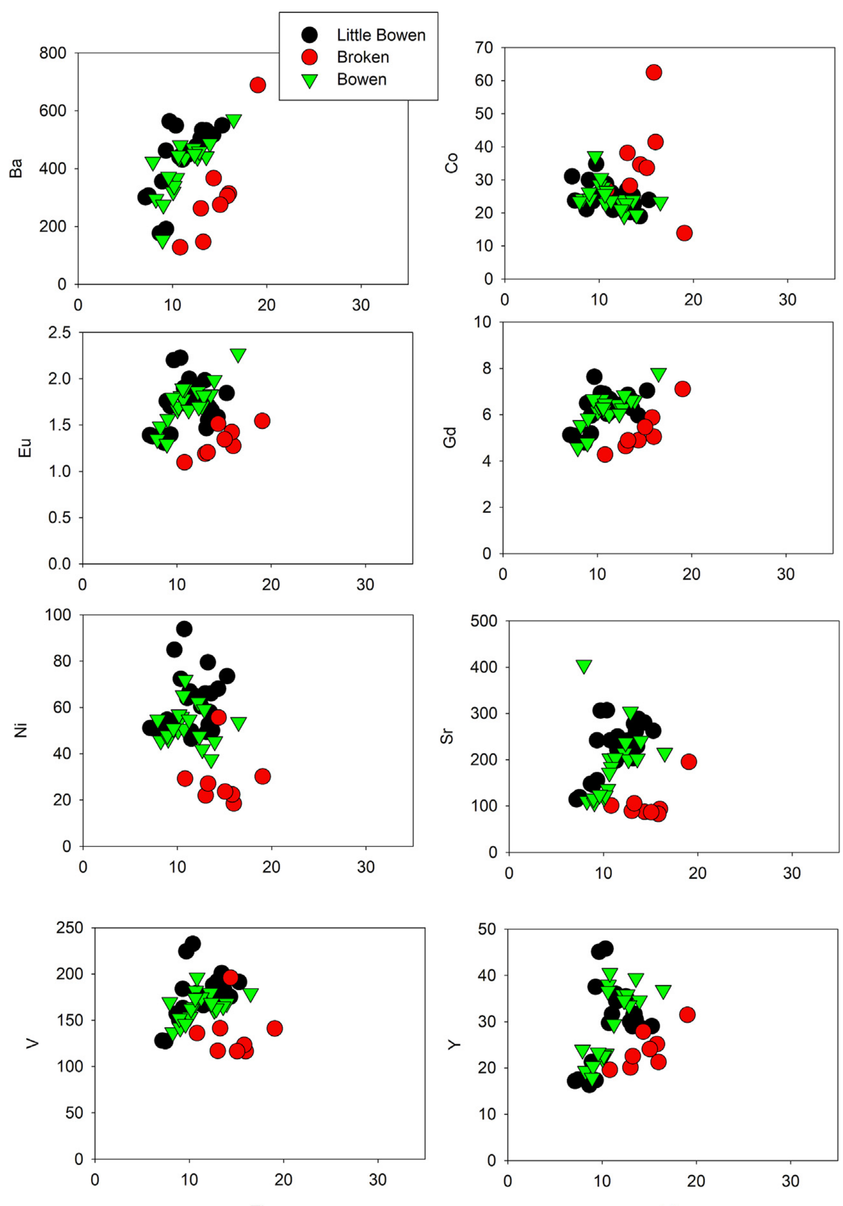

Fig. 6. Selected trace elements plotted against thorium (Th) concentrations. Sample clusters include data collected from the Little Bowen River (black circles), Broken River (red circles) and the sample set collected along the Upper Bowen River section (downstream of the Little Bowen-Broken River junction).

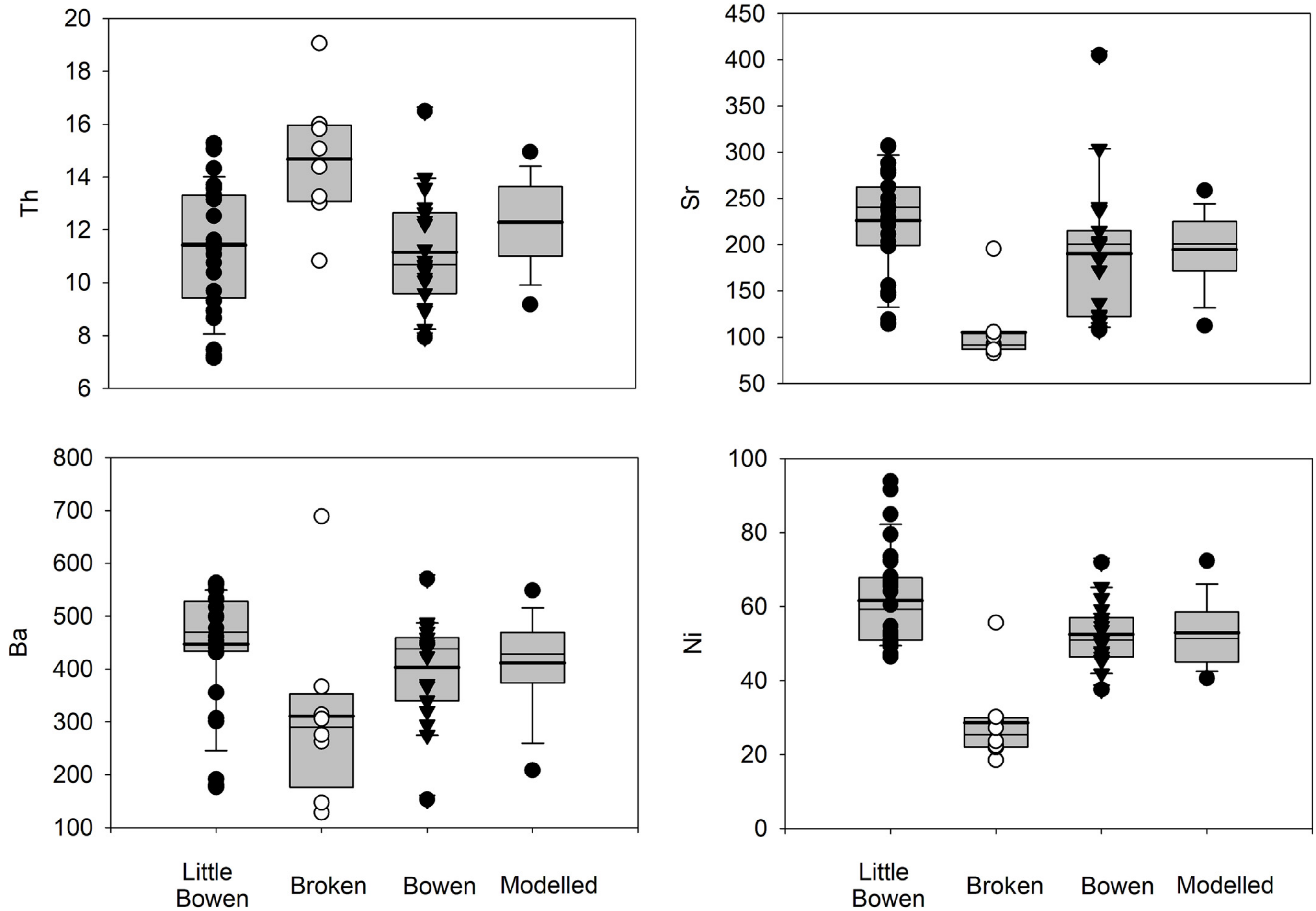

Fig. 7. Box plots and individual sample concentrations for Th, Sr, Ba and Ni for samples collected from the Little Bowen River, Broken River and the Upper Bowen River section downstream of the Little Bowen-Broken River junction, and the modelled distribution. Each grey shaded box indicates the 25 and 75 percentiles; the thick and thin lines crossing each box indicate the mean and median values respectively. For the modelled distribution, the point data indicate the maximum and minimum values generated from the mixing model.

Our mixing model suggest that 75 ± 10 % of the sediment collected downstream of the Little Bowen-Broken confluence is derived from the Little Bowen River, with a Goodness of Fit (GOF_1) of 0.96.

3.3.2.3. Rosella and Parrot Creeks and the Upper Bowen River. Only K_2O and MgO provided discrimination between the samples collected from Rosella Creek and the Upper Bowen River below the Little Bowen-Broken junction. These elements also distinguished between these two sources and samples collected from the smaller Parrot Creek tributary. Using Eq. (1), the distributions of these elements were used to determine these three source area contributions to the sediments from the downstream Bowen River (Myuna) site (Fig. 8). Box plots of the distributions for each element and the modelled distributions are shown in Fig. 9. Whilst it is acknowledged that potential source areas (channel banks, minor tributaries) were not captured in this mixing model, our best estimates suggest that the Upper Bowen River section contributes 66 ± 24 %, Rosella Creek 33 ± 24 %, and Parrot Creek ~1 %, with a Goodness of Fit (GOF_1) of 0.98.

3.3.2.4. Contributions at Myuna. Our mixing model indicated that 75 ± 10 % of the sediments collected downstream of the Little Bowen-Broken confluence are being derived from the Little Bowen River and 25 ± 10 % from the Broken River. These sediments then contribute 66 ± 24 % to the sediments collected at Myuna. This means that the Little Bowen River contributes 50 ± 20 %, the Broken River 16 ± 10 %, Rosella Creek 33 ± 24 %, and Parrot Creek ~1 % to the sediments sampled at the Myuna site (Table 1). The Parrot Creek tributary is the least represented of these sites across the combined tracing dataset. Given this tributary is a known degraded area within the Bowen catchment (Brooks et al., 2020) and that the Dynamic SedNet model predicts it makes a greater sediment contribution (Table 1), additional data especially during wetter periods, are required to further resolve the discrepancies across the two methods.

3.3.3. End of the Bowen River, and Inkerman

Where sample numbers were limited, at the end of the Bowen River ($n = 3$), and at Inkerman ($n = 1$ triplicated sample at peak flow), element concentrations were compared directly between the downstream samples and samples collected from upstream. For each element the concentration ratio (R_i) was calculated such that:

$$R_i = C_{iu}/C_{id} \tag{3}$$

where C_{iu} is the concentration of element i in the upstream sample and C_{id} the concentration in the downstream samples. A ratio of 1 indicates a perfect match. Absolute deviations were summed to determine the average deviation (GOF_2) such that

$$GOF_2 = 1 - \left(\frac{1^*}{n}\sum_{i=1}^{n}|1 - R_i|\right) \tag{4}$$

where R_i is the result of Eq. (3). The upstream samples with a value closest to 1 were considered the closest match.

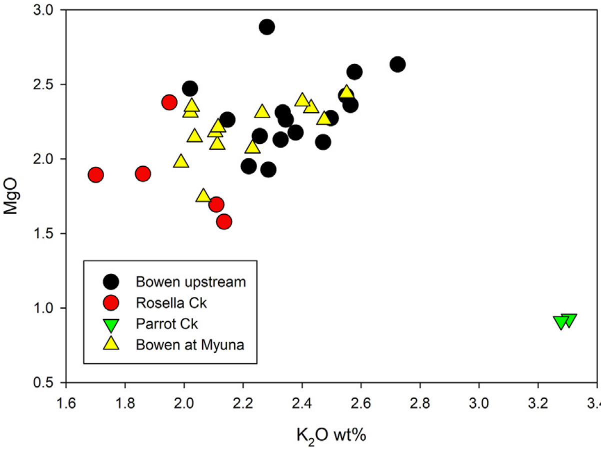

Fig. 8. Sample concentrations of K_2O and MgO for samples collected from the Upper Bowen River section (upstream of Rosella Creek), Rosella Creek, Parrot Creek and the Bowen River downstream at Myuna.

3.3.3.1. Comparison of element ratios. Of the thirty-three elements compared between the samples collected from the Bowen River at Myuna ($n = 14$ samples) and Pelican Creek ($n = 8$), three of the majors (CaO, SiO_2, and TiO_2) and eight trace (Ce, Co, La, Ni, Pr, Rb, U and Th) elements passed the Mann-Whitney *U* test, indicating that they could be used to discriminate between these two sources. The plotted trace element data (Fig. 10) show that many of the elements can also distinguish the Glenmore Creek sample (n = 1) from these other two sources.

The element concentrations of the three samples collected from the Lower Bowen River (yellow triangles in Fig. 10) all fall within the concentration range of the samples collected from the Bowen River (Myuna) site. Comparisons of the data from these three samples with the data from the Bowen River (Myuna), Pelican and Glenmore Creek using element ratios identified the best match was with samples from the Bowen (Myuna), with GOF_2 of 0.90, 0.93, and 0.97, respectively. This result highlights the dominance of the catchment source upstream of the Bowen River at Myuna, with negligible contributions from Pelican and Glenmore Creeks. This is further supported by the comparison of the normalised rare earth, Y, and Sc concentrations (see Suppl. Fig. 1). Indeed, these additional elements provide another line of evidence to independently support the mixing model results produced from the other major and trace element data.

Finally, using the same element ratio approach we compared the element concentrations for the samples collected from the Bowen River (Myuna) and the Bogie ($n = 11$) Rivers with the sample collected from the Burdekin River (Inkerman Bridge) coinciding with the peak flow during the March 2017 flood. Ratios from the Bogie River samples have several elements with significant deviations from 1 (right-side, Fig. 11). In particular, Sr was greatly enriched ($\gg 1$) whilst Ni was both enriched ($n = 2$) and depleted ($n = 9$), Cr and Co were both depleted and Na_2O was considerably enriched. The best match from the Bogie has a GOF_2 of 0.88 but with significant individual element ratio deviations in particular for K_2O, Na_2O, Ni, Cr and Co. In contrast, the closest matched sample from the Bowen River (Myuna) has a GOF_2 of 0.94 with only Na_2O, Cr, Tm and U concentrations deviating by >10 % from those measured in the end of river Inkerman sample; only this sample is plotted on the left-hand side, Fig. 11. The closest matched Bowen River sample was collected at Myuna during the 2017 March event. The data strongly indicate that the sediment sampled from the Burdekin River at Inkerman during the March 2017 flood peak was derived from the Bowen River catchment upstream of the Myuna gauge site.

4. Discussion

4.1. Comparison of monitoring and source tracing with the current spatial model

Three independently derived sediment budgets for the Bowen and Bogie catchments have been developed to form a multiple lines-of-evidence examination of fine sediment contributions (Table 1). All three approaches identify the Little Bowen and Rosella Creek tributaries as the largest fine sediment contributors, both in total load and by areal rate contribution. The Dynamic SedNet modelled loads and contributions to Myuna mostly fall within the uncertainty bounds of both field-measured budgets, however, both empirical budgets suggest the current model likely underestimates the Little Bowen contribution. The Little Bowen fine sediment load (488,800 ± 14 % t/yr) estimated by monitoring is almost double that of the current modelled load (282,300 t/yr). These empirical budgets provide minimal information about the specific sediment erosion process sources within the Little Bowen catchment. Gully density is moderate in some sections (Fig. 2). Gully, sheet and rill erosion have been observed on a variety of soil types and are not constrained to any specific soil properties – for example, slaking soils are as equally erodible as dispersive soils (Land Resources & Science, Dept of Resources, pers. comm; Wilkinson et al., 2013, 2015). In the steeper headwaters of the catchment, where shallow soils are more common, low ground cover leads to sheet and rill erosion and associated sediment transport. In these uplands, drainage lines with

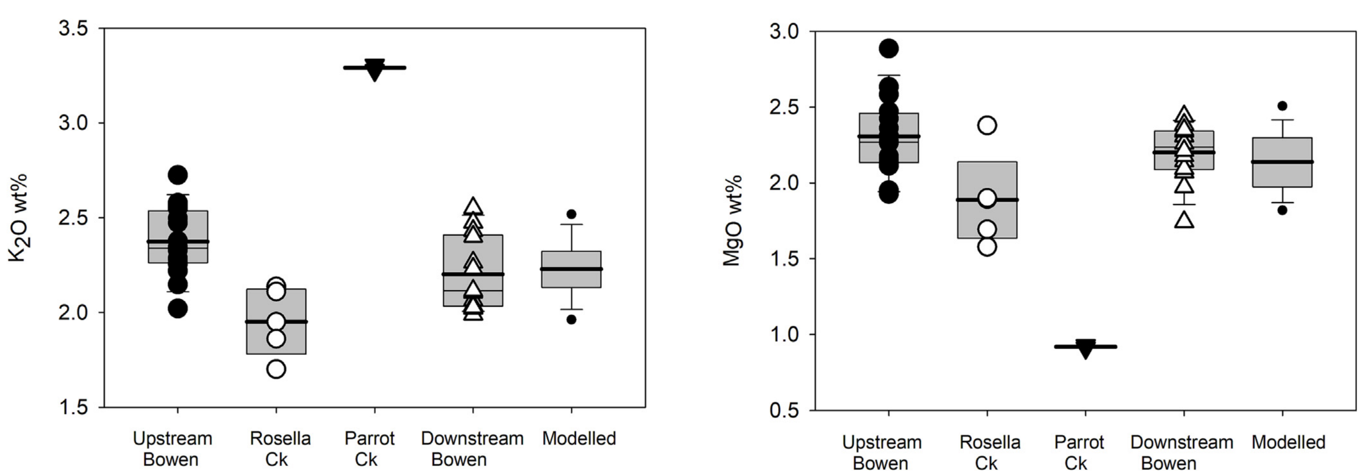

Fig. 9. Box plots of K_2O and MgO concentrations for samples collected from the Upper Bowen River section (upstream of Rosella Creek), Rosella Creek, Parrot Creek and the Bowen River downstream of these tributaries (at Myuna), and the modelled distribution. Each grey shaded box indicates the 25 and 75 percentiles; the thick and thin lines crossing each box indicate the mean and median values respectively. For the modelled distribution, the data points indicate the maximum and minimum values generated from the mixing model.

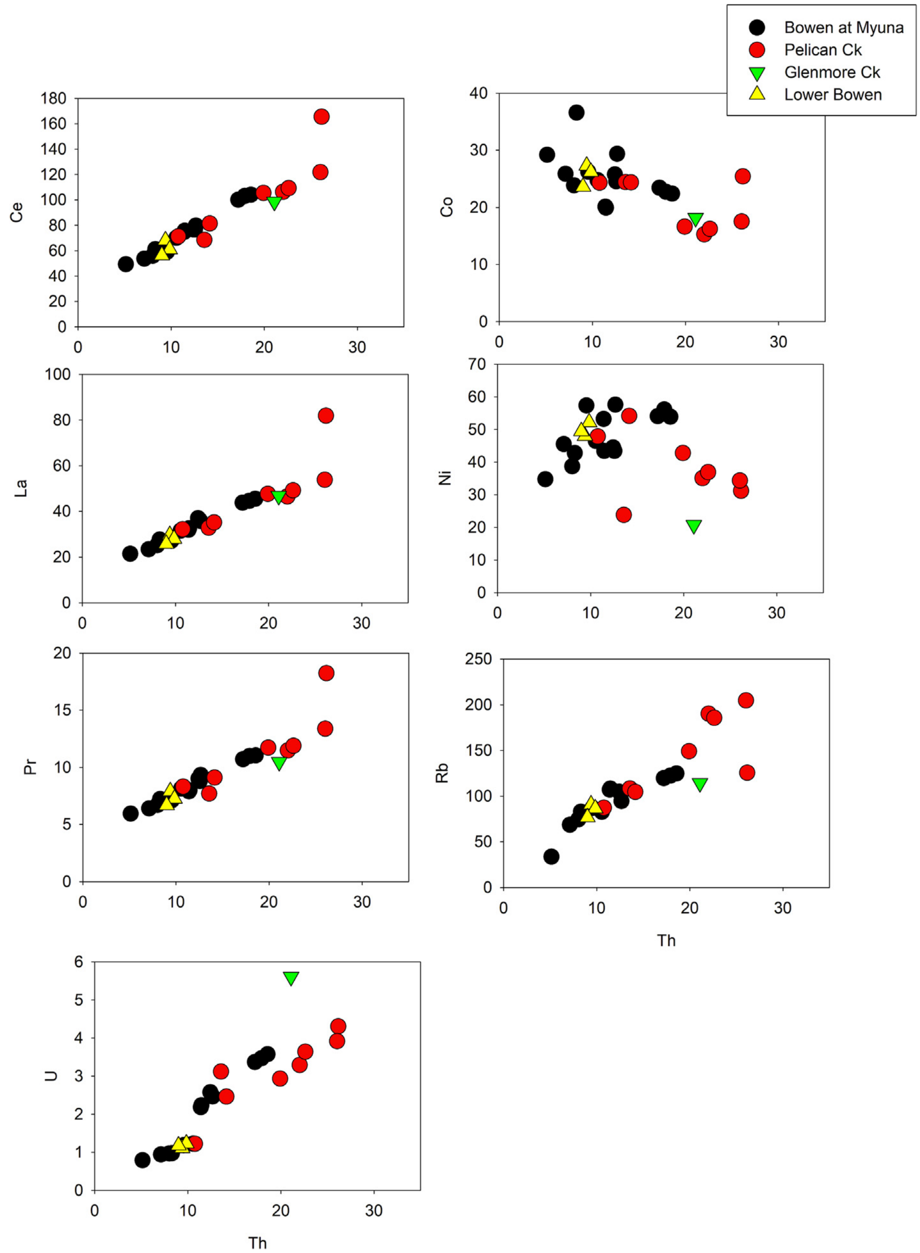

Fig. 10. Selected trace elements plotted against thorium (Th) concentrations for samples collected from the Lower Bowen River (yellow triangles), Bowen River at Myuna (black circles), Pelican (red circles) and Glenmore (green triangle) creeks.

deeper soils are characterised by active gully and streambank erosion. In the lower half of the catchment large gully complexes are associated with texture contrast soils in thick (>10 m) relict alluvia on either side of the river floodplain. The river valley is inherently an erosional landscape, thus a proportion of the erosion evident is likely to be naturally occurring, but the effects of livestock and periods of low ground cover undoubtedly lead to accelerated erosion (Land Resources & Science, Dept of Resources, pers. comm; Bartley et al., 2006).

The sediment tracing data supports the current modelled Broken River fine sediment contribution to Myuna (16 ± 10 % and 13 %, respectively), however, the Broken River was also well sampled by the monitoring program and the monitored load contribution (~1 %) suggests that the Dynamic SedNet modelled contribution is overestimated (Table 1). The monitoring data strongly supports the modelled Pelican Creek fine sediment load, and loads are also similar for Glenmore Creek, although further monitoring of this site is required. The monitoring and sediment tracing budgets do not capture the modelled load contribution from smaller tributaries (i.e. Ten Mile, Flagstone Creeks) (Table 1). We also caution the potential limitations associated with short term monitoring datasets (<5 years) and the uncertainties of both concentration measurements and modelled flow. The longer-term monitoring of the Bogie River (197,400 ± 12 % t/yr) suggests the current modelled load (117,000 t/yr) may underestimate the downstream contribution from this source. Water quality monitoring and sediment tracing data have been critical for validating modelled outputs over time, and in this case where multiple datasets agree, this budget is being used to further constrain load contributions within the Bowen and Bogie catchments within the Dynamic SedNet (model rebuild - Phase 4 - currently underway). In the case of the Broken River tributary, this includes incorporation of a refined dataset on surface rock exposure to improve the RUSLE calculation of the bare ground sediment contribution in this granitic landscape. Numerous publications outline how the RUSLE is not suitable for rangeland environments (Weltz et al., 1998; Spaeth et al., 2003) primarily due to the higher levels of heterogeneity in soils and plant properties at the plot scale, relative to cropping

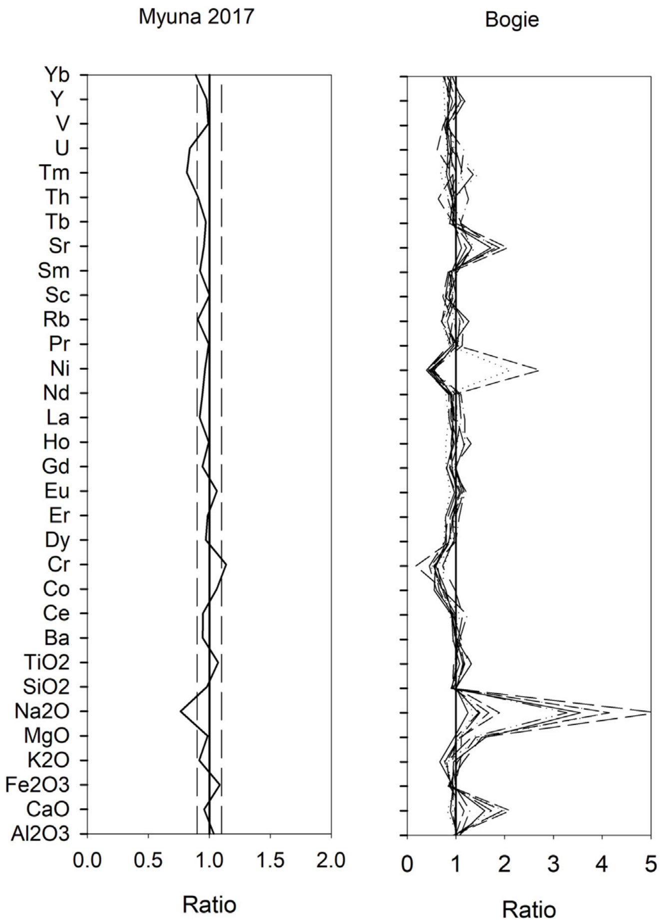

Fig. 11. Element concentration ratios for the best match from the samples collected from the Bowen River (Myuna) (left) and all of the samples collected from the Bogie River (right), relative to the Burdekin end-of-basin at the peak of the March 2017 flood. The dashed lines on the left-side figure indicate ∓10 %, solid straight lines in both indicates a ratio 1 (a perfect match). Note the change in scale between the figures.

landscapes (Nearing et al., 2011). GBR specific studies have also identified that the RUSLE generally over-predicts hillslope erosion (Hughes and Croke, 2011; Brooks et al., 2014). Several other studies have determined that runoff is generally a better predictor of sediment loss than average ground cover (Bartley et al., 2014b; Tiwari et al., 2021) and biomass and the arrangement of cover are likely better predictors of runoff than average hillslope cover (Roth, 2004; Bartley et al., 2006). Dougall and McCloskey (2017) suggest improved resolution DEM and remote sensing data will help improve RUSLE predictions, which continues to be used in the GBR Dynamic SedNet due to its utility and ability to parametrise models that cover large spatial areas using sparse datasets. In addition, empirical data from landform mapping (e.g. repeat LiDAR) would provide more data to better quantify the dominant areas of active erosion (e.g. specific gully erosion rates) to further inform the model (see relevant discussion in McCloskey et al., 2021).

Whilst our combined approach provided a much-refined representation of catchment sources, some discrepancies were identified that need further investigation. Specifically, a considerable difference between the long term mean-annual monitored load (1.8 Mt) and modelled load (0.84 Mt) at the Bowen River (Myuna) gauge site was evident and is yet to be fully explained (Table 1). Whilst the monitored load calculation for this site accounts for key hydrological processes (e.g. rising/falling limb stages, discounted flow) and draws upon longer-term measurement data, high uncertainty (which incorporates both flow and concentration measurements) remains in the annual loads calculated (Suppl. Table A2). This site experiences extreme variability in measured SS concentration data (<0.10 to 14 g/L) and has amongst the largest variability in annual sediment loads (0.1 to 7.2 Mt) across the GBR catchments (Suppl. Table A2). Continued and targeted sampling of the extreme event years (i.e. drought breaking and sediment exhaustion events) would provide SS concentration (and ideally continuous turbidity) data required to reduce the uncertainties in measured loads, and further elucidate the sediment supply and transport processes occurring in this catchment to better inform the model. In turn, these additional data may help to improve any errors associated with the modelled load calculations. Some of this discrepancy may also be due to the variations in grain size where the SS concentration measured by monitoring captures all suspended particles whilst the Dynamic SedNet model exclusively calculates the fine sediment (<20 μm) load (e.g. see Bainbridge et al., 2021). We recommend that a grain size specific SS load is calculated for future monitoring at the Myuna site so the monitoring data can be directly compared with the modelled outputs.

Our study also illustrates the benefits of involving landholders in water quality sample collection to improve the knowledge of finer-scale sediment contributions, as most of these sampling locations were inaccessible by road during wet season rainfall events. Additional water quality monitoring, including sampling of uncaptured source areas and the installation of continuous turbidity probes at key sites may reduce remaining uncertainties between the contributions from the Little Bowen, Rosella and Parrot Ck tributaries, and enable the use of more dynamic load estimation approaches. Another approach that could help better reconcile monitoring and modelling data has been demonstrated by Gladish et al. (2016), where a spatio-temporal statistical model within a Bayesian hierarchical framework was developed to assimilate the available monitoring data with the outputs of the Dynamic SedNet model, and account for uncertainties in both the measurements as well as the model defining the process. Such a modelling framework can be used to build confidence in the sediment budgets as well as further identify tributary areas for management prioritisation (e.g. see Kuhnert et al., 2018).

4.2. Strengths and limitations of the three approaches and integration

Deriving sediment budgets for large catchments in variable climates is challenging. Whilst several tools are available to define spatial patterns in sediment sources, each has its strengths and limitations which have been outlined in Table 3. It has been recognised that the power of each approach is increased when multiple lines of evidence are combined (Wilkinson et al., 2015; Owens, 2022). This study has demonstrated that combining the three approaches of water quality monitoring, sediment tracing and processed-based spatial modelling, is effective at improving the confidence of the spatial representation of erosion and associated sediment supply. The study has built on the strengths of each approach and compensated for some of their limitations (Table 3). An example of one of the challenges is the selection of the most appropriate grain size fraction for analysis, some of which relate to the different classification systems in the fields of soil science and sedimentology (i.e. sand-silt and silt-clay boundary variations), whilst others relate to the most suitable fraction for geochemical tracing analysis (<10 μm). As the Dynamic SedNet model calculates the <20 μm load and this also coincides with the fraction that travels furthest in the GBR lagoon (Bainbridge et al., 2021), we recommend the <20 μm fraction is the favoured approach in catchment to reef studies.

Combining multiple approaches requires greater effort than undertaking single studies. It typically requires collaboration across multi-discipline research teams, which requires coordination and functional institutional frameworks. Further, the benefits of catchment sediment source characterisation that applies several independent methods are realised when it is translated into policy development and actions. This can require a larger transdisciplinary approach to science and its application (Owens, 2020). Indeed, the use of a trained network of volunteers to collect water samples not only benefited this study to construct sediment budgets, but also provided an important engagement tool for landholders to better understand water quality in their local area. It is anticipated that this

Table 3
Strengths and limitations of each method for defining spatial patterns in sediment sources.

Method	Sediment budget/source modelling	Water quality monitoring	Geochemical sediment source tracing
Strengths	• Can model large river basins at fine spatial resolution • Assessment over long time periods and wide range of climatic conditions • Integrates a large number and type of input datasets (Wilkinson et al., 2014) • Represents primary source processes • Accounts for downstream sediment connectivity (Wilkinson et al., 2009) • Enables scenario modelling of source control (Lu et al., 2004)	• Concentrations and calculated loads are direct measurements of water quality rather than representations • Provides sediment yields in highly variable geographic and climatic catchments (Griffiths and Topping, 2017) useful for source identification and model calibration • Engagement as a management intervention tool	• Allows discrimination of sources upstream of sampling location • Sediment properties are less temporally variable than suspended sediment concentrations, and integrate sources during preceding events depending on sampling approach
Limitations	• Spatial resolution and accuracy of output is dependent on the input data • Large data requirement • Erosion process representations are approximations • Insufficient information to uniquely define each parameter value (for example resulting in accurate downstream load estimation but incorrect patterns of sediment sources) (Wilkinson et al., 2009). • Uncertainty in spatial datasets is poorly defined (Wilkinson et al., 2014)	• Site establishment costs limit the spatial resolution of the resulting pattern in sediment loads • Finite sampling period can misrepresent mean behaviour, especially in variable climates (e.g., Darnell et al., 2012) • Variable suspended sediment concentrations increase uncertainty, especially in streams where transport is supply-limited (e.g., Kuhnert et al., 2012) • The majority of sediment transport occurs in a very small proportion of time (Rustomji and Wilkinson, 2008), and so gaps in sampling can result in large uncertainty.	• Spatial resolution of predicted contributions is limited by the requirements for sampling and source differentiation. • Incomplete sampling of sources increases uncertainty in predictions • Finite sampling period • Sediment sources vary by unknown degrees during and between runoff events (Vale et al., 2020) • Source characteristics differ spatially (Wilkinson et al., 2015), especially as catchment area increases • Source properties vary with particle size (Collins et al., 2020)
Methods to control limitations	• Test predictions against independent datasets before management applications (this study) • Refine model inputs based on their significance to uncertainty (this study) • Monte Carlo perturbation of model inputs, or Bayesian hierarchical approaches (Pagendam et al., 2014)	• Automatic water sample collection system • Monitor turbidity as a surrogate for concentration between samples (Gippel, 1995) • Target manual sampling to runoff events (this study) • Involve and train local landholders as sample collectors (this study)	• Identify and sample all sources through catchment inspection • Sample multiple events or seasons, ideally representing climate variations of interest (this study) • Sample tributary bed sediments or use time-integrating suspended sediment sampler as more consistent sources than soils (Wilkinson et al., 2013; this study). Or sample with high temporal resolution and characterise temporal variation in properties (Vale et al., 2020). • Define the particle size distribution of sources and target sediments (Collins et al., 2020). Size-fractionate samples before analysis (Wilkinson et al., 2013; this study) • Test tracer conservativism and source differentiation and exclude those prone to non-conservative behaviour (Collins et al., 2020; this study). Trial multiple composite fingerprints (Collins et al., 2020) • Monte Carlo uncertainty and error analysis (Collins et al., 2020)

improved understanding may facilitate the uptake of improved management practices, forming a management intervention tool in itself.

4.3. Broader lessons learnt and considerations for policy

A sediment budget provides a method of accounting for sediment inputs and outputs through a drainage network, thereby enabling the major subcatchment sources of sediment in a catchment to be identified and targeted for remediation. The construction of sediment budgets in the Bowen and Bogie catchment area has evolved from a large reliance on modelling using limited monitoring data, to a more comprehensive modelling platform informed by targeted (community supported) water quality monitoring and localised sediment tracing studies. In the Bowen and Bogie catchments the use of monitoring and tracing data has improved and built confidence in the modelled sediment budget. These improvements provide greater confidence that several large Government funded remediation programs (e.g. Reef Trust Program and the Major Integrated Projects) will now target the dominant sediment sources. This avoids prioritising investments in the wrong locations and improves the chances that the remediation activities will help meet regional Reef 2050 water quality targets. Whilst monitoring and tracing approaches are traditionally considered a much more expensive exercise to develop sediment budgets in reality, at least in our example, they comprise <3 % of the remediation investment currently allocated to the Bowen and Bogie catchments. The use of trained landholders to collect water samples not only reduces the costs of monitoring but can also be used as an important engagement tool to foster improved landscape management. A multiple lines of evidence approach should be extended to other GBR regions and used to inform prioritisation of remediation investment. The coupling of modelling and measurement data will also provide increased community confidence that the modelling tools being applied are supported by regionally collected and validated data sources. This confidence would be further increased if the community are engaged in the project through sampling activities and ongoing communication of project progress and outcomes.

5. Conclusions

This study has explored the benefits and limitations of water quality monitoring, sediment source tracing and spatial modelling to identify the dominant spatial sources of fine sediment and demonstrated the benefits of integrating information from these methods in the Bowen River catchment, which is a large contributor of fine sediment to the GBR. Early spatial modelling studies developed predictions (hypotheses) about source areas at relatively fine spatial resolution which were subsequently tested by sediment source tracing. These validation efforts have resulted in progressive improvements in both model data inputs and outputs, and ultimately refined the accuracy and spatial resolution of sediment budgets.

Additional water quality monitoring and source tracing in this study have provided an even finer resolution test of the spatial sediment budget model, largely building on and further supporting these previous improvements. These data also provide priorities for further investigation of erosion processes in areas now consistently identified as having highly elevated contributions to fine sediment yield; the Little Bowen River, Rosella and Pelican Creek tributaries. The use and integration of multiple methods minimises the effect of the limitations of each method on the final result. In this application, large temporal variability in discharge and in some cases sediment concentrations within the four-year duration of sampling resulted in uncertainty in source contributions for both concentration monitoring and sediment geochemistry. Where large investments in remediation actions are proposed, it is recommended that sediment budgets be constructed using multiple methods to build confidence in the modelled dataset before prioritisation of remediation commences. Where this is not feasible, we recommend that limitations of such preliminary assessments in the absence of empirical data are acknowledged, with the view to incorporate future field measurements to refine the budgets such as in this GBR example.

These data also provide priorities for further investigation in areas of the catchment which remain uncaptured or poorly sampled, including the central corridor adjacent to the river, and for refinement of model inputs in these areas. The spatial configuration of drainage systems complicates concentration monitoring and source tracing in that area, and improved mapping of hillslope, gully and streambank erosion appears to be a more advantageous approach, especially of gully erosion given the large contribution predicted by the model. We note that as model predictions have improved over two decades of sediment studies in this catchment, the practical benefit from further spatial sediment budget model refinement for targeting investment in erosion remediation will be smaller than from past improvements. Quantifying the effectiveness of remediation investments to reduce erosion and fine sediment loss in these priority areas is a greater priority for further investigation in this catchment.

CRediT authorship contribution statement

Zoe Bainbridge: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft, Funding acquisition. **Jon Olley:** Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Scott Wilkinson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Rebecca Bartley:** Supervision, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Stephen Lewis:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Cameron Dougall:** Methodology, Formal analysis, Writing – review & editing. **Sana Khan:** Visualization, Writing – review & editing. **Petra Kuhnert:** Formal analysis, Writing – review & editing. **Joanne Burton:** Resources, Writing – review & editing, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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