

Target the right gullies using the right approach to achieve the GBR Water Quality Targets

Andrew P. Brooks^{1,2}, James Daley¹, John Spencer¹, Justin Stout^{1, 4}, Graeme Curwen³, Tim Pietsch¹, Robin Thwaites¹, Nicholas Doriean¹.

¹Griffith Coastal and Marine Research Centre, Griffith University, Southport, QLD

²School of Environment and Science, Griffith University, Southport, QLD

³Australian Rivers Institute, Griffith University, Nathan, QLD

⁴Utah State University, Logan Utah, USA.

Key Points.

- Prior to the establishment of the NESP Tropical Water Quality Program in 2015, there was little understanding of which gullies were the dominant sediment sources to the GBR, how they should be remediated, what sort of sediment reductions could be achieved, how many and which ones needed to be remediated to achieve GBR water quality targets, how long it would take to achieve such reductions, and at what cost?
- NESP Research between 2016 and 2020 addressed each of these issues and key results are presented:
- It has been demonstrated that large scale (i.e. sites > 1ha) rehabilitation of alluvial gullies can achieve >95% sediment reductions in 1 – 2 years
- High resolution gully mapping in priority sub-catchments shows us that 30% of the fine sediment load is sourced from between 1.5–3.5% of the gully population. Alluvial gullies produce the majority of the sediment in the small cohort of gullies producing 30% of the yield. This now provides the means to identify which individual gullies should be targeted for rehabilitation.
- These data show that the ambitious Reef2050 water quality targets for sediment are now achievable, at substantially less cost than the previous estimate of ~\$8Bn (likely < \$1Bn). However, substantial coordination and upscaling of current effort remediating the priority gullies is required to meet the targets, given that the net sediment reduction from the experimental sites presented here represent around 1% of the sediment reduction target for each catchment.

Keywords

Gully rehabilitation effectiveness, gully mapping, Great Barrier Reef, water quality targets, gully prioritisation

Introduction

Fine sediment is a threat to the Great Barrier Reef (GBR) and there has been increasing recognition over the last decade that gully erosion represents a major source of post-European accelerated erosion and consequently a major source of sediment and nutrient pollution to the GBR Lagoon (GBRL) (Brooks et al., 2013; Olley, et al., 2013; Wilkinson et al., 2015). Current estimates are that on average around 40% - 50% of the fine sediment load delivered to the GBRL is sourced from gully erosion (Wilkinson et al. 2014, McCloskey et al., 2021), although these modelled estimates are only loosely constrained, and vary considerably between catchments.

Given the pressing need to reduce the stress on the GBR from impaired water quality, amongst other stressors, the Australian and Queensland Governments have jointly developed ambitious water quality improvement targets for each of the GBR catchments and regions, as outlined in the Reef 2050 Water Quality Improvement Plan (Anon 2018). Initial estimates of the investment required to meet the fine sediment reduction targets across the entire GBR by were put at \$7.8bn to achieve a reduction of around 3 million tonnes of fine sediment (Alluvium 2016). For the Normanby and Burdekin catchments which are the focus of this paper, the end of catchment (EOC) fine sediment reduction targets are 15 kt/yr and 890 kt/yr respectively by 2025 (Anon 2018). If we assume a delivery ratio of 0.45 and < 20µm material fraction of 60%, (Brooks et al., 2020; Howley, 2020), in the Normanby this equates to an erosion reduction at source of around 55 kt/yr;

and in the Bowen/Bogie/Broken (BBB) sub-catchments in the Burdekin this amounts to around 1.1Mt at source (assuming the BBB is the source of 70% of the Burdekin EOS sediment load – *sensu* Bainbridge et al 2014, with a P2R SDR of 0.94 and an average < 20 μ m material fraction of ~60%). Sediment tracing data indicates that at least 84% of the fine sediment in the Normanby was derived from sub-surface sources (i.e. channel and gully erosion) (Olley et al., 2013), and even higher than this (90-95%) in the upper catchment from where the majority of the sediment is sourced. In the Burdekin sub-surface sources represent 83-94% of the sediment load (Wilkinson et al., 2013). Hence, significant inroads into the water quality targets in these catchments will only be made through rehabilitation of the key sub-surface sediment sources, particularly gully rehabilitation, given that addressing channel erosion has not been a major focus in either catchment to date.

At the commencement of the NESP Tropical Water Quality Hub Program in 2016 gully erosion rehabilitation efforts undertaken in GBR catchments were focused on the less active, smaller scale gullies which could be dealt with using grazing management, manual labour and low-tech solutions (Thorburn and Wilkinson, 2013, Wilkinson et al., 2015). At this time there was no accepted practice as to how these major alluvial gully pollution sources could be successfully rehabilitated and stabilized, nor was there verified evidence of what sediment reductions could be achieved. Some initial plot-scale trials that had been undertaken in the Laura/Normanby Catchment in Cape York (Shellberg and Brooks, 2013; Brooks et al., 2016) suggested that reductions of sediment yield of 80% -90% were achievable in periods of 1 – 2 years, but there was very little published evidence for how *whole* alluvial gully systems should be treated and the likely effectiveness and longevity of these treatments. International examples for treating similar types of gullies was also lacking (Bartley et al., 2020).

In this paper we firstly present results from high resolution gully mapping that was undertaken across ~5300km² in the Normanby, Bowen/Bogie and Fitzroy catchments that provides insights into where effort needs to be targeted and how many (primarily alluvial gullies) need to be rehabilitated in order to achieve the GBR water quality targets. We then present key results from the first large experimental alluvial gully rehabilitation projects at Crocodile Station (-15.6699S;144.5944E) in the Normanby catchment (4 gullies), and Strathalbyn Station (14 gullies) in the Burdekin catchment (-20.1897S;147.3261E). Full details of the study sites, the treatment approaches and the project methods can be found in Brooks et al. (2021) and Daley et al (2021). Detailed analysis of the differences between different treatments is beyond the scope of this paper, so here we summarise the net sediment reductions achieved across the study sites and the key findings from the gully mapping and prioritisation.

Methods

Gully Mapping and Prioritisation

Semi-automated gully mapping was carried out at a resolution of 1m² across an area of 5,288 km² within gully hotspot regions in three GBR catchments; the BBB, Fitzroy and Normanby (Daley et al., 2021). Lifetime sediment yields were determined for all gullies using an objective method for reconstructing the prior land surface combined with an analysis of the initiation dates derived from detailed site scale analyses of 51 gully systems. A full description of the methods is provided in Daley et al (2021).

Table 1: Summary statistics of gullies within each study area

	BBB	Fitzroy	Normanby	Total
Area of analysis (km ²)	3507	1210	571	5288
No. of gullies	22311	1785	1820	25916
Gully area (ha)	4621	312	563	5496
Proportion of land gullied (%)	1.32	0.26	0.99	1.04
Proportion alluvial:hillslope (%) by area	43	60	91	49

Gully treatments

A full description of the treatments undertaken at all gullies is provided in Brooks et al (2021), so only a brief summary is presented here. At Crocodile, site 2.234 involved full reshaping, gypsum treatment and rock capping of three merged arms of a gully system, while the other treatments (0.1, 0.2 and 1.1) are restricted to rock chutes at the head of single gullies. In this case the experiment was monitoring the effectiveness of full gully treatment compared with just headscarp treatment. The treatments at Strathalbyn all involved the complete reshaping of entire gullies, with gypsum treatment and a range of different surface capping and revegetation strategies, with most involving rock capping and/or various surface mulch treatments of the gully slopes and rock capping and/or series of rock check dams in the gully floor. At each site a Before/After/Control/Impact (BACI) study design was employed to enable comparison between the various treatments and one or more controls before and after the treatments were implemented.

Measuring Rehabilitation Effectiveness

Gully rehabilitation effectiveness was measured in multiple gullies at the two sites, using two fundamentally different and complementary methods. First, detailed high resolution lidar (min 100 ppm²) was collected at regular intervals over the three years of the study (7 surveys total), before and after each wet season, and topographic change determined from DEM of Difference (DoD) analysis with a Limit of Detection (LoD) of 0.2m. From these data total sediment yield was determined at the control gully and each of the treatments. Note the lidar data only measures the erosion from within the active gully. Baseline yields were determined at most sites prior to rehabilitation works being undertaken from lidar DoD analysis and longer term airphoto timeseries analysis. The rehabilitation effectiveness was then determined through comparison of the net sediment yields before and after treatment, as well as by comparison with the untreated control each year. Second, water quality monitoring was undertaken using a range of different monitoring techniques and the suspended sediment concentrations and modelled loads compared with the control each water year. Note that the water quality monitoring data at the gully outlet measures the sediment yield from the gully and its catchment, hence ideally water quality should be sampled at the gully head as well to enable the full effect of the treatment to be assessed. To account for variation in the baseline yields of the respective gully treatment areas with respect to the control (a sometimes significant variation), the observed annual yields are adjusted as a function of the ratio of the baseline yield at the treatment site compared to the control baseline yield, as shown in equation 1:

$$SYT_a = \frac{SYT}{SYT_b/SYC_b} \quad (1)$$

Where SYT_a = the adjusted sediment yield for the given treatment gully in t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC data is being used (assuming that the same metric is used for each term in the equation – i.e. t/ha/mm cannot be mixed with t/m³); SYT = the observed sediment yield for the given treatment gully; and SYT_b and SYC_b are the treatment site and controls baseline sediment yields respectively, all with the same units - i.e. t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC data is being used. In this case the yields do not need to be normalised for area as well, as this is inherent in the discharge calculations. Rehabilitation Effectiveness Ratio (RER) is then defined in two ways; first as:

$$RER_{CI} = \frac{SYC - SYT_a}{SYC} \times 100 \quad (2)$$

Where CI denotes control & Impact (treatment) of different gullies across the same time period; SYC = sediment yield of control gully in t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC data is being used; SYT_a = adjusted sediment yield of the treatment for the same time period as the control in t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC data is being used (i.e. controlling for hydrology), or

$$RER_{BA} = \frac{SYB - SYA}{SYB} \times 100 \quad (3)$$

Where *BA* denotes Before/After treatment; *SYB* = sediment yield of the treated gully before treatment in t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC data is being used; *SYA* = sediment yield of the same gully post treatment in t/ha/mm of incident rainfall for each water year (for lidar DoD data), or alternatively t/m³ of discharge for each water year where monitored SSC is being used (controlling for edaphic factors). Using this metric for assessing the effectiveness of a gully rehabilitation treatment an RER of 100% means the gully is no longer producing any sediment. It is also possible to achieve a RER of > 100% (which means the gully is a net sediment sink).

Results

Gully Mapping and Prioritisation

Gully hotspot areas were identified in three GBR catchments (Normanby, Burdekin, Fitzroy) from previous work (Brooks et al., 2016; Wilkinson et al., 2015) and targeted for lidar data capture. A semi-automated mapping approach was then undertaken to map all gullies across the 5288 km² of target lidar data. The mapping enabled the identification of around 26,000 active gullies across the three regions as outlined in Table 1. A key insight from this mapping is that there are many features in these landscapes that have the appearance of gullies, but many are not actively eroding, and are therefore not priorities. An example of the output derived for the Bowen catchment is shown in Figure 1. Not only were gullies categorized according to sediment yield, but they were also classified according to whether they are alluvial or colluvial (hillslope) gullies, with the colluvial category further sub-divided into a rugged class, as shown in Figure 2 (see Daley et al., 2021). The rugged gullies are found in steep rocky terrain and can be quite numerous in some catchments (such as the Fitzroy), but the rugged variant typically has lower sediment yields than the standard colluvial gullies due to the fact they tend to occur in coarser and less extensive colluvial material. As can be seen in Figure 2 the relative proportions of these major gully types vary between catchments in terms of their spatial extent and varies further again according to the relative sediment yields of each type. For example, in the BBB the area of colluvial gullies is greater than (~ 60%) the total area of alluvial gullies, but when the lifetime sediment yields are compared, the total lifetime yield from all alluvial gullies is around 54% of the total.

The disparity between the type of gully yielding the greater proportion of the sediment to the GBR Lagoon is even greater when we consider the small cohort of gullies that are producing a disproportionately large amount of the total sediment yield. From Figure 3 it can be seen that only 2% of the mapped gullies in the BBB contribute 30% of the total sediment yield, while 6% contribute 50%. Of the 2% of gullies contributing 30% of the sediment load, around 65% are alluvial. Hence by targeting the highest yielding gullies using methods outlined for the Crocodile and Strathalbyn Station sites, significant inroads can be made towards achieving the GBR water quality Improvement targets. Similar curves are evident in the Fitzroy and Normanby catchments albeit with slightly different proportions (1.5% and 3.5% respectively) contributing 30% of the sediment yield, and 4% and 10%, respectively contributing 50% of the yield.

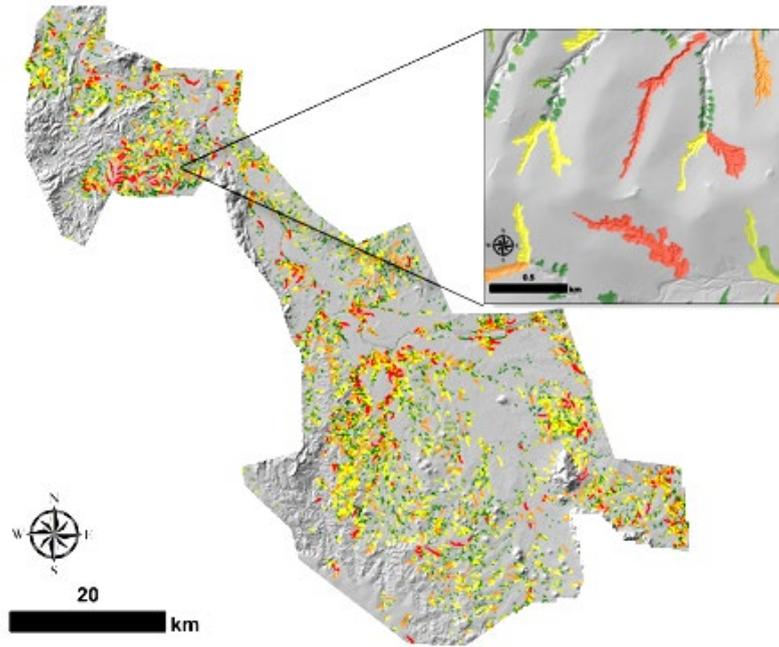


Figure 1. Example of the gully heatmap output for the Bowen catchment with the higher yielding gullies shown in warm colours (orange/reds) and the lower yielding gullies in the cooler colours (yellows/greens).

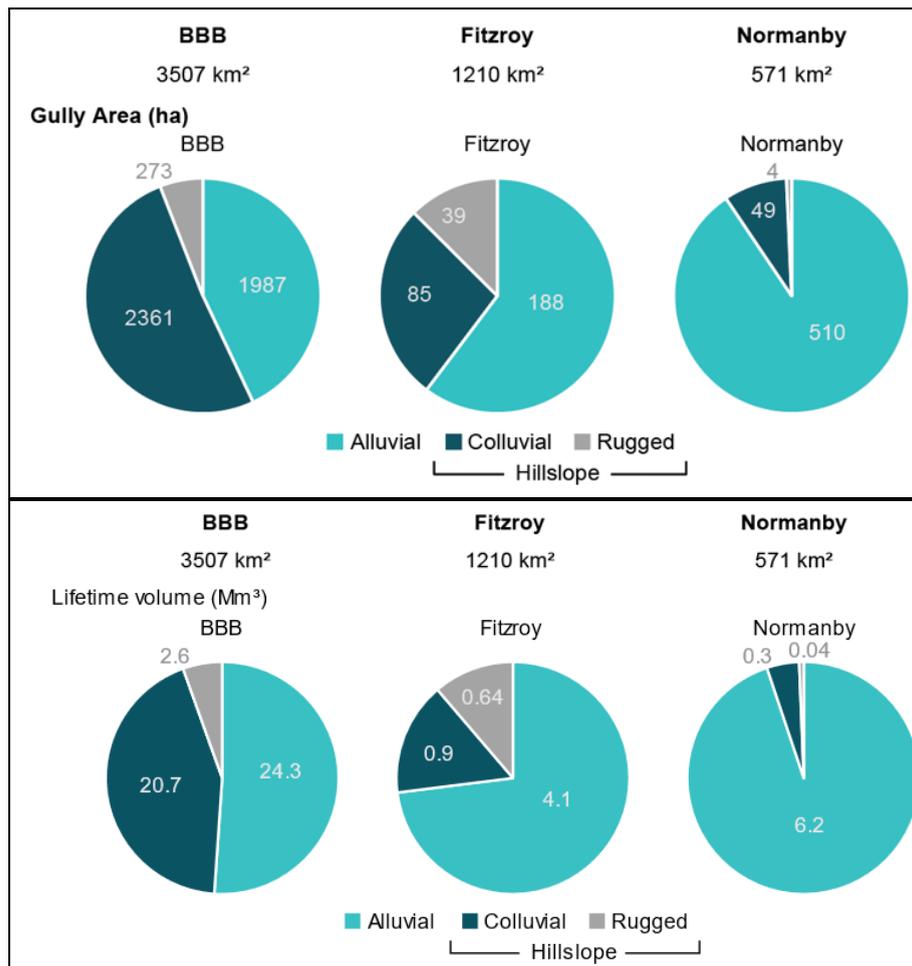


Figure 2. The relative breakdown of the gully population in each region according to gully area (top three graphs) and then according to lifetime sediment yield to present day (lower three graphs)

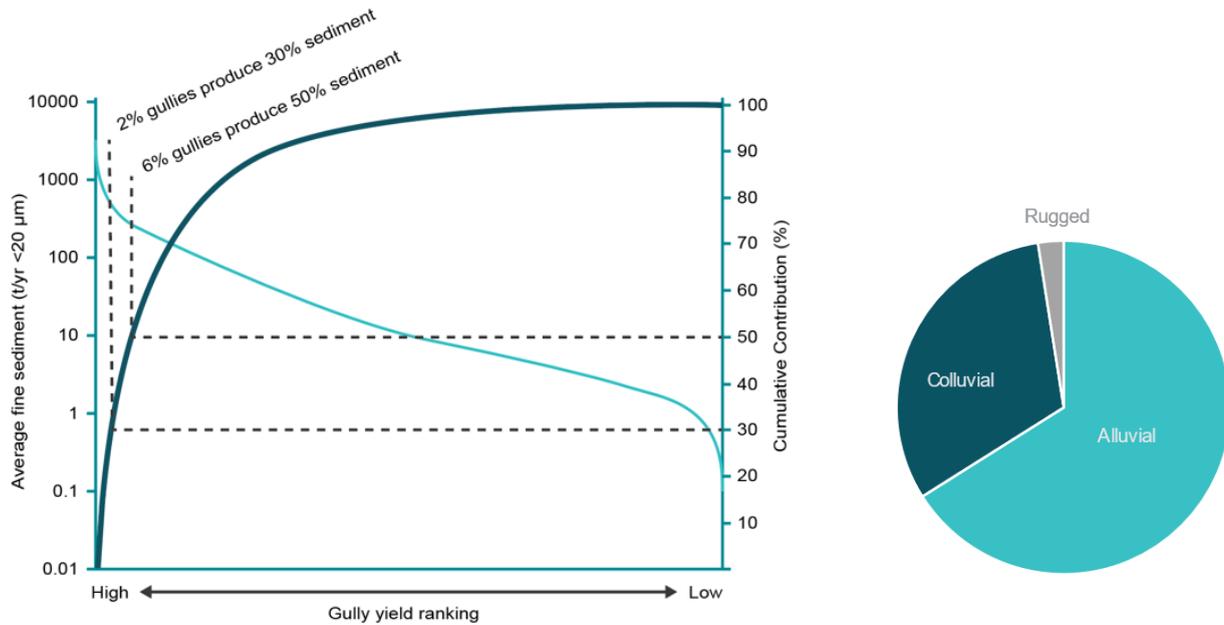


Figure 3. Graph showing the cumulative contribution of individual gullies to the total sediment yield when ranked from highest to lowest; and (right) the proportion by gully type of the 2% of gullies that contribute 30% of the total load. Dark blue line = cumulative contribution; light blue line (LH axis) is the trend line of the sediment yields of individual gullies ranked from highest to lowest (left – right respectively)

Gully Rehabilitation

The following outlines the results of the first two large field experiments of alluvial gully rehabilitation at sites in the Normanby (Crocodile Station) and Burdekin (Strathalbyn Station) catchments which aim to test the effectiveness of rehabilitation treatments that are targeting typical high yielding gullies in GBR catchments. Space constraints do not permit a full description of the experiments and all permutations of the results, so only the headline results are presented here. For a full description of the treatments and the detailed results see Brooks et al. (2021).

Crocodile Station Sites

The images in Figure 4 shows an example of the lidar derived topographic monitoring that was undertaken at all sites, providing one line of evidence of the rehabilitation effectiveness. Space does not permit us to present the evidence from the water quality monitoring, but for the Crocodile sites these can be found in Doriean et al. (2021). The data in Table 2, summarises the rehabilitation effectiveness achieved after 2 years at sites 0.1, 0.2 and 1.1 and three years for site 2.234. Rehabilitation effectiveness ranges from 0.62 – 0.95 comparing both the before/after metric and the control/Impact/ associated with gully head rock chute treatments at sites 0.1-1.1. By comparison the remediation effectiveness at gully 2.234 is slightly more than 100%, reflecting the fact that the gully has experienced net sediment deposition from sediment sourced from the gully catchment. It should be highlighted that the topographic data presented here do not include the gully catchment contributions, which are represented in the water quality monitoring data (Doriean et al., 2021). These data show that at the end of gully SSC has reduced by > 80% post rehabilitation, but the measured input to the gully head can account for virtually all of the remaining sediment export.

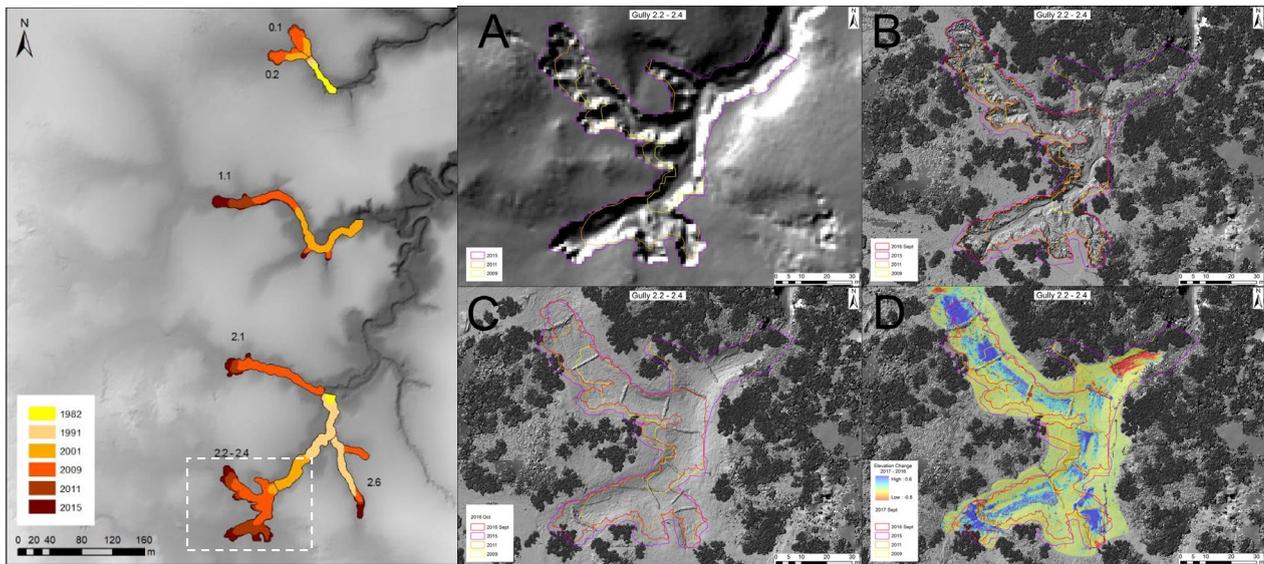


Figure 4 Crocodile Gape site showing the locations of the treatment (and control 2.1) gullies showing their historical growth rates from which baseline yields were determined. A-D shows the before and after treatment gully condition for gully 2.234 (see inset box). NB site 2.6 not part of the study. Repeat surveys of standard airborne LiDAR shown in (A) were used to determine baseline erosion rates. Repeat surveys from 2009, 2011 & 2015 (yellow, orange & purple lines respectively) show gully growth rates over this 6 year period. Terrestrial LiDAR surveys from Sept 2016 (B); Oct 2016 (C) and Oct 2017 (D) show the gully before (B) and after rehab (C) and then DoD changes after 1 wet season post rehabilitation (D) where blues are deposition and reds erosion.

Table 2. Effectiveness data for all sites for the 2018/19 wet season and for sites 2.234 and Control for the Rehabilitation effectiveness between 2016-19. A full description of the two RER terms is outlined in the text.

Sept 2019 - Sept 2018		annual RF (mm) = 929				adjusted load of baseline (t/ha/mm)	RER _{CI} (lidar)	RER _{BA} (lidar)	diff.
Treatment	area (ha)	t (lidar)	t/ha	t/ha/mm					
2.1 Control	4.2	131.9	31.4	0.03	0.034				
2.234	13.5	2.8	0.2	0.0002	0.0003	99%	98%	1%	
1.1	10.4	55.3	5.3	0.0057	0.0051	85%	77%	8%	
0.1	7.4	14.2	1.9	0.0021	0.0016	95%	93%	2%	
0.2	1.9	10.1	5.3	0.0057	0.0086	75%	62%	13%	
Sept 2019 - Sept 2016		3 yr RF (mm) = 2969							
2.1 - Control	4.2	336.8	80.2	0.03	0.027				
2.234	13.5	-1.1	-0.1	-0.00003	-0.00004	100.2%	100.2%	0%	

Strathalbyn Station Sites

The location of the fourteen gully treatment and control sites encompassing around 20 ha of active gully can be seen in the map in Figure 5, which also shows the locations of various sampling equipment. The associated rehabilitation effectiveness data for each of these treatments are presented in Table 3 from which it can be seen that average effectiveness when data is pooled across all sites is 98% across both monitoring years. Note, however, that there is some variation at a couple of the sites (notably Site A1 and Treatments 2, 6 and 8B) where lower cost treatments were used to test the effectiveness of lower cost surface treatments. Also included in the tables are the water quality monitoring results normalized to gully discharge to account for the fact that there are differences in catchment area between the treatment sites, and that the catchment area changes as a function of the rehabilitation strategy. These data demonstrate that for the large highly active gullies (e.g. treatments 1, 3, 4) for which we have both topographic and monitored loads data, that the rehabilitation effectiveness ratios are very similar regardless of which method is used. This provides a considerable degree of confidence in these results.

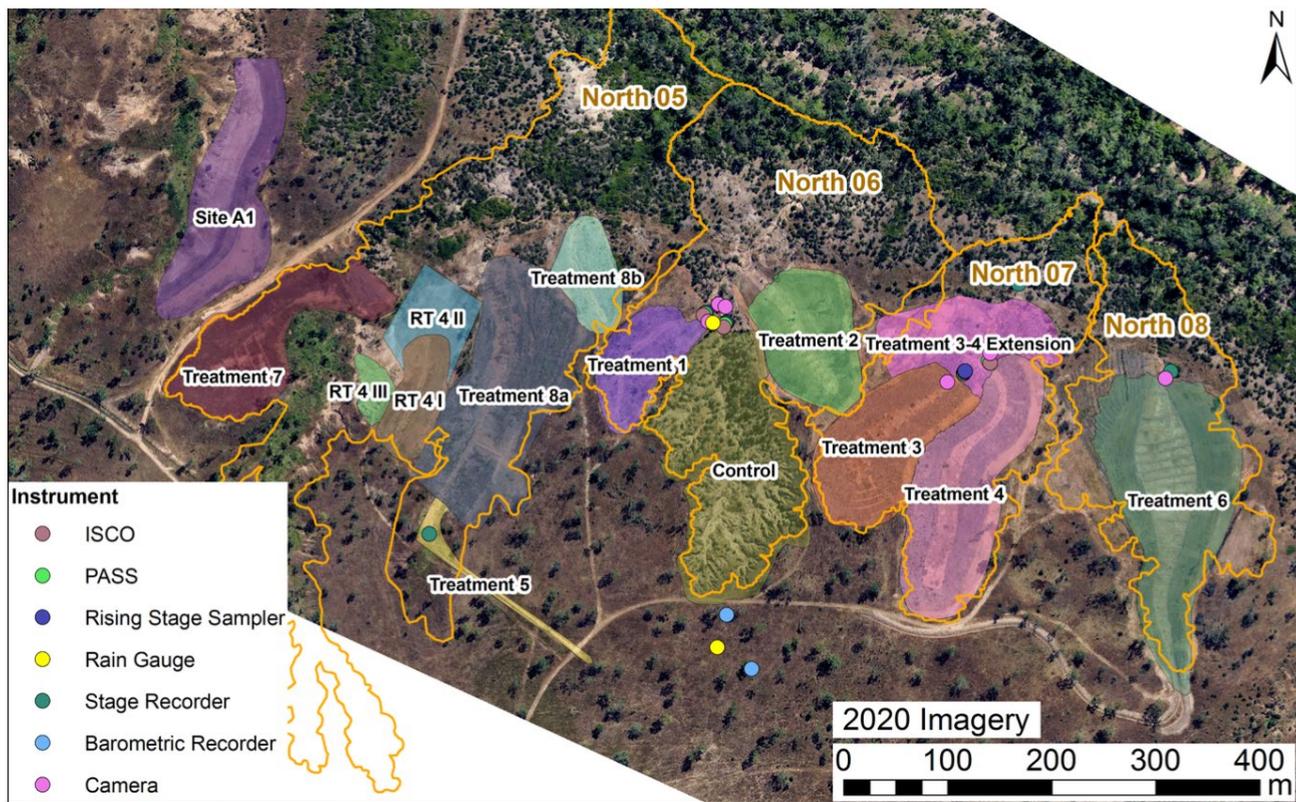


Figure 5. Location of the various gully treatments and control gullies at the Strathalbyn Northern Gully site. For a full description of the treatments refer to Brooks et al., 2021.

Discussion of Rehabilitation Effectiveness

From the results presented in Table 3, it is apparent that the optimal treatments employed here (i.e. full reshaping and excavation of all tunnels, terra forming, soil amelioration using gypsum, gully slope/sidewall capping using rock and/or organic mulch treatment, and gully floor capping with rock and/or rock check dams) can achieve very significant fine sediment reductions that are highly resilient if completed to these high standards. The treatments that employed these more stringent treatments (e.g. treatments 1, 3, 4, 7 & 8a) achieved an average sediment reduction of 98% over a period of one to two years with only minimal need for maintenance. Treatments that employed lower cost treatments, and particularly those that had bare ground exposed on the gully floor, and/ mulch only surface treatments of the gully slopes (e.g. treatments 2, 8b, 6, and site A1) tended to have lower effectiveness ratios requiring more maintenance. Time will tell whether the cost saving upfront is worth the ongoing costs that will incurred as a result of the lower cost treatments.

The results from all of the rehabilitation experiments at both these sites fills a major knowledge gap that existed when this NESP research program commenced just 5 years ago. For the first time we now have a robust method for achieving the GBR water quality targets at the appropriate scale. However, despite the success of these experiments they both only represent about 1% of the water quality reduction targets for each catchment respectively. Hence for the targets to be achieved, a significant upscaling of effort and investment is required. For this to be achieved the right gullies need to be targeted. Fortunately, we now have the means for targeting such efforts based on high resolution mapping and prioritization of the highest yielding gullies (Daley et al., 2021).

Table 3. Summary statistics showing the DoD erosion data for the various treatments from Sept 2018 to June 2019 & Sept 2019 – May 2020. Mean bulk density for conversion of volume to mass was 1.67. Note these are total erosion figures. Erosion rates for each treatment gully are shown in terms of total annual load (t), specific yield (t/ha), and specific yield per mm of incident rainfall recorded on site. Also shown are the Rehabilitation Effective Ratios both as a comparison between the control based on the adjusted rainfall normalised load (t/ha/mm) and the ‘before’ baseline data for the same site. Last row = WQ monitoring data.

June 2019 - Sept 2018		annual RF (mm) = 1071							
Treatment	area (ha)	t	t/ha	t/ha/mm	adjusted load cf			diff.	Effectiveness ratio SSY/m ³
					baseline (t/ha/mm)	RER _{CI} (lidar)	RER _{BA} (lidar)		
Control	2.77	2530.6	914.75	1.78	1.78				
RT 4 I	0.54	3.5	6.45	0.01		98%	98%	0%	
RT 4 II	0.48	3.1	6.49	0.01		98%	32%	66%	
RT 4 III (control)	0.25	87.6	345.35	0.32		cntrl			
Site A1	1.08	64.2	59.47	0.06	0.84	53%	21%	32%	
Treatment 1	0.73	3.9	5.34	0.00	0.01	99%	99%	0%	99%
Treatment 2	1.12	33.8	30.18	0.03	0.19	89%	82%	7%	
Treatment 3	1.45	16.0	10.99	0.01	0.01	99%	99%	0%	96%
Treatment 3-4 Ext	1.08	9.5	8.85	0.01	0.02	99%	98%	1%	
Treatment 4	1.93	2.6	1.33	0.00	0.00	100%	100%	0%	99%
Treatment 6 (baseline)	3.90	1060.7	272.32	0.25					
Treatment 7	1.51	10.75	7.13	0.01	0.02	0.99	0.98	1%	
Treatment 8a	2.41	37.54	15.60	0.01	0.04	0.98	0.96	1%	
Treatment 8b	0.54	30.99	57.87	0.05	0.28	0.84	0.73	11%	
Totals	19.78	3894.8							
	all treatment average		16.8	0.014		98%			
	all control average		278.8	0.542					

Summary & Conclusion

The results presented here provide significant optimism that the Reef 2050 water quality improvement targets are indeed achievable if the optimal treatments outlined here are implemented and if the high yielding gullies identified (along with surrounding gullies) are targeted for rehabilitation. Additional works have been completed at Strathalbyn since these results were finalized, and it is now apparent that fine sediment savings of around 10,000 t/yr have been achieved at this property at a capital cost of around \$3.8M, or around \$5.5M if all overheads are taken into account. While good progress is being made towards addressing the targets using approaches like those employed here, if the interim sediment reductions in the Burdekin alone are to be achieved, an additional ~ 83 sites of a similar magnitude are required to achieve the targets in that catchment. If significant efficiencies and economies of scale can be found due to upscaling and prioritization of effort the GBR wide targets are achievable for less than \$1Bn, which is substantially less than the original estimates of ~ \$8Bn.

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