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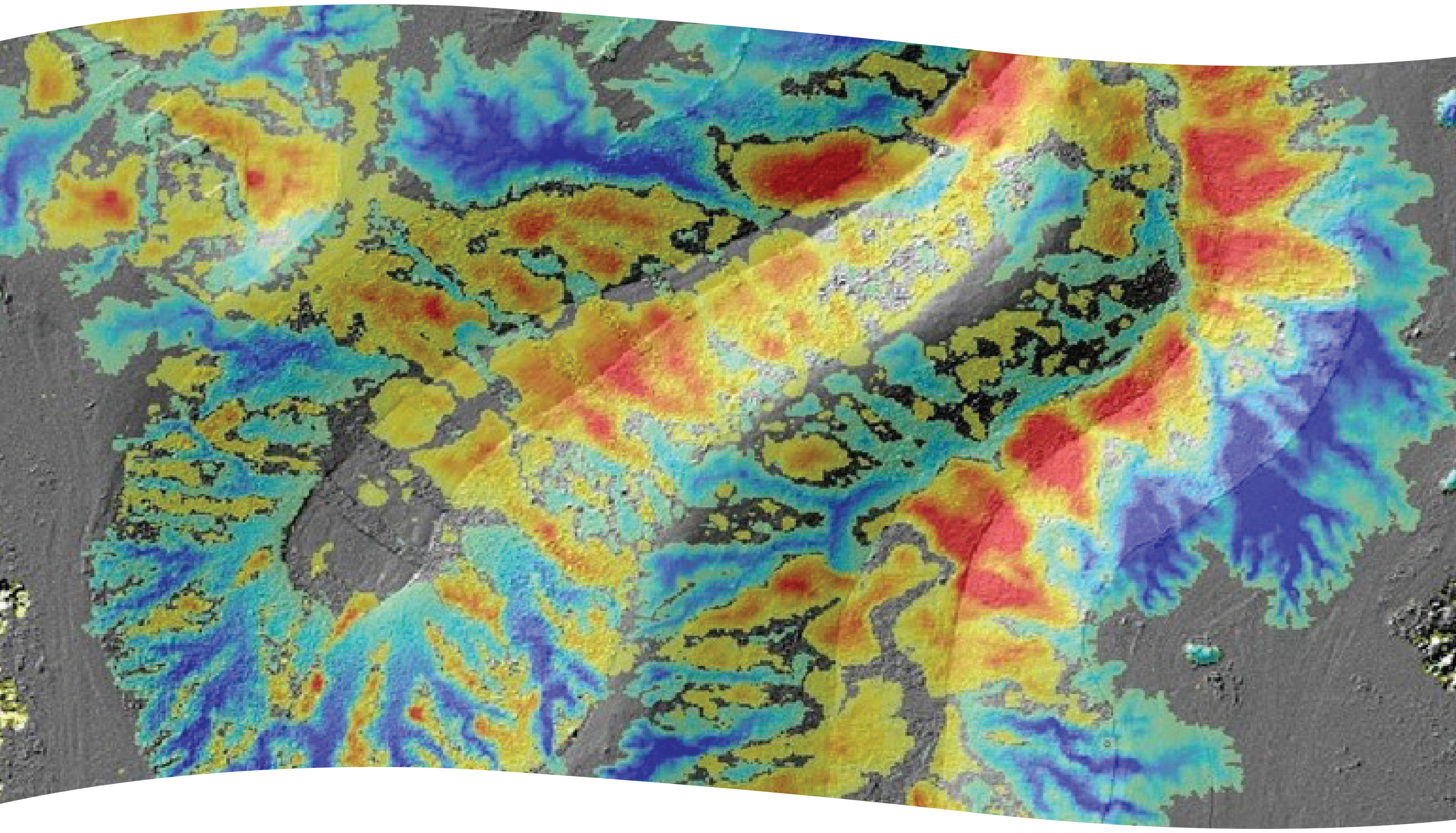
Final Report

The Effectiveness of Alluvial Gully Remediation in Great Barrier Reef Catchments

Andrew P. Brooks, John Spencer, Nicholas J. C. Doriean, Robin Thwaites, Alexandra Garzon-Garcia, Syezlin Hasan, James Daley, Jo Burton, Peter Zund



Griffith UNIVERSITY

The Effectiveness of Alluvial Gully Remediation in Great Barrier Reef Catchments

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Cover photographs: (front) Strathalbyn Treatment 3 and 4 Lidar DoD – pre- and post- construction. Image: John Spencer; (back) Gully remediation works. Image: Andrew Brooks.

This report is available for download from the NESP Tropical Water Quality Hub website:
http://www.nesptropical.edu.au

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ACRONYMS

ASC .... Australian Soil Classification
BACI .... Before After Control Impact (study design)
BAN .... Bioavailable Nutrients
BBB .... Bowen, Broken and Bogie Catchments
BPN .... Bioavailable Particulate Nutrients
BRF SMS ..... Bowen River Floodplain Soil Material System
CE .... Cost-Effectiveness
CEC .... Cation Exchange Capacity (of soil)
CYPLUS .... Cape York Peninsula Land Use Study
CYNRM .... Cape York Natural Resource Management
DEM .... Digital Elevation Model
DES .... Department of Environment and Science (Queensland)
DIN .... Dissolved Inorganic Nitrogen
DoD .... Digital elevation map (DEM) of Difference (comparison between multi-temporal DEMs)
EAL .... Environmental Analysis Laboratories (for soil material analysis)
EC .... Electrical Conductivity (of soil)
EMP .... Exchangeable Magnesium Percentage
EOG .... End of Gully
EOS .... End of System
ESP .... Exchangeable Sodium Percentage (of soil)
FSS .... Fine Suspended Sediment (< 20um)
GA .... Greening Australia
GBR .... Great Barrier Reef
GBRL .... Great Barrier Reef Lagoon
GM .... Geometric Mean
IGRP .... Innovative Gully Remediation Project (Greening Australia and DES Qld Govt)
ILSC .... Indigenous Land and Sea Corporation
JCU .... James Cook University
LDC .... Landholders Driving Change
Lidar .... Light Detection and Ranging (airborne laser survey technique)
NESP .... National Environmental Science Program
NQDT .... North Queensland Dry Tropics
P2R .... Paddock to Reef
PASS .... Pump Activated Suspended Sediment
PDR .... Peninsula Development Road
PN .... Particulate Nitrogen
PP .... Particulate Phosphorus
PSD .... Particle Size Distribution
PSE .... Prior Surface Estimation
RER .... Remediation Effectiveness Ratio
RRRC .... Reef and Rainforest Research Centre Limited
RSS .... Rising Stage Sampling
SCYC .... South Cape York Catchments
SDR .... Sediment Delivery Ratio

SM .... Soil Material
SMS .... Soil Material System
SMU .... Soil Material Unit
SPC............... Soil Profile Class (soil type)
SCYC .... South Cape York Catchments
SSC............... Suspended Sediment Concentration
SSY............... Suspended Sediment Yield
T.................... Treatment
TSS............... Total Suspended Solids
TWQ.............. Tropical Water Quality
USACE .... United States Army Corps of Engineers

ABBREVIATIONS

kt/yr .... thousands of tonnes per year
m................... metre
t/m^3 .... tonnes per cubic metre
t/ha/mm .... tonnes per hectare per millimetre of rain
t/yr .... tonnes per year
µm................. micrometres

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At the Crocodile Station site we would firstly like to acknowledge the Traditional Owners of the Laura Valley on which the project was conducted. We thank Cape York Natural Resource Management (CYNRM) without whom this project would not have been possible, in particular Will Higham and Mike Goddard. We thank Roy and Karlene Shepherd from Crocodile Station and the Indigenous Land and Sea Corporation (ILSC), Sue Marsh and the Laura Rangers for sample collection/checking and eyes on the ground.

At Strathalbyn we acknowledge the Biriah people, the Traditional Owners of the land on which the project was conducted. We thank the current landholders, Bristow and Ureisha Hughes for hosting the project, and we thank Greening Australia, in particular Ross Andrewartha who got this project off the ground, Lynise Wearne and Sunny Behazadnia for their tireless efforts; Damon Telfer from Fruition Environmental for overseeing site design and supervision of construction as well as sample collection, and to the Queensland Government for funding and guiding the project, particularly Scott Robinson, Jean Erbacher, Ben Hammill and Lex Cogle. We would also like to acknowledge the Queensland Water Modelling Network, Department of Environment and Science (DES) for the Bioavailable Nutrient (BAN) monitoring data for the 2018-2019 wet season and the Great Barrier Reef Foundation for contributing funding for BAN monitoring during the 2019-2020 wet season.

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Author Contributions

Andrew Brooks was the project leader and was responsible for the original conceptualisation of the study, the overall compilation of the report, as well as being involved in site selection, collection of field data, data analysis and reporting for the life of the project.
John Spencer was involved in all aspects of field data collection and much of the data processing. In particular he was responsible for all Terrestrial lidar data collection and analysis, and all airborne lidar data analysis.
Nic Doriean was responsible for all water quality data collection at Crocodile, and part of the data collection at Strathalbyn (along with Damon Telfer/Greening Australia (GA)/Fruition and Sunny Behazadnia/GA who set up the autosamplers, velocity meters and level loggers, collected samples, some rainfall and stage data). He was also responsible for all Total Suspended Solids (TSS), Suspended Sediment Concentration (SSC) and particle size sample analyses, and all of the sediment water quality data analysis and write up. He was the primary author for the report sections on water quality for both sites.
Robin Thwaites was responsible for the soil material sampling and mapping, soil data synthesis and the write up of the soil landscape setting sections for each site.
Alexandra Garzon-Garcia was responsible for the nutrient sample processing and data analysis at both sites and was the primary author on the bioavailable nutrient section in the report for each site.
Syezlin Hasan is responsible for the economic analysis at both sites; she developed the cost framework and wrote the cost-effectiveness sections for the two sites.
James Daley is responsible for the baseline data analysis at both sites, and the write up of the baseline yields sections for both sites. He also provided editorial and graphic design assistance for the whole report.
Jo Burton was responsible for the conceptualisation of the bioavailable nutrient monitoring section for the two sites and was the project manager for that aspect of the project until April 2020. She provided editorial input to the final report.
Peter Zund was responsible (with Robin Thwaites) for the soil material sampling and mapping.

EXECUTIVE SUMMARY

1. This study provides the first comprehensive quantification of alluvial gully remediation effectiveness and cost-effectiveness in Australia.
2. The study demonstrates that alluvial gullies can be cost-effectively remediated to the point where they achieve an ***effectiveness factor of >95%*** (i.e. reducing the sediment yield from the gully by more than 95%) within one year. After two years a number of gullies had an effectiveness factor of 100% (i.e. complete cessation of gully erosion) (**see Sections 3.1.5, 3.1.7, 3.1.8, 3.2.5, 3.2.8**)
3. The highest effectiveness ratios were documented at sites that had full reshaping and rock capping (**see Sections 4.1.2, 4.2.2**).
4. Gullies treated with organic mulch and other non-rock surface treatments experienced somewhat lower effectiveness ratios than the gullies treated with rock capping (**see Sections 4.1.2, 4.2.2**).
5. Provided that basic maintenance is adhered to, including cattle exclusion, there is every reason to believe such sediment reductions can be maintained for the foreseeable future. However it is likely non-rock based treatments will require more maintenance over the longer term.
6. In one gully (Crocodile Station 2.234) an effectiveness factor of > 100% was observed, i.e. where the gully was fully stabilised plus had sediment deposited within the gully floor from water delivered to the gully from both the gully catchment and river backwatering (**see Section 4.1.2**).
7. Gullies 0.1, 0.2 and 1.1 at Crocodile Station were constructed too late in the 2017 dry season and the construction site was impacted by an early storm. This resulted in the sediment yield for the first year post construction being double that of the baseline. ***Key Lesson –*** *Do not risk undertaking site works late in the dry season* (**see Section 3.1.6**).
8. The results from this study suggest that the current effectiveness ratios for alluvial gully remediation in the Gully and Stream Bank Toolbox are significant under-estimates of what can be achieved using best practice approaches. Effectiveness ratios of > 90% should be achievable for most remediation projects (**see Section 4.1.2**).
9. Gullies treated with rock capping and soil ameliorants are resilient to major events. In the most extreme test to date, one gully was inundated by 4 m of backwater flow from the adjacent river during a large flood (third largest on record), with no negative impact on the gully remediation (**see Section 3.1.4**).
10. Alluvial gully backwatering is a major consideration for both remediation design and water quality monitoring. All alluvial gully water quality monitoring strategies need to consider how they will accommodate major backwater events, which should be considered inevitable in most cases (**see Sections 3.1.4, 3.2.4, 6.1.2.5**).
11. The relationship between gully remediation and nutrient reductions is currently conflicted, as nutrient status is likely affected by the short-term addition of ameliorants during remediation. As such an effectiveness factor for reducing nutrient yield from gullies has not been calculated. Furthermore, we are currently unable to assess the contribution of gully remediation to meeting water quality targets for dissolved inorganic nitrogen (DIN), particulate phosphorus (PP) and particulate nitrogen (PN). However, available data suggests that gullies treated with rock capping alone result in a reduction in nutrient yields (both particulate and dissolved) that is commensurate with the reduction in sediment yields. Gullies treated with rock and organic ameliorants (e.g. mulch,

bagasse etc.), or organic ameliorants alone, demonstrate a reduction in particulate nutrient yield, but a **net increase in dissolved nutrient** yields. Current data from Strathalbyn suggests this effect is still evident two years post treatment. Whilst it is expected that this effect would dissipate with time, ongoing monitoring is required to determine how long the elevated dissolved nutrient loads persist after treatment. This information will enable the calculation of effectiveness factors for reducing nutrients from gullies as well as an assessment of the contribution of gully remediation to meeting DIN, PP and PN water quality targets (**see Sections 3.1.10, 3.2.9**).

12. There is some evidence that fine sediment emanating from treated gullies is flocculating and forming aggregates, however further work is needed to confirm the mechanism and whether this is a consistent trend (**see Figure 64**).
13. In the Normanby catchment, using a 7% discount rate over 25 years, the ranges in End of Gully (EOG) cost effectiveness (CE) are: $26/tonne - $58/tonne, while in the Burdekin catchment they are $40/tonne - $80/tonne. Using the same discount rate, End of System Cost Effectiveness (EOS CE) in the Normanby (having a sediment delivery ratio (SDR) of 0.45) becomes $58/tonne - $128/tonne, while in the Burdekin (SDR 0.94) EOS CE is $43/tonne - $85/tonne. The 7% discount rate and 25-year lifetime enable the upfront cost to be converted to its annualised equivalent cost so that it can be compared with annual sediment reduction (**see Sections 4.1.3, 4.2.3**).
14. The cost-effectiveness metrics reported in this study only include the upfront costs. Maintenance costs are not included because at this stage the scale and frequency of maintenance required over the next few years is not known – but is thought to be low at ~ 1% upfront costs every 3 - 5 years (acknowledging that there were mobilisation cost savings made for repairs undertaken in 2019 due to the presence of crews on site undertaking further primary works) (**see Sections 4.1.1, 4.2.1).**
15. EOS cost-effectiveness as outlined could be used as a metric to inform investments in gully remediation across different GBR catchments, recognising that there are different ecological risk profiles for different sections of the Great Barrier Reef (GBR) (e.g. Cape York *cf* Burdekin).
16. The greatest proportion of the uncertainty in determining the sediment abatement from gully remediation is associated with the determination of the historical baseline sediment yield. Proportionally all errors associated with the monitoring process are dwarfed by the uncertainty in baseline yield determination. Far more effort and resources need to be directed towards baseline sediment and nutrient yield determination to ensure the integrity of estimates of GBR water quality improvement (**see Sections 2.1.1, 2.2.3, 5.2, 6.1.1)**.
17. Results from this study suggest that high yielding alluvial gullies remediation effectiveness ratios (RER) can be determined from sediment concentration alone, rather than the considerable additional effort required to determine gully discharge, and hence sediment loads (with appropriate caveats as described regarding high baseline yields and highly effective treatments) (**see Section 6.1.2**).
18. The Pump Activated Suspended Sediment (PASS) sampler developed by Nic Doriean as part of his PhD undertaken through this project, is ideally suited for the cost-effective and rigorous collection of pre- and post-treatment sediment concentration data.
19. Results from this study suggest that when using the highly effective gully treatments applied in this study, that Before / After or Control / Impact data are comparable, and that other than in ongoing research experiments, it is probably unnecessary to collect both.

The same caveats apply as those used for justifying the non-collection of loads data (pt 17 above) (**see Section 6.1.2**).

20. Conventional surface soil survey and classification is not appropriate for characterising soil materials in alluvial environments as inferring particle size, bulk density, soil chemistry, and nutrient data at depth from surface soil description and mapping can potentially lead to errors in baseline sediment and nutrient yield determination. The characteristics of alluvial sediments (being transported materials) below the depth of soil core observation are unrelated to the surface soil formation in many aspects. A geomorphological soil material assessment and mapping approach, employing stratigraphic principles, should be adopted to ensure that the soil material data adequately represents the gully for design purposes and for baseline sediment and nutrient yield characterisation (**see Section 5.2**).
21. The net EOS fine sediment abatement achieved at the Crocodile Station and Strathalbyn Station sites respectively by May 2020 are 0.165 and 4.43 kt/yr. These reductions equate to 1.7% and 0.8% of the water quality targets for the Normanby and Bowen catchments respectively (Table 1).
22. In order to meet the 2025 water quality targets for the Normanby and Bowen catchments respectively we estimate that 61 and 129 sites equivalent to those documented in this report need to be remediated in each catchment respectively (Table 1).

Table 1. Reef 2050 WQIP interim Targets that need to be met by 2025 for the Normanby and Burdekin Catchments

	2025 EOS FSS reduction targets kt/yr	Best Estimate verifiable catchment reduction to date (kt/yr) (2013-20)	EOS FSS Abatement achieved from Study Project sites kt/yr	Project outcome % of remaining target	**Number of equiv. sites required to achieve remaining 2025 target**
Normanby	15	5[#]	0.165	1.7%	61
Burdekin (total)	890		.		
BBB/Lwr Burdekin (sub-set of Burdekin)	623	50*	4.43	0.8%	129

[#] From verified data from all RT2 and RT4 projects + a generous allowance for reductions achieved between 2013 – 2016, prior to RT2. (NB these differ from claimed P2R modelled reductions, which are unverified)
*This is a very generous upper limit of verifiable reductions achieved to date in the Burdekin.

Recommendations

Overview

The results presented here represent the first comprehensive quantification of alluvial gully remediation effectiveness in the GBR, and there is clearly a need for further data to be collected on similar remediation efforts within the GBR catchment to ensure that we are appropriately quantifying the remediation effectiveness and the cost-effectiveness. However, the effort and expense involved in collecting the data to the level outlined here is unlikely to be repeated, other than in a research context. However, there are lessons from this research that should enable us to streamline the process in the future, potentially making the process much more cost effective for ongoing remediation efforts so that they can be fed back into the GBR catchment modelling, providing greater confidence in cumulative GBR water quality improvements.

Baseline Data Collection

Remediation effectiveness ratio (RER) and cost effectiveness (CE) calculations are highly dependent on the baseline sediment yields determined for each gully. Whilst it is important to focus on rigorous post-treatment water quality monitoring methods, to date little consideration has been given to the most important part of the RER and CE equations; the baseline sediment and nutrient yield. To ensure baseline sediment yields are as accurate as possible we recommend that baseline yields be determined by a centralised independent entity (to be determined) underpinned by an ongoing program to collect repeat airborne lidar every 2 – 5 years and water quality data. Baseline sediment yield data would then be determined by a combination of the following datasets:

- Historical airphoto analysis (2D) – as outlined in Daley et al. (2020).
- Where possible additional photogrammetry using the historical airphoto dataset
- Volumetric analysis based on the prior surface elevation reconstruction, also outlined in Daley et al., 2020, and Stout et al., (2019) - requires at least a baseline lidar dataset
- Standard airborne lidar DoD analysis (once the repeat lidar data coverage is built up)

The number of gullies requiring this detailed baseline can be limited to a set of several hundred high priority gully systems that have been identified through a separate prioritisation process (such as that undertaken for the Landholders Driving Change (LDC) Project – Brooks et al., 2020). In this way a set of priority gullies will have their baseline sediment yields assessed prior to allocation for treatment. Using this approach, gully remediation resources would only be allocated to a pre-determined set of gullies, for which the baseline data analysis has been undertaken.

In addition, the historical sediment yield analyses at the selected gullies, “before” water quality monitoring would be undertaken to collect sediment concentration data using a combination of low-cost methods (e.g. RSS and PASS sampling), for at least two years prior to any remediation being undertaken. This would provide the necessary data for undertaking a Before/After SSC comparison to determine the RER for the selectively remediated gullies. The before SSC monitoring would also establish whether the gully meets the criteria for deriving the RER from sediment concentration data alone.

Soil and sediment sampling would be undertaken at the prioritised sites using the Soil Material (SM) sampling approach, to establish the particle size characteristics for the sites, the soil chemistry and baseline nutrient status (which would be built into the sediment baseline yield determination). These data would serve the purpose of providing the soil material data required for remediation design purposes as well.

General Gully Monitoring Recommendations

The successful execution of monitoring water quality conditions in gullies situated in remote and harsh conditions, such as those described in this study, requires extensive planning, appropriate budget, and incorporation of equipment redundancy. The years of monitoring water quality at Crocodile and Strathalbyn Stations have provided much needed experience regarding what is required to successfully monitor water quality in actively eroding and remediated gully systems. The following framework is intended as a guide for future gully monitoring projects. Adherence to the different components of the framework will ensure the best possible monitoring outcome is achieved by avoiding external influences (i.e., flooding and insect/animal damage to equipment) and method-based bias (i.e., use of appropriate monitoring equipment).

Gully Catchment Monitoring

All gullies are connected to a catchment upstream that discharges water into the eroding structure. Thus, any water quality monitoring plan related to gully remediation needs to account for water quality conditions in the catchment upstream of the gully and at the gully outlet. This will allow for the assessment of remediation success without the uncertainty associated with catchment processes occurring upstream. Furthermore, to enable cross comparison between water quality monitoring data and topographic monitoring data, which is only focused on the actively incised and treated component of the gully complex, it is necessary to be able to disaggregate the gully catchment water quality from the active/remediated gully portion.

Meteorological monitoring

A rain gauge with datalogging capabilities should be placed in a location that will measure rainfall totals that are representative of rainfall volumes in the gully and catchment. The rain gauge should be equipped with a datalogger and be capable of recording high resolution data (i.e. date and time stamp each 0.2 mm increment of rainfall). Ideally, two rainfall gauges should be used on the one site, in-case of equipment failure or damage. Rainfall data is an essential component for the following monitoring objectives: provide context for the characteristics of the wet season monitored compared to historical records; relate gully flow intensities to rainfall; identify backflow events; and provide data as redundancy for discharge modelling if needed.

Hydrological Monitoring

Water discharge measurements are required to estimate the yield of suspended sediment or nutrients discharged from the gully and catchment. Doppler velocity sensors were used at Crocodile and Strathalbyn Stations. Velocity sensors work well in streams and rivers, however the sensors were unable to provide the necessary data to accurately estimate water discharge when deployed in remediated and actively eroding gullies. A major complication with the use of doppler technology for measuring water discharge is the influence of turbulence from channel structures (e.g. debris or rocky channel surfaces) and the risk of equipment becoming covered or stranded as a result of vertical channel bed movement from scouring or aggradation respectively. Recent studies have identified that flume structures (e.g. ramped weir or Parshall flume) are the most reliable and accurate discharge measurement methods for ephemeral streams, such as gullies (Turnipseed and Sauer, 2010). These structures reduce the influence of channel bed scour or aggradation and rely on water level in the flume structure to infer water discharge, via a predetermined velocity/water level rating curve formula (Turnipseed and Sauer 2010). As outlined in the discussion above, it may not always be necessary to collect discharge data, particularly where the expected decline in sediment discharge is greater than an order of magnitude

Water quality monitoring

At a minimum, two water quality monitoring methods should be used in tandem to collect samples from the catchment or gully outlet. The use of two methods is necessary as it ensures potential sampling bias can be measured and to provide redundancy for unexpected failures or damage. Initially, samples should be collected for SSC and Particle Size Distribution (PSD) analysis. Note, SSC analysis is not interchangeable with total suspended solids (TSS). The analysis method for TSS was designed for measuring effluent from wastewater treatment plants rather than natural surface waters (Gray, 2000). TSS analysis results are known to significantly underestimate (10-30%) total SSC measurements in natural waters as noted by other authors (Gray 2000; Howley et al., 2018) and as demonstrated experimentally in this study. For the estimation of suspended sediment yields, it is ideal to collect discrete samples that represent different stages of a flow event hydrograph (i.e., rising stage, peak, and falling stage) of several flow events over a wet season should be collected. If this is not feasible, then event time-integrated samples (e.g., PASS samples) should be collected for as many individual flow events as possible. Sample equipment intakes should be placed in a location where the most representative sample will be collected (i.e., facing downstream in the centre of the channel at a height that is approximately 60% of ambient flow height). If a flume structure is used, sampling intakes may be placed on the side wall of the flume, instead of the centre, because the structure will create a high level of sediment mixing compared to a natural or constructed open channel (Turnipseed and Sauer, 2010). Refer to the gully suspended sediment monitoring method evaluation study by Doriean et al., 2020a for more information.

Backwatering

All of the monitoring sites at Crocodile and Strathalbyn Stations were inundated with floodwaters from backwater events generated by nearby rivers and creeks. The findings of this study suggest that backwater events may be a common feature of alluvial gully systems, with inundation water levels ranging from 0.25 to 4 m depending on gully elevation relative to nearby waterways. Backwatering should be taken into consideration when monitoring all alluvial gullies. Failure to do so can result in the loss of data and damage or loss of equipment. For example, the backwater events that occurred at both monitoring sites during the 2018/19 wet season caused extensive damage to monitoring equipment and contaminated over 100 samples with floodwater. Had the sample times not been cross checked with the stage data, the true sediment concentration emanating from the gullies could have been significantly misrepresented. Samples collected during a backwater event are more representative of the concentrations within the stream or river flow rather than the gully – and as such cannot be used for determining gully sediment or nutrient yields.

Cost effectiveness Determination

To date there has been considerable confusion surrounding the appropriate approach for calculating the cost-effectiveness of gully remediation, and indeed all water quality improvements within the GBR. We recommend that a guideline is established that will outline the agreed methods for calculating the cost-effectiveness of all water quality improvements (including cross-comparison between disparate approaches), along the lines of those published by the World Health Organisation for public health investments (WHO, 2003).

1.0 INTRODUCTION

1.1 Background

There has been increasing recognition over the last decade that gully erosion represents a major source of anthropogenically accelerated erosion within Great Barrier Reef (GBR) catchments and consequently a major threatening process to freshwater aquatic ecosystems and a source of sediment and nutrient pollution to the GBR Lagoon (GBRL) (Brooks et al., 2013a; Olley., et al., 2013; Wilkinson et al., 2015). Current estimates are that on average around 40% of the fine sediment load delivered to the GBRL is sourced from gully erosion (Wilkinson et. al. 2014), although this proportion is only loosely constrained, and varies considerably between catchments. In some catchments (e.g. the Bowen) it is around 60%, and others substantially less.

Early iterations of the GBR catchment sediment budget models assumed that hillslope gullies were the dominant gully form in GBR catchments (McKergow, 2005; Kroon et al., 2012), and management practices were tailored to that assumption (e.g. Wilkinson et al., 2018). Alluvial gullies (Brooks et al., 2009; Figure 1), however, have increasingly been recognised as contributing a significant proportion of gully derived fine sediment and nutrients to the GBR lagoon, with around 65% of the gully derived fine sediment load being from alluvial gullies in the Normanby Catchment (Brooks et al., 2013a) (now considered an under estimate), and just under 50% in the Bowen and Bogie catchments (Brooks et al., 2020). It has also been demonstrated that a disproportionate amount of the gully derived sediment is coming from a very small number of large alluvial gullies. For example, in the Bowen and Bogie catchments, of the 22,300 active gullies mapped thus far at high resolution (Brooks et al., 2020), 30% of the cumulative fine suspended sediment load (<20µm) is delivered from 2% of the gullies (~500 gullies) which are primarily alluvial. Hence focused rehabilitation of these large, high yielding alluvial gullies is critical for achieving GBR water quality improvement targets.

At the commencement of this project in 2016 there was no accepted practice as to how these major alluvial gully pollution sources could be successfully rehabilitated and stabilised. Apart from some initial plot-scale trials that had been undertaken in the Laura/Normanby Catchment in Cape York (Shellberg and Brooks, 2013a; Brooks et al., 2016a) there was very little published evidence for how whole alluvial gully systems should be treated and the likely effectiveness and longevity of these treatments. Prior to 2016 gully erosion rehabilitation efforts undertaken in GBR catchments were focused on the less active, smaller scale gullies which could be dealt with using manual labour and low-tech solutions (Thorburn and Wilkinson, 2013). Large alluvial gully rehabilitation was discouraged because it was thought to be too risky and expensive (Wilkinson et al., 2015a). Treatment of small gullies was thought to represent a cheap approach that could be undertaken by landholders and natural resource management (NRM) agency staff. Whilst that is true, such activities have since been shown to be cost-ineffective to implement when one considers the cost per tonne of sediment reduction resulting from such direct treatments (Wilkinson et al., 2019 – unpublished data). Furthermore, it is logistically infeasible to implement such an approach at a scale that would enable water quality improvement targets to be achieved in the required timeframe. Such approaches can do little to stabilise and reduce sediment yields from the large active alluvial gullies that are prevalent in major sediment producing catchments like the Normanby, Bowen-Bogie & lower

Burdekin Rivers. Sampling between 2005-2009 demonstrated that these sub-catchments delivered, on average, around 65% of the silt/clay fraction from the Burdekin catchment from around 11% of the catchment area, representing around 30% of the total silt-clay input to the entire GBR lagoon (Bainbridge et al., 2014). As outlined by Hancock et al. (2014), sub-surface sources represent > 90% of the Bowen fine sediment yield, a significant proportion of which is from gullies.

Similar proportions of sub-surface source dominance have been found in most of the large catchments draining to the GBR (Hughes et al., 2009; Tims et al., 2010; Olley et al., 2013), with extensive gullies being responsible for a significant proportion of fine sediment load in all of the large dry-tropics catchments. Large alluvial gullies are also one of the most connected sources of fine sediment, delivering sediment in many cases directly into the mainstream channels of the largest rivers draining to the reef. A recent study has also demonstrated that alluvial gullies are major sources of particulate nutrients to the GBR (Garzon-Garcia et al., 2016). Hence, significantly reducing the loads derived from these alluvial gullies is critical if Reef 2050 targets are to be met (Anon 2018).

A series of plot-scale trials had been undertaken in the Normanby catchment between 2011 and 2013 with extremely promising results, indicating that erosion rates could be reduced by as much as 80% over a few years with the appropriate treatment of the dispersive alluvial soils (see Shellberg and Brooks, 2013; Brooks et al., 2016a). However, these plot scale trials needed to be upscaled to complete alluvial gully complexes and different treatments tested at the whole of gully scale to ensure that the sort of results achieved at the plot scale can be replicated at the gully complex scale.

Figure 1. A selection of alluvial gullies from the Bowen catchment. (All photos Andrew Brooks except top right John Spencer)

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). For the two catchments that are the focus of this study, the Normanby and Burdekin, the end of system (EOS) fine sediment reduction targets are 15 kt/yr and 890 kt/yr respectively by 2025 (Anon 2018). In the Normanby this equates to an erosion reduction at source of around 55 kt/yr (using the P2R sediment delivery ration of 0.45 and < 20µm material fraction of 60%); 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 Paddock to Reef (P2R) SDR of 0.94 and an average< 20µm 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., 2013a). Hence, significant inroads into the water quality targets in these catchments will only be made through remediation of the key sub-surface sediment sources, particularly gully remediation, given that addressing channel erosion has not been a major focus in either catchment to date.

Given these extremely ambitious targets (and notwithstanding the fact that the Normanby had apparently already achieved its target before most gully remediation projects were initiated in the catchment - see 2018 Reef Report card[1]), approaches for achieving major reductions to gully derived fine sediment and nutrients are required if these water quality targets are to be met.

In recognition of the need to pivot remediation effort towards sediment sourced from high yielding alluvial gullies so that the ambitious 2025 catchment water quality improvement targets could actually be achieved, NESP TWQ Hub Project 2.1.10 was undertaken to scope up the sorts of large scale landscape remediation efforts that would be required to be implemented at scale within the GBR gully erosion hotspot areas (Brooks et al., 2016b). The consensus view that came out of a workshop convened through NESP TWQ Hub Project 2.1.10 was that landscape-scale strategies were required to remediate large active alluvial gullies, more along the lines of the approaches used in mined land rehabilitation.

When this project (NESP TWQ Hub Project 3.1.7) was developed in 2016, there were no accepted approaches or practices for undertaking large scale gully remediation, nor any data on the likely effectiveness of the treatments. This project was therefore established in parallel with two gully remediation projects that were just getting underway at the time, which aimed to begin to develop methods to undertake large scale alluvial gully remediation. The first project was undertaken by Cape York NRM with funding through the Reef Trust II program at Crocodile Station on the Laura River in Cape York. The second project was a collaborative project supported by the Queensland Government's Reef Innovation Fund and Greening

[1] Note there is a significant disparity between the modelled water quality improvements outlined in the 2018 Reef Report card (which suggest the Cape York water quality improvement targets have already been achieved) and the evidence for quantifiable sediment supply reductions associated with gully remediation works, or indeed any other sediment reduction activities, undertaken on the ground in Cape York.

Australia's Reef Aid Program which would become known as The Innovative Gully Remediation Project (IGRP). This project was focused on Strathalbyn Station on Bonnie Doon Creek, a right bank tributary of the lower Burdekin at a site identified through earlier reconnaissance mapping undertaken by the project team.

Table 2. Estimates of erosion control effectiveness for different gully remediation options from the Reef Trust Gully Toolbox v3. (From Wilkinson et al., 2019)

Channel erosion type (see definitions in Section 1.1)	**Erosion control activity** **(darker colours denote foundational activities, which should also support more intensive activities shown in lighter colours) in my mind the Dark/light should be reversed**	**When to consider applying activity (criteria for when to consider stepping to the next / higher cost option)**	**Recommended complementary activities** **(those in brackets apply in some cases)**	**Relative unit area cost / technical complexity** **(assuming all recommended complementary activities are undertaken)**	**Estimated erosion control effectiveness** **(assuming all recommended complementary activities are undertaken)**
Hillslope gully (dry tropics and/or wet tropics if present)	1. Improving grazing management in gully catchments	On properties with land in poor condition, and on which other erosion control activities are also implemented.	2	$	0.1 (A)
	2. Fence to control livestock access to erosion control sites	Essential pre-requisite for all activities where livestock are present (may result in additional watering point being required).	1	$$	0.2
	3. Actively revegetate gully (including brush matting or compost & contour debris placement on slopes)	After fencing & any other works have been undertaken Soil EAT[B] class >2.	1, 2 (4, 5, 6)	$$$	0.3
	4. Porous check dams	Small catchment areas and non-dispersive soils (see detail).	1, 2, 3	$$$	0.4
	5. Road and catchment runoff management including diversion banks and contour ripping	Where overland flow or road runoff is contributing to erosion and diversion can be safely implemented. Ripping of dispersive subsoils is not recommended.	1, 2, 3, (4)	$$$	0.2 (B)
	6. Gully head drop structures	At gully headcuts migrating at > 1m/yr over last 10+ yrs.	1, 2, 3, 4, 5	$$$$	0.6
	7. Gully reshaping + gypsum	Rapidly eroding gullies with dispersive/slaking soils – EAT[B] class 1 & 2.	1, 2, 3, 4, 5, (6)	$$$$	0.6
Alluvial gully – additional options to above	8. Gypsum/lime + composting or mulching to support reveg *without* major reshaping	Small active gullies/scalds with dispersive/slaking soils EAT[(c)] class 1 & 2.	1, 2, 3, (4, 5, 6)	$$$$	0.6
	9. Soil capping with stable soil/rock as alternative to 8	Highly active gullies with dispersive/slaking soils –EAT[B] class 1 & 2. Land management agreement ensures no grazing for at least 5 years.	1, 2, (3, 4, 5, 6, 8)	$$$$	0.5
	10. Reshaping	Highly active gullies with dispersive/slaking soils – EAT[B] class 1 & 2. Land management agreement ensures no grazing for at least 5 years.	1, 2, 3, 8/9, (4, 5, 6)	$$$$	0.6

1.2 Project Objectives

The objective of this project was to measure the effectiveness of large-scale alluvial gully remediation using approaches typically undertaken in mined land rehabilitation and large-scale civil engineering works (such as highway construction). This report presents the results of a four-year monitoring program (2017 – 2020) that was established to work in partnership with these two on-ground remediation projects. For comparison, the current best estimates of the alluvial gully remediation effectiveness from the Gully and Stream Bank Toolbox second edition (Wilkinson et al., 2019) are between 0.5 and 0.6 depending on the extent of the treatment.

1.3 Research Questions

This study for the first time provides quantitative data on effectiveness ratios for large scale alluvial gully remediation, and evidence as to the time required to achieve these reductions. This report presents the results from three years of monitoring at the first two large-scale alluvial gully remediation projects undertaken in the GBR catchments; at Crocodile and Strathalbyn Stations in the Normanby and Burdekin catchments respectively, commencing in 2016. The projects were set up to answer the following questions:

1.3.1 Primary Questions

1) What is the erosion control effectiveness factor for alluvial gully remediation in different settings, using different remediation techniques?
2) How long does it take to achieve significant reductions in sediment and nutrients associated with large scale alluvial gully remediation?
3) How resilient are the treatments in large events?
4) Is there a commensurate reduction in bioavailable nutrients associated with observed reductions in fine sediment yield associated with gully remediation?
5) How cost-effective is large scale gully remediation?

1.3.2 Secondary Questions

6) What are the best ways to monitor gully erosion remediation efforts at scale?
7) What are the minimum requirements for baseline site analysis at a new gully remediation site? (i.e. as the basis for site design and sediment abatement determination).
8) Is the conventional surface soil mapping and classification appropriate for characterising the deep alluvial gully soil landscape?

1.4 Study Design

The study was setup with a partial Before After Control Impact (BACI) study design at the two sites (Figure 2), in which a single untreated control gully was monitored for the life of the project and several of the treated gullies monitored for either one or two years prior to treatment (i.e. providing Before data), and between one and three years post treatment. All sites were monitored using annual repeat high resolution airborne lidar survey (~ 0.1m resolution) and/or terrestrial lidar to measure baseline erosion rates and to detect changes post-treatment. For cost and logistical reasons, only six of the 14 treatment sites at Strathalbyn Station had comprehensive water quality monitoring undertaken; the Control site and five Treatments (T1, T2, T3, T4, T6) as indicated in Figure 10. At Crocodile Station the Control and first treatment gully (2.234) were monitored using a comprehensive suite of water quality sampling methods (including autosamplers), while three of the treated gullies were monitored with a slightly less comprehensive set of techniques. The suite of monitoring techniques used at both study sites is summarised in Table 8 and Table 9.

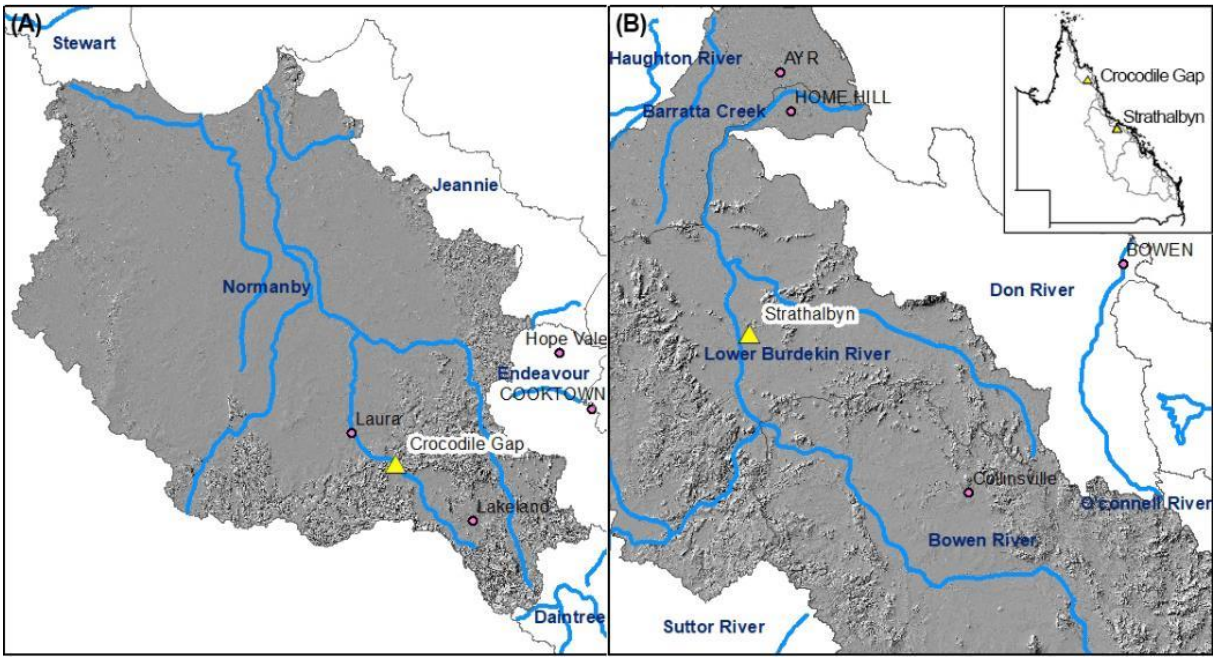

Figure 2. Regional catchment map showing the site locations of (A) Crocodile Station in the Normanby River Catchment, and (B) Strathalbyn in the lower Burdekin River catchment

1.4.1 Measuring Remediation Effectiveness

To measure remediation effectiveness, data was collected using two fundamentally different and complementary methods. First, detailed high resolution lidar was collected at regular intervals over the three years of the study, before and after each wet season, and topographic change determined from DEM of Difference (DoD) analysis. From these data total sediment yield was determined at the control gully and each of the treatments. Baseline yields were determined at most sites prior to remediation works being undertaken from lidar DoD analysis. The remediation 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. 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:

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

Where $SYTa$ = 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/m^3 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/m^3); SYT = the observed sediment yield for the given treatment gully; and $SYTb$ and $SYCb$ 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/m^3 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.

Remediation Effectiveness Ratio (RER) is then defined in two ways; first as:

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

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/m^3 of discharge for each water year where monitored SSC data is being used; $SYTa$ = 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/m^3 of discharge for each water year where monitored SSC data is being used (i.e. controlling for hydrology), or

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

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/m^3 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/m^3 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 remediation 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).

1.4.2 Crocodile Station Site Selection

The Crocodile Station site was identified as a priority as part of an analysis undertaken for the Cape York Water Quality Improvement Plan (CYNRM and SCYC, 2015). Gully erosion was analysed in the Normanby catchment as part of the Normanby sediment budget study (Brooks et al., 2013a) and this analysis was further refined in the Normanby Basin Gully Prioritisation report (Brooks et al., 2015) to inform the Eastern Cape York Water Quality Improvement Plan. This analysis demonstrated that the Crocodile Station area was a major sediment source hotspot at the catchment scale and an appropriate place to begin to focus large scale gully rehabilitation efforts. A total of 24 gully complexes were identified in the Crocodile Station area on both sides of the Peninsular Development Road (PDR). The proximity of the main PDR makes this the easiest of all sites to access in the Normanby Basin, which should make the rehabilitation of these sites some of the most cost effective. The six sub catchments that overlay lidar block 16 are in the top 100 sediment yielding sub catchments within the Normanby Basin (Brooks et al., 2015). Total erosion from these 24 complexes, was 7,107 t/yr (or ~2010 t/yr FSS EOS) for the sample period. The five gullies selected for the study in this area have a cumulative baseline FSS EOS yield of 300 t/yr.

1.4.3 Strathalbyn Site Selection

The Bonnie Doon Creek gully sites initially identified as a prospective site during an aerial reconnaissance survey in 2015 by the first author, and a subsequent prioritisation process undertaken by Ross Andrewartha at Greening Australia confirmed the suitability of the site from multiple perspectives, the most important of which was the willingness of the landholders, Bristow and Ureisha Hughes to host the project on their land. A report quantifying the baseline sediment yields for this site, and verifying the appropriateness of the site, was produced for Greening Australia in 2017 (Brooks et al., 2017), and updated in 2020 (Daley et al., 2020).

2.0 STUDY SITES AND METHODS

2.1 Crocodile Station

The study site is located on Crocodile Station in the Normanby River Catchment of Cape York (Figure 2). A sequence of gullies that have formed in the alluvial floodplain and terrace of the Laura River (Figure 3). The tropical climate of the region is characterised by wet (October to April) and dry (May to September) seasons. Approximately 95% of the annual rainfall occurs during the wet season (Brooks et al., 2014a). The long term rainfall record for the site is shown in Figure 4 while the annual rainfall recorded at site over the life of the study can be seen in Figure 5. The study site is located within an alluvial terrace, into which prior gullying had occurred during the Holocene, giving rise to an undulating topography draining from the old alluvial ridge. The alluvium is surrounded by sandstone ranges of the Jurassic/early Cretaceous Gilbert River sandstones. The alluvial sediments comprising the floodplain/terrace are derived from the Laura River catchment, which is dominated by the Ordovician Hodgkinson Formation meta-sediments, the Gilbert River sandstones, and Quaternary/Neogene Maclean Basalts (Brooks et al., 2013; Brooks et al., 2014b).

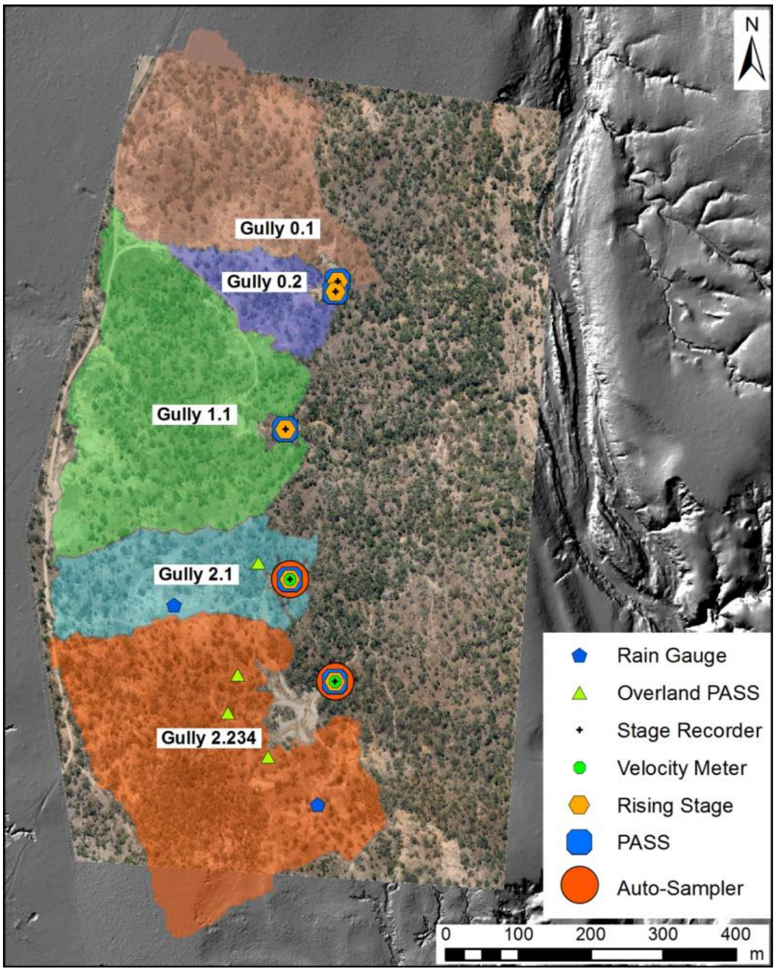

Figure 3. Site map of the Crocodile Station study area showing the 5 study gullies and their catchments and the locations of monitoring equipment. Note Gully 2.1 is the Control for the study.

The study site is mainly composed of alluvial deposits from the Laura River and Earls (or Redbank) Creek deposited during the late Quaternary Period. Within the Crocodile Gap study area, the landscape can be divided into three geochronological geomorphic units described, from oldest to youngest and in Table 3.

Table 3. Depositional layers and landforms within the study site.

Landform / Alluvial deposit	Definition
Recent alluvia	Alluvial sandy sediment deposits originating from the Laura River catchment
Older alluvia	Alluvial fine sandy and clay sediment deposits originating from palaeo-Earl's (Redbank) Creek catchment and the Laura River
Colluvial fan	Colluvial fan deposits and associated soils from the Byerstown Range made up of greywacke, slate, mudstones, as well as sandstones and conglomerate

Downstream of the study site, the Laura River passes through a narrow passage between the Byerstown Range and the Deighton Tableland which has acted as a constriction on the Quaternary Laura River floods. This restriction to flood flows causes the build-up of alluvial deposits upstream where the sediment transporting energy is reduced, thereby creating a plain of alluvial erodible materials that is now being incised owing to the lower flow levels of the Laura River and tributary creeks compared with those of the Quaternary.

Project NR02 of the Cape York Land Use Study (CYPLUS) collated all existing soils information on Cape York, including the soil information and conclusions from the Mitchel-Normandy Survey. Within our study area, they defined the following broad soils on the colluvial slopes of the Hodgkinson Formation and the alluvial plains of the Laura River; Gibson (Yellow or Grey Sodosol) on colluvial/alluvial fan derived from greywacke and slate. Kingjack (leached mottled Grey Dermosol or Grey Sodosol) overlying sediments. Greenant (Yellow Sodosol) and Wakooka (Yellow Dermosol) formed on alluvial plains derived from the Hodgkinson Formation. Victor (Red Chromosol), and Mitchel (Brown/Red Kandosol) on recent alluvia from the Laura River. Victor and Greenant soils were associated with extensive soil erosion (Biggs and Philip, 1995).

The main area of gully formation is in a central broad valley zone of silty to sandy clay alluvial material between higher ridges of red clay loams and sandy loam materials. These ridges and higher ground possibly represent the remnants of an older land surface, maybe modified, of terraces or benches of a larger Earl's Creek tributary, or possibly a branch of the, then braided, Laura River. Upstream in the Earl's Creek catchment are further examples of elevated residual land surfaces, often lateritised (deeply weathered with red soils and ironstone gravels). The red soil rises in the study area are possibly an extension of these old land surfaces and are of similar age.

To the west of the central red clay loam rise is an old backplain deposit which accommodates a series of low-lying depressions with very sodic soils. The backplain creek arises here and flows across the alluvial plain to the Laura River further north. The backplain is bounded to the west by colluvial soils and deposits and alluvial fans related to the Byerstown range slopes by the main Laura-Lakeland highway. The alluvial materials have given rise to very sodic soils that have eroded extensively over the 'paleo-valley' and is characterised distinctively by coverings of calcite nodules and 'gully coral'.

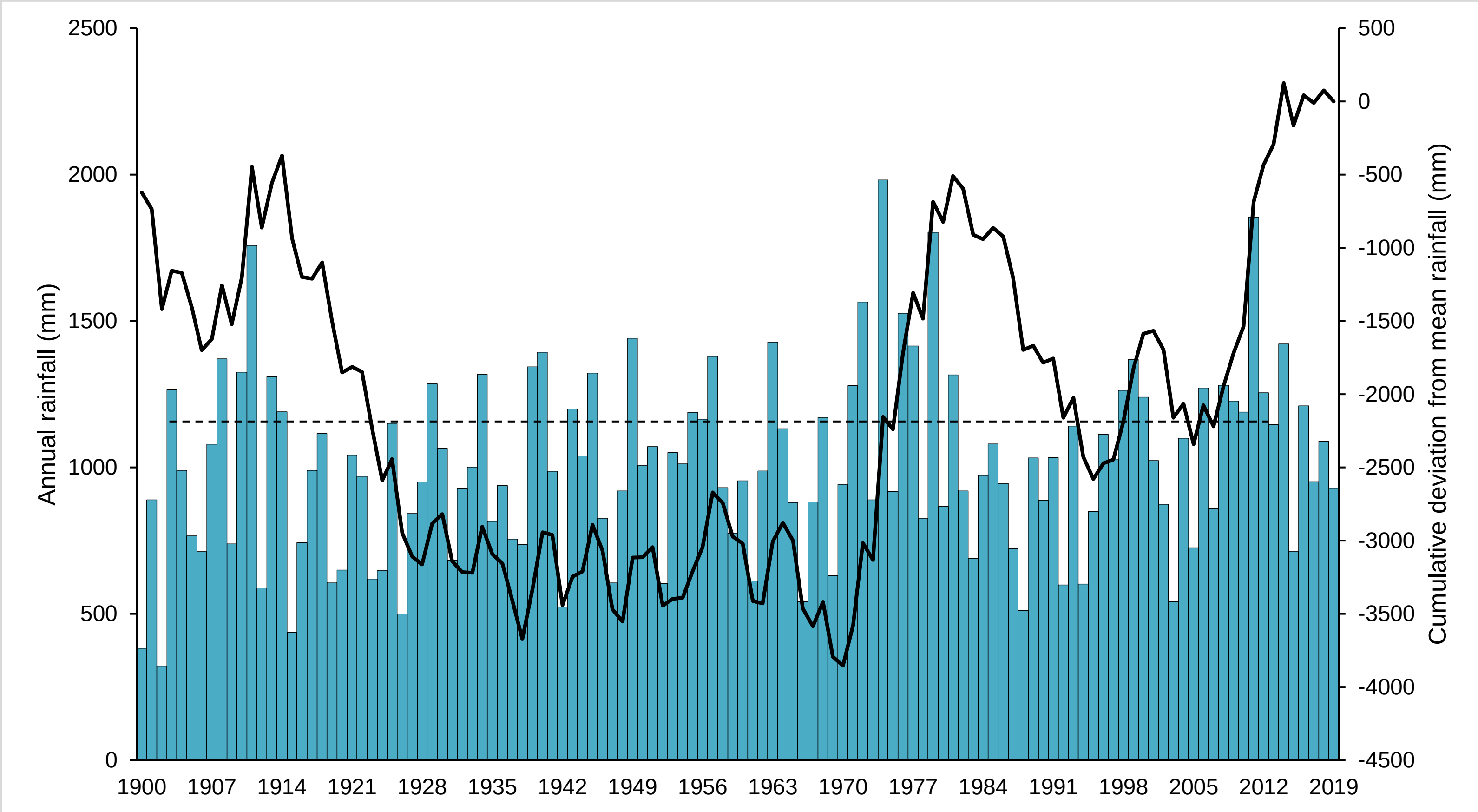

Figure 4. Annual total rainfall since 1900 at the Crocodile Station gully remediation site. The black line represents the cumulative departure from the annual mean rainfall (for total record). Increases in slope indicate a wetter year and decreases in slope represent a drier year (than average). Source BoM Grid data + study rainfall gauge (2018 -19). Dashed line is the 120-year average – 1004 mm.

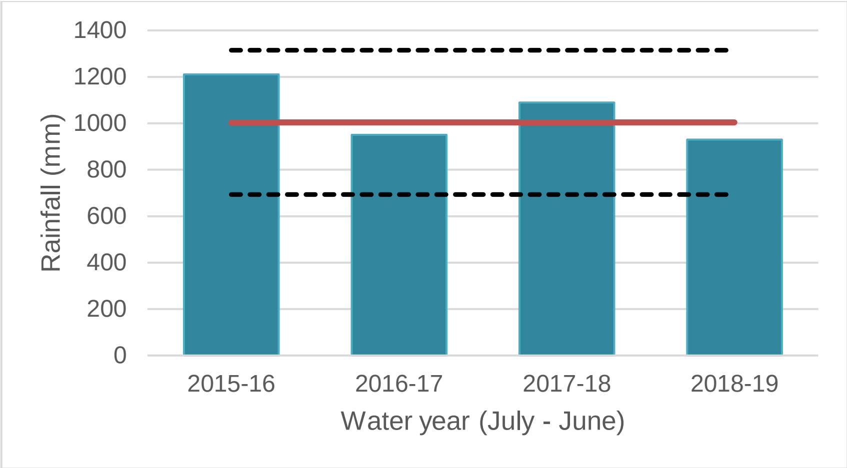

Figure 5. On-site measured rainfall at the Crocodile Station study site for the study period with the solid line representing the long-term average annual (water year) rainfall for the site and the dashed lines representing +/- 1 standard deviation.

2.1.1 Baseline Sediment Yields for the Study sites

Baseline yields were derived from historical air photo analyses and the Prior Surface Estimation (PSE) method described in Daley *et al.* 2020 and Stout *et al.* (in prep). The PSE utilised the most recent DEM for the site and creates an artificial DEM within the gully boundaries to represent the surface and drainage pattern prior to being gullied. Historical gully margins were digitised from orthorectified aerial imagery, observing headcut retreat through time (Figure 7). At Crocodile Station, all gullies initiated within the availability of aerial imagery. Where gullies initiated between two air photos, the start year was estimated from measured retreat rates and rainfall patterns (Figure 4). These margins were clipped from the PSE DEM to determine the volume of sediment eroded in each time period, under the assumption that all erosion in that zone occurs within that period (i.e, gully erosion is dominated by headcut retreat rather than down-wearing or secondary incision). Where available, lidar DoD data was prioritised over PSE data, with 2009-11 and 2011-15 DoD correlation used to apply a correction factor to the PSE-derived volumes. Each period had an R^2 value > 0.95 between the two methods, with a total R^2 across all data points of 0.73 (Figure 6).

Table 4 shows the end of gully (EOG) and end of system (EOS) annual yields for the Crocodile Station gullies, averaged across the life of the gully. These results indicate 21000 t of sediment has eroded from the Crocodile Station site since they initiated after 1988, with an average annual fine sediment yield of 650 tonnes per year.

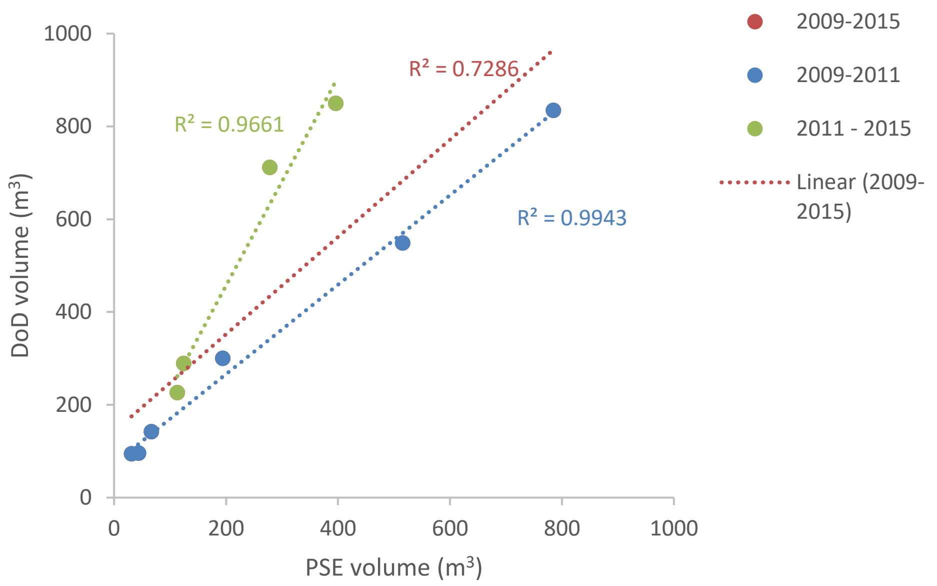

Figure 6. A comparison of gully scale sediment volumes at Crocodile Station derived from the PSE method and multi-temporal lidar analyses. As the PSE method assumes all erosion occurs within each time slice, it is anticipated to underpredict erosion, as demonstrated here

Table 4. Summary of sediment yields from Crocodile Station gullies. Quantities have been adjusted using a correction factor derived from multi-temporal lidar analyses. Start dates assumed from aerial photo analysis.

Gully ID	Gully Area (m^2)	Catchment Area (ha)	Start year	Finish year	Quantity eroded (t)	EOG FSS yield (t/yr)*	SSY (t/yr/ha)	EOS FSS yield (t/yr)* **
2.1	0.166	4.2	2000	2019	2990 ± 400	119 ± 18	28.4 ± 4.24	60 ± 8
0.1	0.067	7.4	1992	2017	2890 ± 390	69 ± 10	9.3 ± 1.38	30 ± 5
0.2	0.064	1.9	1992	2017	1940 ± 260	47 ± 7	24 ± 3.64	20 ± 3
1.1	0.287	10.4	1995	2017	6070 ± 810	182 ± 27	17.5 ± 2.61	86 ± 13
2.234	0.306	12.1	2000	2015	4610 ± 620	184 ± 27	15.2 ± 2.27	87 ± 13
2.6	0.132	3.5	1988	2015	2310 ± 310	50 ± 7.6	14 ± 2.15	20 ± 4
Total	**1.022**	**39.6**	**-**	**-**	**20800 ± 2800**	**652 ± 97**	**16.5 ± 2.46**	**308 ± 46**

*Assumes a fine sediment proportion of 60% and BD of 1.8

**Assumes a Sediment Delivery Ratio of 0.45 as provided by the Paddock to Reef modelling.

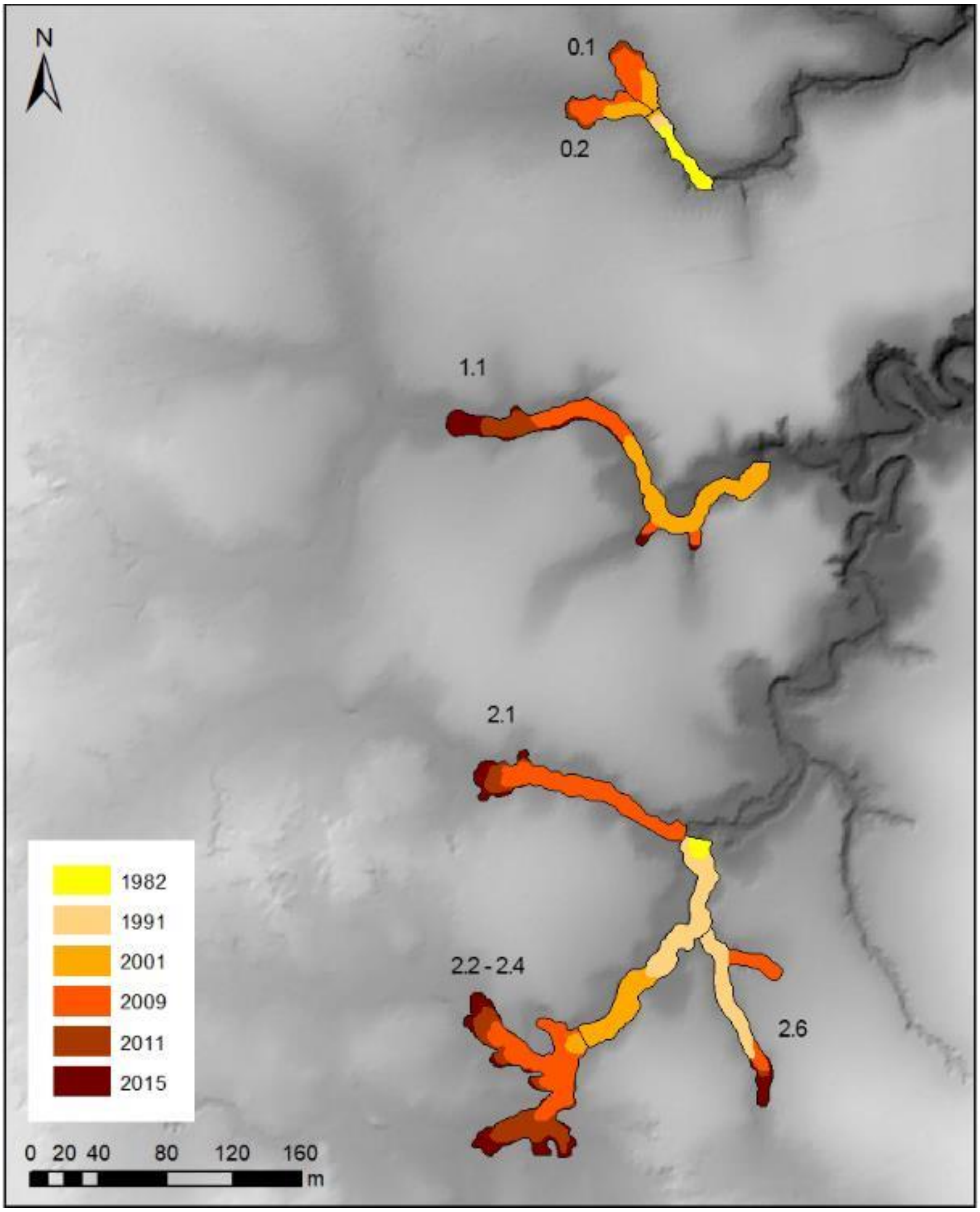

Figure 7. Historical gully boundaries for Crocodile Station determined from Aerial Photograph analysis of headcut migration. No discernible gullying was apparent in 1952 or 1960 imagery. Note gullies 0.1-0.2 only display to the 2011 boundary as no 2015 data was available for this site.

2.1.2 Gully remediation strategy

Four gullies were remediated at Crocodile Station, on Crocodile Station between Laura and Lakeland in 2016 and 2017, with a total area of just over 1 ha remediated in two phases (gully 2.2, 2.3, 2.4 combined into a single treatment – hereafter described as gully 2.234). These gullies were treated by fully reshaping the gully, treating the dispersive/slaking soil materials with gypsum, capping the reshaped gully with locally sourced rock material, and constructing rock check dams in the gully floor to help trap sediment in the gully floor and form the substrate for grass colonisation to help trap and stabilise further sediment. Gullies 0.1, 0.2 and 1.1 were treated with rock chutes at the head of each gully, following reshaping of the gully head and treatment with gypsum at 20t/ha. All chutes were also underlaid with geotextile. Further details about the site design can be found in Appendix 1.

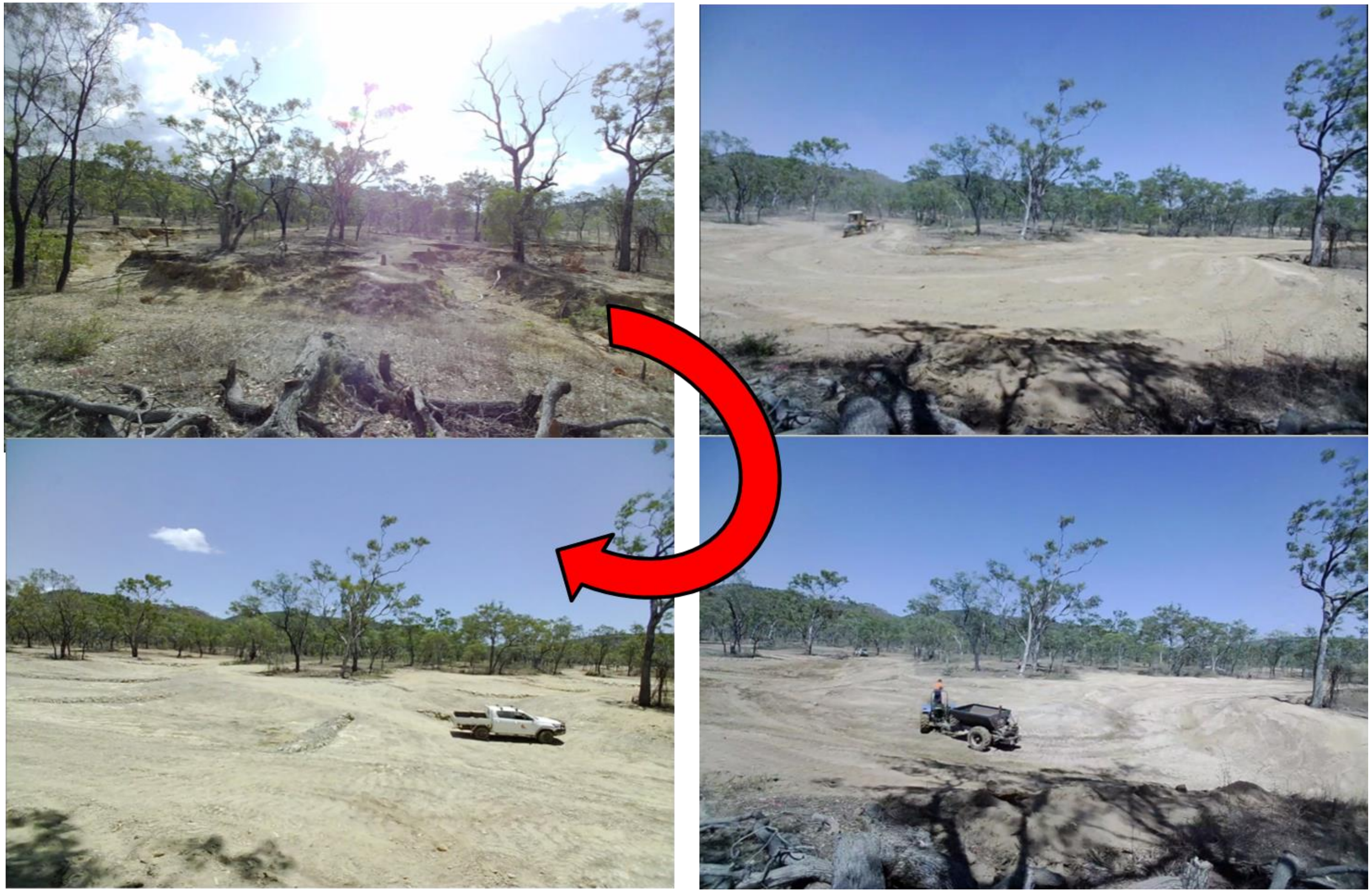

Figure 8. Time lapse sequence of construction at gully 2.234 in October, 2016

2.2 Strathalbyn Station

2.2.1 The Innovative Gully Remediation Project: Overview

The Innovative Gully Remediation Program was established to trial different gully remediation methods whilst also evaluating the best configuration of water quality monitoring methods to assess the effectiveness of remediation on mitigating gully soil erosion. In order to meet these objectives, the configuration of methods used to monitor water quality at the study site have changed with time. These changes were done for one or more of following reasons: improve data integrity, ease of operation, affordability, and reliability. The water quality monitoring methods used as part of the Innovative Gully Remediation Program are described in the following sections.

A total of 17.5 ha of actively eroding alluvial gullies have been remediated over a three year period as part of the IGRP using a variety of different approaches as outlined in Telfer (2018) and Table 6. An additional 1.2 ha was also remediated in the same area as part of a NQDT Reef Trust IV project, however these sites will not be included in the analysis reported here, other than through their incorporation into the lidar data analysis. The individual treatment areas discussed throughout the report are shown in Figure 10. The Innovative Gully Remediation Project is a collaborative project supported by the Queensland Government's Reef Innovation Fund and Greening Australia's Reef Aid Program with support for the monitoring component through this project (NESP TWQ Hub Project 3.1.7).

The project site is at Strathalbyn Station, 45km north-west of Collinsville and 60km due south of Ayr, located in the Burdekin-below-dam catchment on the eastern bank of the Burdekin River (Figure 2). The property is owned by the Hughes family, with Bristow Hughes managing all aspects of the property's grazing enterprise. The initial analysis of the gullies along Bonnie Doon Creek and tributaries identified three main clusters of gullies (Brooks et al., 2017).

2.2.2 Project Area

The study gullies are a set of alluvial gully systems along the Bonnie Doon Creek, a right bank tributary of the Burdekin River on Strathalbyn Station. These gullies were initially mapped in December of 2016 and delineated into three groups North, Central and Southern gullies (Brooks et al. 2017; Figure 9). For the purpose of this analysis the original gully system names are maintained given that the broad baseline sediment yields and the base line nutrient loads were determined for these broader gully systems (Figure 9).

The area is characterised by extensive alluvial sediments of considerable depth interspersed with 'blacksoil' cracking clay alluvia and local basalt origins. The alluvial sediments here are of varying depth on a planed granite surface, eroded by a paleo-Burdekin river. The sediments are thought to be of late Pleistocene age.

The main drainage network on this elevated floodplain/terrace is that of Bonnie Doon Creek flowing from the rugged hills of varied volcanic geology further to the east. Along the lower reaches of the creek much active and deep gullying occurs in cracking silty loam sediments. Bonnie Doon Creek takes a right-angled change to a westerly direction at a range of granite hills where it is joined by a similar sized tributary also draining from the eastern volcanic hills. At this confluence there is an extensive area of deep 'blacksoil' cracking clays (Vertosols) with prominent normal, melonhole and linear gilgai (active surface micro-topography). The research site of gullies occurs immediately downstream of this confluence and blacksoil plain.

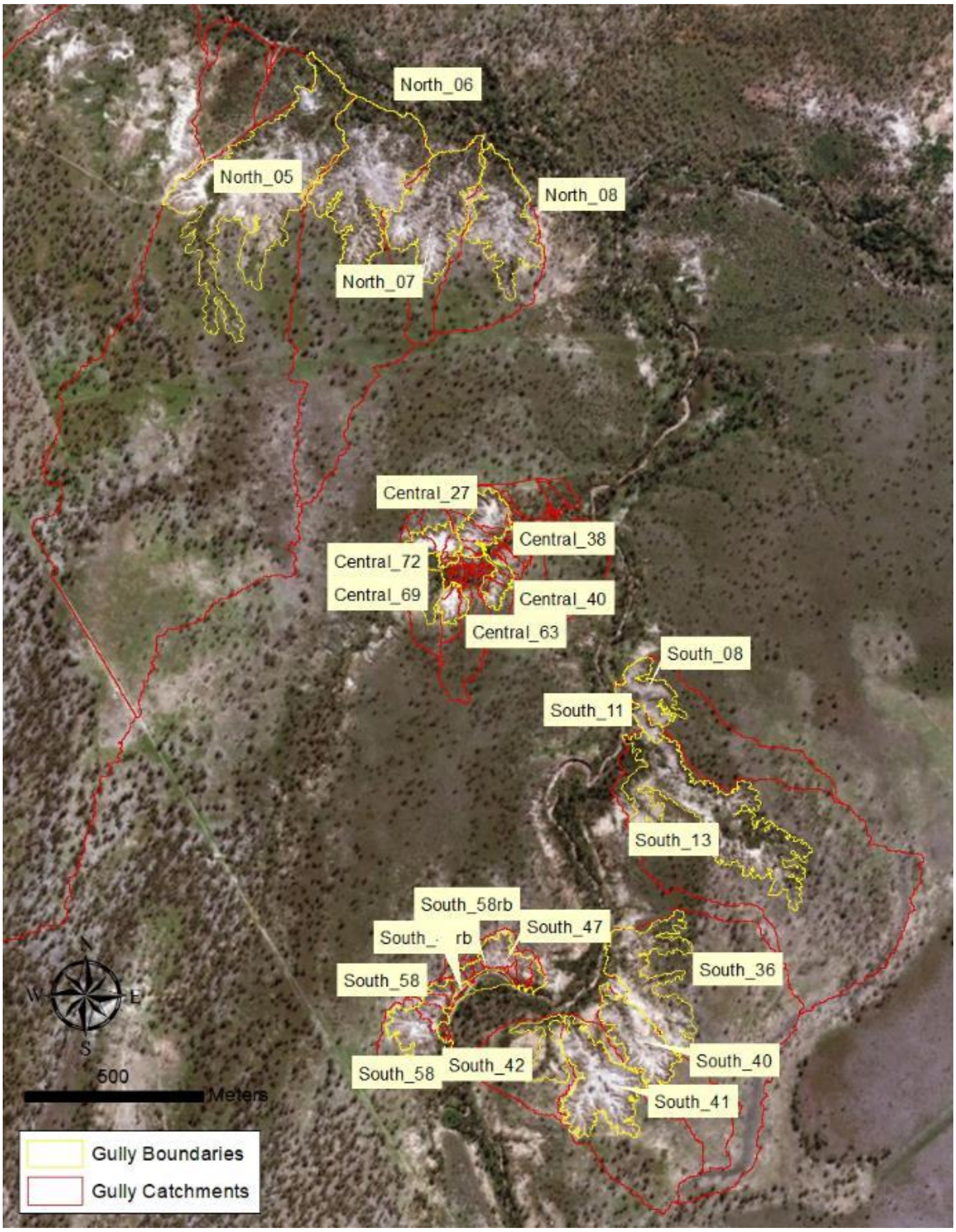

Figure 9. Location of the three groups (northern, central and southern) of gullies along Bonnie Doon Creek, Strathalbyn Station. Bonnie Doon Creek flows north from the base of the figure and converges with the Burdekin River approximately 3 km downstream from the Northern Group gullies

The study site is in the dry tropics, receiving the majority of rainfall during summer months. The average annual rainfall is approximately 695 mm, though features high interannual variability. The variable annual rainfall results in wet and dry phases that can last for more than a decade (Figure 11). Note that these data presented here were derived from the Australian

Gridded Rainfall dataset, which provides a daily time series (predicted) from July 1900 until June 2018.

Historical rainfall (ca 1950 to 2020) data for the region was also analysed from the closest official Australian Bureau of Meteorology Rain Gauge located in Dalbeg, QLD (station number: 33291, Lat: 20.31°S Lon: 147.30°E, BoM 2020) 13 km from the study site. The measured annual rainfall from Dalbeg for the study period is shown in Figure 12. Rainfall experienced during the study includes one year of around average rainfall, two years of below average rainfall, and one year (2018/19) that is well above average. Indeed the 2018/19 wet season is the 6th wettest year over the 120 years of records.

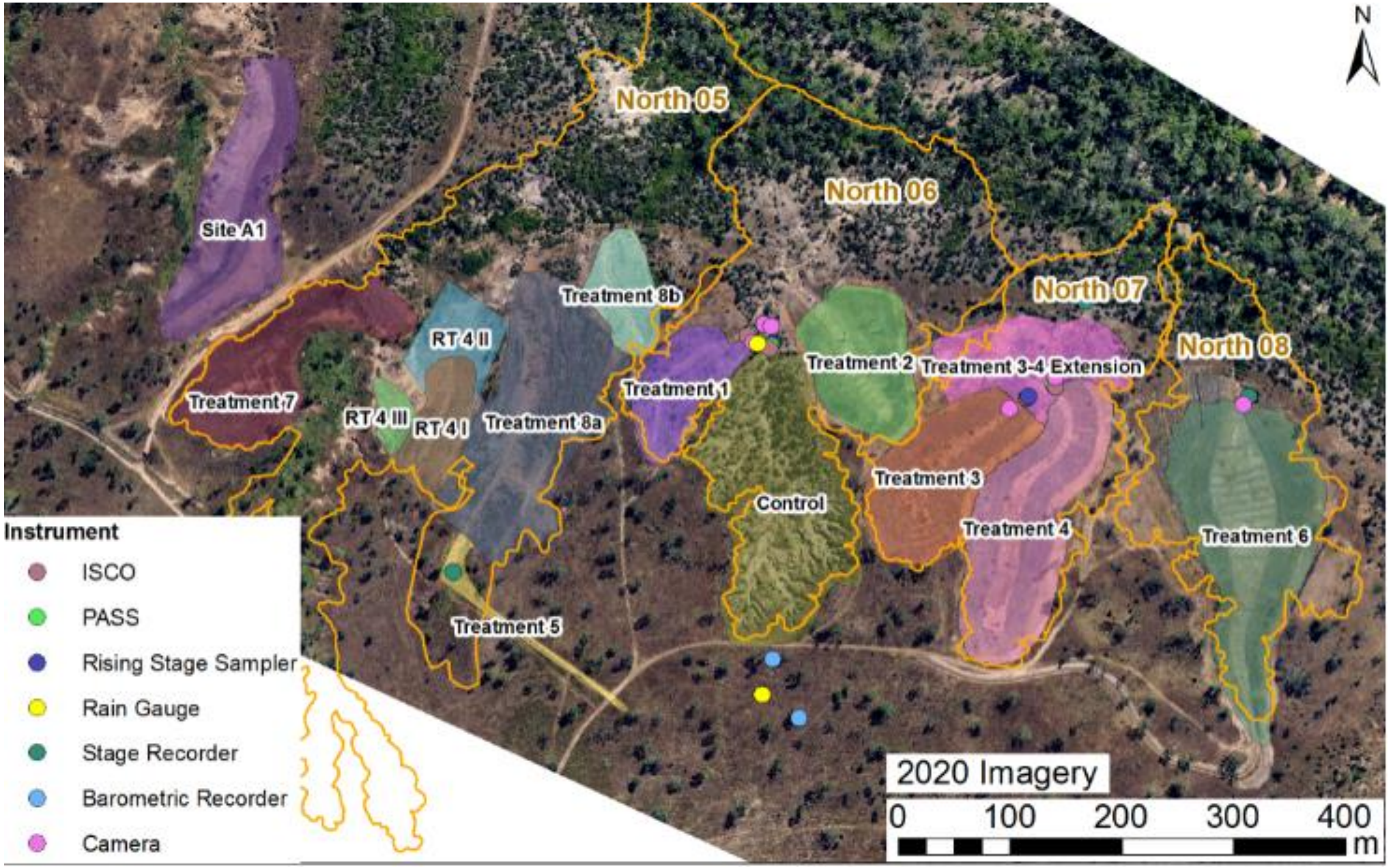

Figure 10. Location map showing the location of the monitoring equipment at the respective gully treatments. Also shown are the larger gully systems originally delineated in Brooks et al (2017) and which are the basis for the baseline sediment yield determinations.

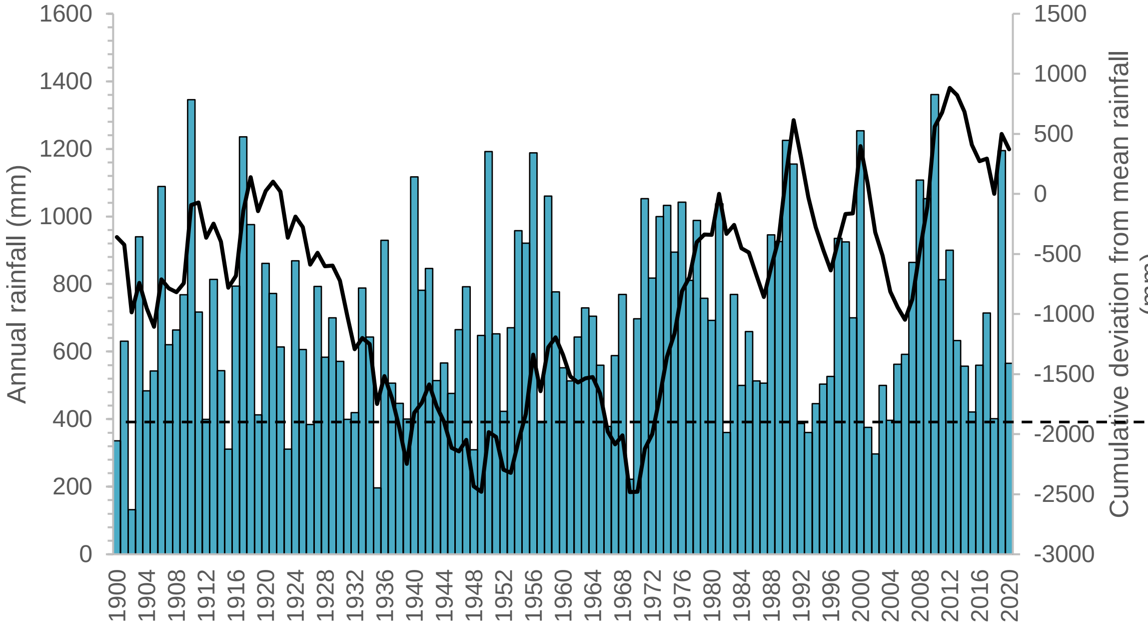

Figure 11. Annual total rainfall over the period of record at the gullies. The black line represents the cumulative departure from the annual mean rainfall (for total record). Increases in slope indicate a wetter year and decreases in slope represent a drier year (than average). Source BoM Grid data + Dalbeg Gauge (2019 -20). Dashed line is the 120-year average – 695 mm.

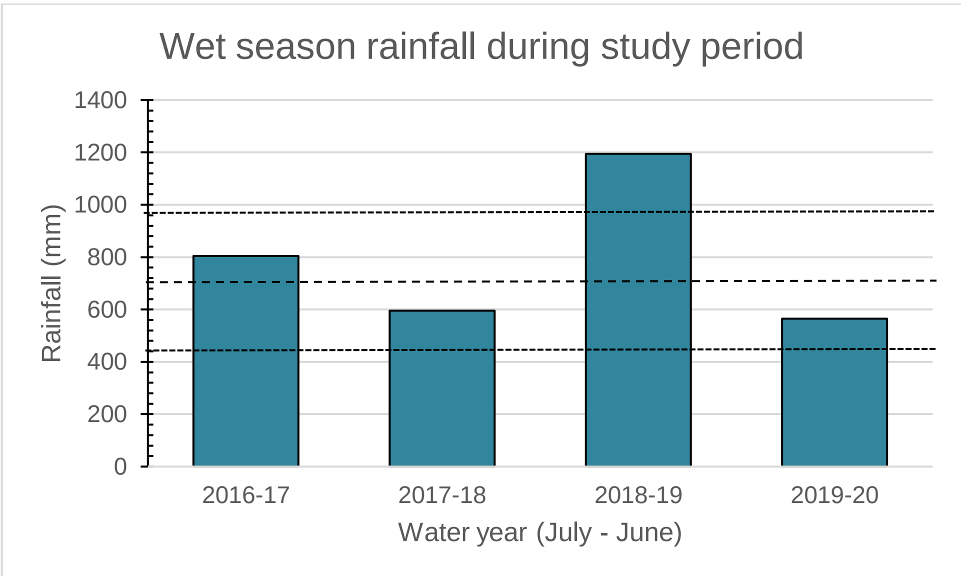

Figure 12. Annual (water year) rainfall at Dalbeg BoM Station 33291. Long term average (120 from the gridded data) is shown +/- 1 standard deviation.

2.2.3 Bonnie Doon Creek baseline sediment yields

A full description of the baseline yield calculation is included in Daley et al. (2020), but a brief summary of the baseline yields derived for each site are included in Table 5.

The data presented here is intended to form a baseline dataset on the quantity and the yield of fine sediment eroded (<20 µm) from each of gullies (prior to treatment in the Northern group). A combination of historical air photo and lidar datasets (Figure 13, Figure 14), GIS methods, field surveys and soil material sample analysis have been used to quantify the total yield (tonnes) of sediment derived from each of the gullies over the period of observation (1945 to 2016), and to estimate the baseline sediment yield and erosion rates presented in Table 5. Erosion rates were calculated for both the total yield of sediment and for the fine fraction (<20 µm) sediment, which comprises at least 72% of the sediment load (326,000 tonnes) and is expected to have a high sediment delivery ratio to the receiving water bodies.

In total, the gullies in the study area contributed approximately 450 thousand tonnes of sediment since 1945, with 37% of this amount eroded in the last 20 years. The 20-year fine sediment baseline from these gullies is roughly 121,000 tonnes and overall appears to be increasing in sediment yield. Erosion trends over the period of observation indicate that the gullies along Bonnie Doon Creek are either eroding at a constant rate or are increasing. None have a declining rate of sediment yield. The fine sediment yields in the baseline period (last 20 years) are 28% higher than across the total period of observation due to the net acceleration of erosion rates (Table 5). As such, rather than projecting declining erosion rates, potential abatement yields have been estimated as constant with the baseline period or by extrapolating erosion rates with high r^2 values. Prior to remediation, these gullies were contributing, on average, 6300 t of fine sediment to the GBR lagoon each year.

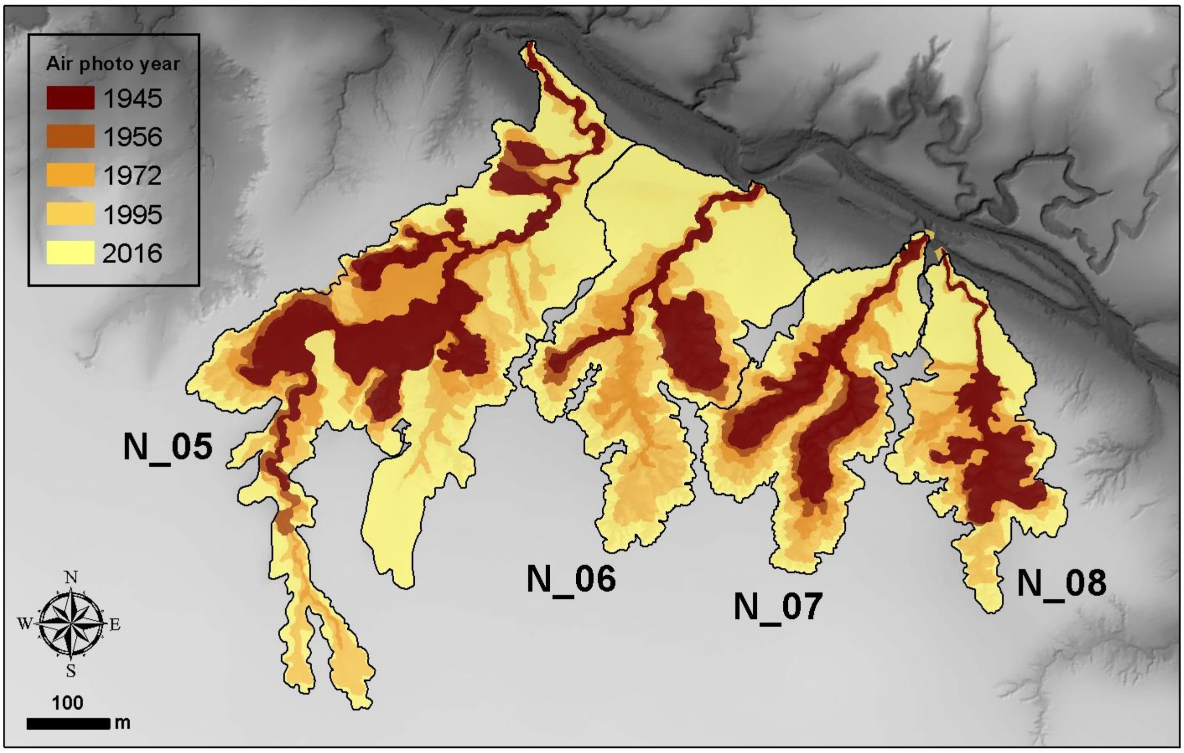

Figure 13. Gully growth progression as mapped from historical air photos

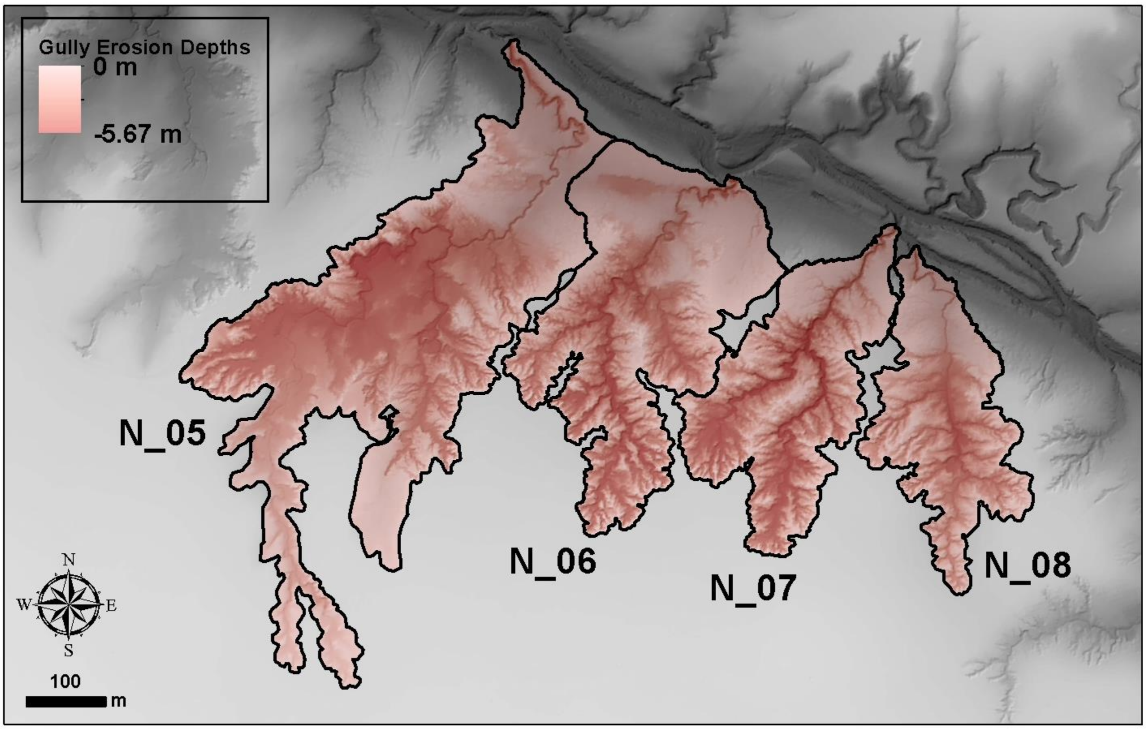

Figure 14. Gully erosion depths for the Northern Gullies derived from the reconstructed gully "lids" (prior surface estimation) which represent the pre-erosion land surface.

Table 5. Summary of sediment yields for Northern Group treatments. Each treatment provides the baseline rate for individual Reef Credit Accounting Zones

Gully ID	Gully Area (Ha)	Period of observation (1945-2016)					Baseline Period (2000-2020)	
		Vol Eroded (m^3)	Quantity eroded (t)	SSY (t/yr/ha)	Fine sed. quantity (t)	Fine sed. yield (t/yr)*	Vol Eroded (m^3)	Fine sed. yield (t/yr)*
Treatment_1	0.96	14800	24700 ± 1700	362 ± 25	17900 ± 3700	253 ± 52	4870	283 ± 42
Treatment_2	1.41	12700	21100 ± 1500	212 ± 15	15300 ± 3200	216 ± 45	4010	240 ± 96
Treatment_3	1.77	27500	45800 ± 3200	366 ± 25	33300 ± 6900	469 ± 97	9140	490 ± 160
Treatment_4	2.24	36100	60300 ± 4200	380 ± 26	43800 ± 9000	620 ± 130	10900	620 ± 200
Treatment_3-4_Ext	0.61	6400	10680 ± 740	248 ± 17	7800 ± 1600	109 ± 22	2090	98 ± 33
Treatment_6	3.57	41700	69700 ± 4800	275 ± 19	51000 ± 10000	710 ± 150	15500	810 ± 240
Treatment_7	1.58	24400	40700 ± 2800	363 ± 25	29500 ± 6100	416 ± 86	6300	430 ± 140
Treatment_8a	2.34	33400	55800 ± 3800	336 ± 23	40500 ± 8300	570 ± 120	17900	1280 ± 190
Treatment_8b	0.58	9320	15600 ± 1100	381 ± 26	11300 ± 2300	159 ± 33	4960	569 ± 85
NQDT/RT4 I	0.63	5060	8450 ± 580	188 ± 13	6100 ± 1300	86 ± 18	2900	198 ± 29
NQDT/RT4 II	0.53	3260	5440 ± 370	140 ± 10	3950 ± 810	56 ± 11	3260	88 ± 63
North Control	2.42	54600	91200 ± 6300	530 ± 37	66000 ± 14000	930 ± 190	18600	1180 ± 180
Total	**18.6**	**269000**	**450000 ± 31000**	**340 ± 23**	**326000 ± 67000**	**4600 ± 950**	**100000**	**6300 ± 1500**

*Assumes a Sediment Delivery Ratio (SDR) of 0.94; BD = 1.67

2.2.4 Strathalbyn IGBP Gully Treatment Strategy

A full report on the treatment strategy is provided in Greening Australia (2018), however the overall approach is summarised in Table 6, with the location of the various treatments shown in Figure 10. The photos in Figure 15 show the remediation at various stages (before and after treatment) through the process. The timing of the implementation of the different treatments over the study period is shown in Table 7.

Figure 15. A selection of photographs showing the Strathalbyn Northern Gullies in various stages of construction, both before (top left), during (top right) and after (bottom). Note the trucks and excavators in the photo at the top right for scale. (photos top Damon Telfer - bottom Andrew Brooks).

Table 6. Details of treatments undertaken at each gully within the northern gully group (from Greening Australia, 2018)

Site	Works implemented																		
	Catchment treatments			Gully Scarp treatments				Gully bed treatments			Regraded batter treatments								
	Fenced for managed stock access	Diversion bund to intercept catchment flows	Rock chute to control diverted flows to gully bed	Earthworks to reshape/regrade	Gyspum application and incorporation to 0.15m	Capping with gravel materials nominal 100mm	Capping with borrowed topsoil	Graded rock bed	Porous Rock check dams	Gypsum application and incorporation	Coir mesh applied over batters	Blanket mulching - Hay	Patchily spread hay mulch	Blanket mulching - Bagasse	Bagasse applied with a spreader or blower	Hay bunds on the contour	Debris bunds on the contour	Direct seeding – exotic grasses	Direct seeding with sub-surface incorporation
Treatment 1	×	×		×	×	C		×		×			×					×	
Treatment 2	×			×	×		×			×	×							×	
Treatment 3	×	×		×	×	×			×	×			×					×	
Treatment 4	×	×		×	×	×		×		×		×				E		×	
Treatment 3-4 Extension Area	×	×		×	×	×			×	×			×				F	×	
Treatment 5	×	×	×	×	×					×									
Treatment 6	×	×	×	×	B				×							×	×	G	
Treatment 7	×	A		×	×	×			×	×				×					×
Treatment 8	×	×	×	×	×	×		D	×	×					H	I	J	×	
Treatment 8b	×	×		×	×	×			×	×				×				×	

A – diversion bund implemented under an adjacent Greening Australia – Australian Government funded Reef Trust 4 program: B – incorporated to 0.2m depth: C – nominal 200mm thick: D – upstream half of Treatment 8 bed has been treated with graded rock: E – on north east batter only: F – on north west batter only: G – to be undertaken in September 2019: H – bagasse spread with a semitrailer mounted blower on parts of the eastern and all of the western batter: I – hay bales spread on the contour on the north eastern batter only: J – Debris spread on the contour in the inter-rows of the hay contours on the north eastern batter.

Table 7. Timeline for the implementation of the site scale remediation works within the Northern gully group (from Greening Australia, 2018).

	2017				2018								2019		
	September	October	November	December	May	June	July	August	September	October	November	December	May	June	July
Quarry development	■	■													
Treatment 1		■	■	■											
Treatment 1 maintenance works								■							■
Treatment 2							■	■							
Treatment 3						■	■								
Treatment 3 maintenance works															■
Treatment 4					■	■									
Treatment 4 maintenance works															■
Treatment 3-4 Extension Area							■								
Treatment 5 Diversion bund and rock chute			■												
Treatment 6													■	■	■
Treatment 6 Diversion bunds and rock chute														■	■
Treatment 7								■	■						
Treatment 8									■	■					
Treatment 8 maintenance works															■
Treatment 8b										■					
Project site stock management fencing												■			
				End 2017 Works								End 2018 Works			End 2019 Works

2.3 Monitoring

Measuring the sediment yield from a gully, often in a remote and inaccessible location, is not a straight-forward process, and consequently no one method can be used to measure the sediment load. By their nature, gullies are hydrologically extremely flashy systems, delivering the majority of their annual discharge, and hence sediment load at timescales that can be measured in hours rather than days or weeks. Hence, they are challenging to accurately sample using standard stream gauging techniques. In this study we have used multiple monitoring methods, including a new time integrated PASS sampler developed specifically for this project (Doriean et al., 2018, 2019).

2.3.1 Meteorological and hydrological monitoring

Crocodile Station

Two rainfall gauges (Hydrological Services tipping bucket design - 0.2 mm/tip with HOBO data logger) were deployed in the catchments of gullies 2.234 and Control (Figure 3). The rain gauges provided a near-continuous record of rainfall during each wet season monitored (2015-2019). Two rain gauges were used to provide redundancy in case of equipment failure and to evaluate for potential variance in rainfall across the two adjacent gully catchments.

Water level measurements in gully channels and select catchment drainage areas (only gullies 2.2.3.4 and Control) were collected every two minutes using water level loggers (In-situ rugged troll 100®). The loggers were secured on the surface of a straight section of gully channel just downstream (<50 m) of the gully head. A pressure transducer with built in datalogger (In-situ barotroll®), placed under the 2.234 catchment rain gauge, was used to measure atmospheric pressure, it recorded pressure every 15-mintues. The barometric data collected was used to calibrate the water level logger measurements, by differentiating atmospheric pressure from water pressure when the gullies were flowing.

Opportunistic water velocity measurements were collected using a handheld velocity measurement instrument (JDA, water velocity probe (0.1-3 m/sec)) at the outlets of gullies 2.234 and Control. Measurements were collected in accordance with the equal discharge increment (EDI) method (Wilde et al. 2014).

Strathalbyn Station

An overview of the IGRP monitoring strategy cab be found in a separate report (Telfer 2018), however the two tipping bucket rain gauges (Hydrological Services tipping bucket design - 0.2 mm/tip with either a Hobo data logger or Campbell Scientific datalogger CR1000) were deployed in the catchment of the control gully and remediated area adjacent the confluence of Treatment-1 and the Control gully outlets. Historical rainfall (ca 1950-ongoing) data for the region was obtained from the Australian Bureau of Meteorology Rain Gauge located in Dalbeg, QLD (station number: 33291, Lat: 20.31°S Lon: 147.30°E, BoM 2020).

Gully flow event water level was measured and recorded every 10 minutes using pressure transducers with built in dataloggers (in-situ rugged troll 100, Onset HOBO U20L, and Campbell Scientific CS451/CS456) (Table 9). The majority of water level loggers used (in-situ rugged troll 100 and Onset HOBO U20L) were non-vented and required barometric pressure correction using data measured and recorded every 10 minutes from a barometric transducer datalogger (In-situ barotroll®) located ~1 m above the ground surface in catchment of the Control and T1 gullies.

Gully water velocity measurement instruments (Unidata, Starflow) connected to dataloggers (Campbell Scientific CR1000) were installed in the gully outlets. The Doppler instruments were deployed, facing downstream, attached to a steel post at a height of ~15 cm above the channel bed in the centre of the channel cross section and were programmed to measure water velocity every 15 minutes

2.3.2 Suspended sediment monitoring

Due to the relatively novel aspect of monitoring suspended sediment in gullies, for the purpose of soil erosion mitigation evaluation, there is a notable amount of uncertainty regarding which methodology provides the most representative data. A focused laboratory and field-based evaluation of the potential uncertainties and limitations of methods, commonly used to monitor suspended sediment dynamics in gullies, was completed as part of the monitoring program conducted on-site (Doriean et al., 2020a). The method evaluation study also included the development and evaluation of a new time-integrated pumped active suspended sediment (PASS) sampling method designed to provide a low-cost alternative or complimentary monitoring method to those currently available for use in gullies (Nunny 1985; Doriean et al., 2019; Doriean et al., 2020a). All sediment samples were processed according to the SSC protocol where possible, unless some sample was required for other purposes (i.e. nutrient analysis) whereby the total suspended solids (TSS) protocol was used. While the underestimation of sediment concentration using TSS is well documented (Gray et al., 2000, Shellberg et al., 2013a) to understand the comparability of the two methods in this study a subset of duplicate samples were processed using both methods (see section 3.3).

Crocodile Station

Suspended sediment measurements were collected using one or more of the following monitoring methods:

- Rising stage samplers (RS sampler); a single stage sampler that collects sediment during the rising water level stage of a flow event (Wilde et al. 2014).
- Automatic sampler (autosampler); An automated sampling device that collects composite or discrete samples (1-24 individual samples) using a peristaltic pump (Wilde et al. 2014).
- Turbidity logger; measures turbidity, in nephelometric turbidity units (NTU), of water by measuring the reflection of emitted light from sediment particles flowing past the logger (Rasmussen et al., 2009).
- PASS sampler; an in-situ sampling device that provides a time-integrated suspended sediment sample for one or multiple flow events by continuously collecting sediment from the water column, using a peristaltic pump, and retaining sediment in a settling column and expelling sampled water (Doriean et al., 2019 and Doriean et al., 2020a).
- Overland flow PASS sampler (OFPASS); a PASS sampler used to collect suspended sediment in runoff flowing through gully catchments (Doriean et al., 2020a).
- Equal discharge interval (EDI) Isokinetic manual sample collection; The use of an isokinetic sampling device (DH-48 sampler) to manually collect flow-proportional discrete samples of suspended sediment, that are representative of the channel cross-section, during the different water level stages of a gully flow event (Wilde et al., 2014).

One or more of the suspended sediment monitoring instruments were deployed in the centre of the channel cross section for each of the five gully outlets and catchments (only the catchments of gullies 2.234 and Control) (Table 8). Suspended sediment samples were analysed for SSC (ASTM standard method D 3977-97) and PSD using laser diffraction spectroscopy (Malvern Mastersizer 3000, Malvern Instruments, resolution of 0.01-2000 µm). Samples were screened using a 2 mm sieve prior to particle size analysis to remove any debris or detritus.

Sediment collected from the eroding sections of the Control gully, at Crocodile Station, was sieved to separate clay and silt (<63 µm) from fine to coarse sand (63 to 2000 µm). The sieved sediment was used to make two treatments: (1) fine sediment (<63 µm); and 2) fine sediment with approximately 23% sand (63 to 2000 µm) by mass). The two sediment groups were made as individual 1 L samples using deionised water, at a range of different concentrations typically observed in water flowing through the control gully at the study site (100, 500, 1000, 5000, 15000, and 20000 mg/L). The samples were analysed using TSS (APHA Method 2540D) and SSC (ASTM standard method D 3977-97) methods. All analyses were performed in triplicate to account for variation in sediment preparation and analytical procedures. TSS and SSC analyses were performed on samples collected, from gully sites located at Strathalbyn, during the 2017/18 wet season. Statistical analysis of monitoring data was conducted using Graphpad Prism. Some of the data was lognormally distributed, in these instances the data was log-transformed before statistical analysis. Data were compared using statistical analysis including: paired and unpaired t-test, repeated measures ANOVA, and other descriptive statistics (minimum, maximum, mean, geometric mean etc).

Table 8. Water quality monitoring instruments deployed at Crocodile Station

Monitoring Equipment	*Description*	*Gully ID*				
		2.1 (Control)	*2.234*	*1.1*	*0.2*	*0.1*
Water level	Non-vented pressure transducer logger, 2 min log interval, placed on channel bed with barro troll logger above high water level	✓	✓	✓	✓	✓
Autosampler	Peristaltic pump sampler, 10 min sample interval, 24 samples per sampler, 800 mL samples, Intake 20 cm above channel bed.	✓	✓	✓	×	×
RS sampler	Six samplers placed at 20 to 45 cm above the channel bed with 5 cm intervals.	✓	✓	✓	✓	✓
PASS sampler	Equipped with 50mL sediment trap at intake and 4.8L settling column, 25 mL sampling flow rate, intake 20 cm above channel bed.	✓	✓	✓	✓	✓
OF-PASS sampler[1]	Equipped with 50mL sediment trap at intake and 4.8L settling column, 11 mL sampling flow rate, intake 9 cm above ground surface.	✓	✓	×	×	×
Velocity logger	Ultrasonic doppler, 15 min log interval, placed 10cm above channel bed.	✓	×	×	×	×
Time-lapse Camera	10 min log interval, infrared flash used for night photos.	✓	✓	✓	✓	×
Rain gauge	Secured to steel posts 1m above ground surface and clear (>10m) of overhead obstructions (e.g., tree branches)	✓	✓	✓	✓	✓

[1]= The OFPASS sampler was developed in 2018, thus, the method was used during the 2018-19 wet season. ✓ and × indicated if an instrument is installed or not installed, respectively, at the referenced location/gully.

Strathalbyn Station

Suspended sediment monitoring was conducted at the site using a combination of RSS and autosamplers for the period of 2016-2018. As the project progressed new suspended sediment monitoring equipment was deployed in select gullies or drainage lines (Figure 10). Three RSS samplers were deployed in each gully with intakes facing downstream at varying heights above the channel bed (5, 10, and 15 cm). The Autosampler intake was mounted, facing downstream, approximately 15 cm above the channel bed. PASS samplers (2017-2020) were also deployed in the centre of the gully outlet channel with the intake facing downstream approximately 15 cm above the channel bed. PASS samplers that were used to sample water runoff from the catchments into the gullies had lower intakes (9 cm above the ground) compared to those deployed in the gullies.

Refer to Table 9 for sample/measurement intervals. Samples were retrieved from the monitoring equipment after each flow event. Occasionally access to the site would be restricted for days to weeks depended on the amount of rainfall in the region. In these instances, samples were could not be retrieved after each flow event. Suspended sediment samples were analysed for SSC (ASTM standard method D 3977-97) and PSD using laser diffraction spectroscopy (Malvern Mastersizer 3000, Malvern Instruments, resolution of 0.01-2000 µm). Samples were screened using a 2 mm sieve prior to particle size analysis to remove any debris or detritus. Refer to Telfer (2018) for more information regarding suspended sediment monitoring at Strathalbyn Station. Statistical analysis of monitoring data was conducted using Graphpad Prism. Some of the data was lognormally distributed, in these instances the data was log-transformed before statistical analysis. Data were compared using statistical analysis including: paired and unpaired t-test, repeated measures ANOVA, and other descriptive statistics (minimum, maximum, mean, geometric mean etc).

2.3.3 Estimation of gully suspended sediment yield

Rainfall runoff modelling software HEC-HMS developed by the United States Army Corps of Engineers Hydrologic Engineering Centre was used to estimate the volume of rainfall runoff discharged from the gullies monitored for this study (USACE-HEC 2020). The HEC-HMS model uses a combination of high-resolution rainfall data to estimate the volume of rainfall runoff for a defined catchment area. Lidar data and digital elevation mapping was used to delineate the catchment boundaries of each gully. Flow event water level measurements collected from the gullies were used to determine the lag time between peak rainfall and peak flow for each gully.

At Crocodile Station, runoff curve number of 89 (poor pasture, grassland, or range in soil with high runoff potential (D)) was used to model ratio of rainfall infiltration and runoff for the gully catchments (NRCS 2004). Geometric mean SSCs of suspended sediment samples were used to estimate the SSC for each monitoring period they were collected during (e.g. a single event or several events over weeks or months) from each gully monitored, except for the Control gully. Evaluation of suspended sediment dynamics in the Control gully indicate that the bulk of sediment is transported during the initial stages of flow (Figure 16). This sediment transport mode, of monotonically decreasing SSC after initial flow has been observed in other ephemeral waterways (i.e. streams and other types of gullies) and can be used as an effective rating curve to predict SSCs from these systems (Dunkerley et al. 1999; Malmon et al. 2007). Thus, Control gully suspended sediment yield estimation was calculated using the logarithmic regression equation ($-1361\ln(x) + 11330$ (R^2 0.61) determined using sample data collected from the gully throughout the monitoring period (2017-2019) (Doriean et al. 2020b) (Figure 16). This method of estimating SSC by using a rating curve typically provides a more conservative, and more representative, suspended sediment yield compared to using flow event or sampling period average concentrations (Malmon et al. 2007). This is further supported by the ability to use rating curved derived SSC data in combination with the 1-min resolution of the modelled water discharge volume estimates.

Annual suspended sediment yield was estimated using the following formula (Crawford 1991):

$$SSY = \mathrm{SSC} \times \mathrm{Q} \qquad (3)$$

where SSY = Suspended sediment yield (t), SSC = SSC (mg/L), Q = volume of water discharged (m^3)

At Strathalbyn Station, a runoff curve number of 49 (fair pasture, grassland, or range in soil with low runoff potential (A)) was used to model ratio of rainfall infiltration and runoff for the gully catchments (NRCS 2004). Geometric mean SSCs of suspended sediment samples were used to estimate the SSC for each monitoring period they were collected during (e.g. a single event or several events throughout over weeks or months) from each gully monitored.

Table 9. Water quality monitoring instruments deployed at Strathalbyn Station

Monitoring Equipment	*Description*	*Gully ID*							
		Control	*T-1*	*T-2*	*T-3*	*T-4*	*T-5*[1]	*Gully-8*	*T-6 Drain*
Water level	Non-vented pressure transducer logger, 10 min log interval, placed on channel bed with barro troll logger above high water level	✓[1]	✓	✓	✓	✓	✓	✓	✓
Autosampler	Peristaltic pump sampler, 24 sample bottles per sampler, 20 min sample interval, 1 L samples, Intake 150 cm above channel bed.	✓	✓	✓	✓	✓	×	✓	×
RS sampler	Three samplers placed at 5 to 150 cm above the channel bed with 5 cm intervals.	✓	✓	✓	✓	✓	×	✓	×
PASS sampler[3]	Equipped with 50mL sediment trap at intake and 4.8L settling column, 25 mL sampling flow rate, intake 20 cm above channel bed.	✓	✓	✓	✓	✓	✓	✓	✓
Velocity logger	Ultrasonic doppler, 15 min log interval, placed 150 cm above channel bed.	✓	✓	✓	✓	✓	×	✓	×
Time-lapse Camera	10 min log interval, infrared flash used for night photos.	✓	✓	×	✓	✓	×	×	×
Rain gauge	Secured to steel posts 1m above ground surface and clear (>10m) of overhead obstructions (e.g., tree branches)	✓	✓	×	✓	✓	×	×	×

[1]= Treatment 5 is the outlet of the drainage diversion bund located in Control and T-1 Gully catchments.

[2]= Vented telemetered level logger deployed from 2019-20 wet season

[3]= PASS samplers were used from the 2018-19 wet season onwards for gullies and for water diversion outlets (T-5 and T-6 Drain)

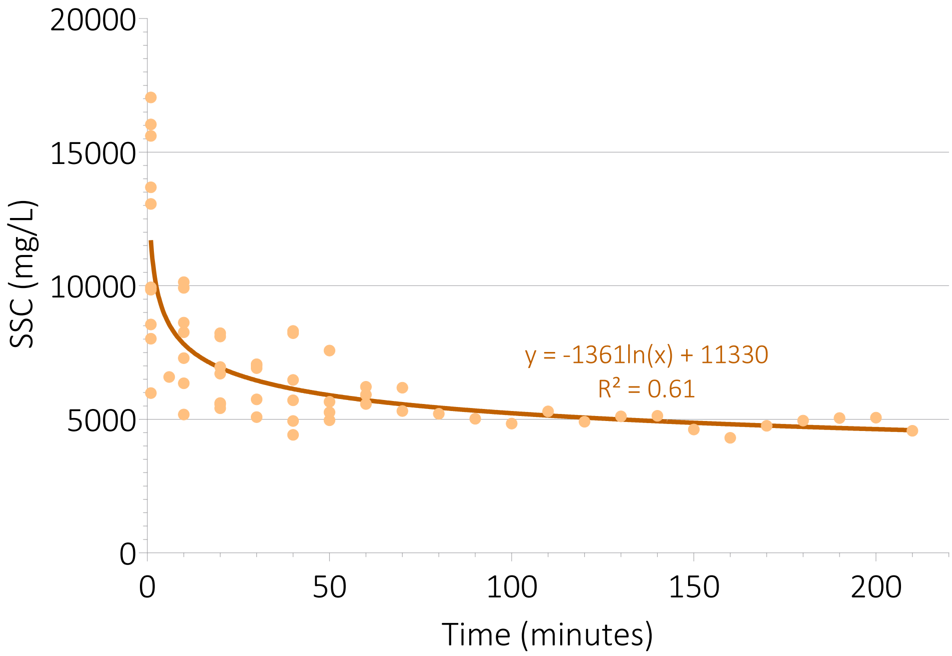

Figure 16. Monotonic relationship of sample SSC and time after initiation of flow, for samples collected from the Control gully during the monitoring period (2017-2019). Modified from Doriean et al., 2020b.

2.3.4 Lidar Monitoring

Crocodile Station

High resolution (~5cm) terrestrial lidar surveys were carried out yearly between 2016 and 2019 to capture the post wet season gully morphology. In addition, some gullies had two lidar surveys in select years, the second, following earth works to capture post-treatment gully morphology ahead of the wet season. In 2019 an airborne lidar acquisition was also included.

Terrestrial lidar was collected with a Leica C10 Terrestrial Scanner, which is a ground base tripod mounted survey equipment. The Leica C10 scanner can collect very high rates of points per square metre in close proximity to the tripod with the rate diminishing with distance from the tripod. To achieve a good spatial distribution of lidar point data it is necessary to perform numerous scans at strategic tripod locations within and around the gully. Benchmarks are required to be included within the terrestrial lidar scans to spatially reference the scans to each other. Benchmarks were surveyed within the vicinity of the gully area and maintained over the four years.

Airborne lidar was collected in 2019 by Airborne Research Australia flown from an Ultralight platform using a RIEGL LMS Q680i-S laser scanner (this type of acquisition is described below for Strathalbyn Station).

The lidar points collected during the scanning have to be classified into ground points and non-ground points (vegetation, structures, etc.). The Leica C10 scanner collects only single returns from laser pulses, in contrast to airborne lidar equipment which collect multiple returns from single laser pulses. This difference has an effect on the relative proficiency of the ground/non-ground point classification.

Thick grass cover and other low vegetation can cause occasional misclassification of lidar points, leaving some vegetation growth being included as surface elevation change. Another source of errors is systematic horizontal and vertical offsets between DEM layers. Any such mis-alignment between the DEM layers has to assessed and rectified prior to calculation of difference.

A DEM of Difference (DoD) was derived for each gully for each consecutive year. The difference layers did contain surface vegetation inclusion errors. A manual editing of the elevation change data was undertaken to remove surface vegetation. The DEM rectification, DoD calculation, and manual editing enabled inter-annual morphological changes to be quantified, representing the erosion across the wet season of untreated gullies (i.e. gully 2.1 (control) and gullies 0.1, 0.2, 1-1 prior to treatment in 2017). The DoDs also enabled the extent of earth works cut and fill to be quantified at each site, providing a record of which part of the reformed land surface represent cut or fill. Hence in addition to providing the basis for measuring any change in the extent of erosion at each gully rehabilitation site, the lidar DoD data for each consecutive year is a visual record of the landform modification which can be used to assist with monitoring any maintenance and modification requirements.

Table 10. Summary of lidar surveys at Crocodile Station completed during the study period.

Survey date	Gully	Key Survey Function	Lidar Platform
Sept 2016	0.1, 0.2, 1.1, 2.1, 2.234	Baseline	Terrestrial Lidar
Oct 2016	2.234	Post 2016 earth works and construction for 2.234.	Terrestrial Lidar
Sept 2017	0.1, 0.2, 1.1, 2.1, 2.234	Post 2016/17 wet season.	Terrestrial Lidar
Nov 2017	0.1, 0.2, 1.1	Post 2017 earth works and construction for 0.1, 0.2, 1.1	Terrestrial Lidar
June 2018	2.1, 2.234	Post 2017/18 wet season.	Terrestrial Lidar
Oct 2018	0.1, 0.2, 1.1	Post 2017/18 wet season. Post 2018 earth works and construction for 0.1, 0.2, 1.1.	Terrestrial Lidar
Sept 2019	0.1, 0.2, 1.1, 2.1, 2.234	Post 2018/19 wet season.	Airborne Lidar
Sept 2019	2.1, 2.234	Post 2018/19 wet season.	Terrestrial Lidar

Strathalbyn Station

High resolution (~10cm) airborne lidar surveys were carried out on twice yearly between 2017 and 2020 to capture the post wet season gully morphology (in the May/June surveys) and the post-treatment gully morphology ahead of each wet season. The one exception to this was in 2017, when only treatment 1 had been completed and the cost of flying lidar over the site could not be justified for just the one site.

Airborne lidar was collected by Airborne Research Australia flown from an Ultralight platform using a RIEGL LMS Q680i-S laser scanner. The use of this instrument on an ultralight platform enables the aircraft to fly low and slow collecting multiple passes of lidar to maximise the number of ground data points collected and thereby the resolution of the surface DEM. A minimum of 100 pts per m^2 were collected which enabled a 10 cm pixel resolution DEM to be derived with a 5cm vertical resolution. The lidar points collected during the scanning have to be class into ground points and non-ground points (vegetation, structures, etc.). Thick grass cover and other low vegetation can cause occasional mis-classification of lidar points, leaving some vegetation growth being included as surface elevation change. Another source of errors is systematic horizontal and vertical offsets between DEM layers. Any such mis-alignment between the DEM layers has to assessed and rectified prior to calculation of difference. A DEM of Difference (DoD) was derived for each consecutive year. The difference layers did contain some surface vegetation inclusion errors. Included in the works were surface treatments such as spreading of mulch layers and mulch contour banks. Some of these surface treatments were put in place between the acquisition dates of the lidar and appear in the data as surface elevation change anomalies. A manual editing of the elevation change data was undertaken to remove surface vegetation inclusion and surface change that was related to surface treatments. The DEM rectification, DoD calculation, and manual editing enabled inter-annual morphological changes to be quantified, representing the erosion across the wet season of untreated gullies (i.e. the control gully and all other treatments prior to treatment in 2018 and 2019). The DoDs also enabled the extent of earth works cut and fill to be quantified at each site, providing a record of which part of the reformed land surface represent cut or fill. Hence in addition to providing the basis for measuring any change in the extent of erosion at each treatment site, the lidar DoD data for each consecutive year is a visual record of the landform modification which can be used to assist with monitoring the reestablishment of tunnelling, which is more likely to occur in areas of fill.

The lidar surveys also enabled the gully catchment areas to be quantified, along with associated changes due to the construction of diversions bunds to redirect overland flow into constructed rock chutes.

Table 11. Summary of lidar surveys at Strathalbyn completed during the study period.

Survey date	Key Survey Function	Treatments undertaken between surveys
Sept 2017	Baseline	
May 2018	Post 2017/18 wet season	Treatment 1, 5
Sept 2018	Post 2018 dry season construction	Treatments 2, 3, 4, 3-4 extension; 7, 8a, 8b, RT4I, RT4II, A1
June 2019	Post 2018/19 wet season	
Sept 2019	Post 2019 dry season construction	Treatment 6
May 2020	Post 2019/20 wet season	

2.3.5 Bioavailable nutrient monitoring and analysis

Water quality monitoring data collected from both case studies (Crocodile and Strathalbyn Stations) were included in an investigative study on bioavailable nutrients and gullies conducted by the Queensland Department of Environment and Science. Sample collection for bioavailable nutrient analysis required the samples to be preserved or analysed within 24-48 of collection. Samples were collected from both remediated and actively eroding gullies, from Crocodile (gullies 2.234, 1.1, and Control) and Strathalbyn (gullies T1, T3, T4, and Control).

Various sampling methods (RSS, autosamplers, manual isokinetic sampling, and PASS samplers) were used to collected samples for bioavailable nutrient analysis. Table 12 lists the analyses conducted on the samples collected. Refer to Garzon Garcia et al. (2020) for more information regarding bioavailable nutrient sampling methods.

Table 12. Nutrient pools analysed or calculated on water quality samples from gullies and their associated analytical methods

Element	Nutrient pool	Method
Carbon	Total organic carbon (TOC)	NDIR
	Dissolved organic carbon (DOC)	NDIR
	Particulate organic carbon (POC)	calculated (POC = TOC - DOC)
Nitrogen	Total Kjeldahl N (TKN)	Kjeldahl digest
	Dissolved Kjeldahl N (DKN)	Kjeldahl digest on filtered sample <0.45 um
	Particulate organic N (PON)	calculated (PON = TKN - DKN - adsorbed NH4-N)
	Dissolved organic N (DON)	calculated (DON = DKN - NH4-N)
	Dissolved inorganic N (DIN)*	calculated (DIN = NH4-N + NOx)
	Ammonium N (NH4-N)*	Dissolved segmented flow analysis (<0.45 um)
	N oxides (NOx-N)*	Dissolved segmented flow analysis (<0.45 um)
	Extracted NH4-N *See BAN methods (Appendix 1)	0.5M K2SO4 extract
	Adsorbed NH4-N (Ads NH4-N) *See BAN methods (Appendix 1)	calculated (Ads NH4-N = Extracted NH4-N - NH4-N)
	Potential mineralisable N at 1 days (PMN1) *See BAN methods (Appendix 1)	calculated (PMN1 = DIN at 3 days - DIN at 0 days)
	Potential mineralisable N at 3 days (PMN3) *See BAN methods (Appendix 1)	calculated (PMN3 = DIN at 3 days - DIN at 0 days)
	Potential mineralisable N at 7 days (PMN7) *See BAN methods (Appendix 1)	calculated (PMN7 = DIN at 7 days - DIN at 0 days)
Phosphorus (P)	Total Kjeldahl phosphorus (TKP)	Kjeldahl digest
	Particulate Kjeldahl phosphorus (PP)	calculated (PP = TKP - DKP)
	Dissolved Kjeldahl phosphorus (DKP)*	Kjeldahl digest on filtered sample <0.45 um
	Phosphate phosphorus (PO4-P)	Dissolved segmented flow analysis (<0.45 um)
	Dissolved organic P (DOP)	calculated (DOP = DKP - PO4-P)
	Colwell P	0.5M NaHCO3 extractable P
	Phosphorus buffer index (PBI)	Total amount of P sorbed by sediment
Bioavailable nitrogen (BAN)	BAN in 1 day (BAN1)	Calculated (BAN1 = DIN at 0 day + adsorbed NH4-N + PMN1)
	BAN in 3 day (BAN1)	Calculated (BAN3 = DIN at 0 day + adsorbed NH4-N + PMN3)
	BAN in 7 days (BAN7)	Calculated (BAN7 = DIN at 0 day + adsorbed NH4-N + PMN7)

*Filtered pool analysed during potential mineralisation experiment at 1, 3 and 7 days (see methods in Garzon Garcia et al., 2020)

2.4 Soil Material mapping and characterisation

Conventional soil assessment and mapping methods were conjectured to be potentially inadequate to characterize and communicate the complexity of soil and sediment material variation in alluvial environments – not only spatially but also vertically into sediment materials deeper than the usual coring limits. This is especially relevant to the mapping of materials with major, deep gully erosion in alluvial sediments. Therefore, 'Soil Materials' mapping, as a combination of pedological and geomorphological approaches, was also employed here as a feasible option to assess the whole depth of materials alluvial gully for erosion management and rehabilitation purposes.

One of the questions to answer in this project, indeed for future major projects in large alluvial gullies, was to substantiate the notion that conventional soil survey methods are inadequate to answer the questions required of alluvial erosion gully environments. A more geomorphologically oriented approach is required.

Therefore, a comparison of the two approaches to assessing soil and alluvial sedimentary materials was made while undertaking both the conventional approach and soil-geomorphic approach to characterising and assessing the gully materials.

Conventional soil mapping aims to provide regional context to the soil types in which the gully systems are developing in the Bonnie Doon Creek region. This is to complete the soil description and classification of the soils that are affected by erosion as well as the surrounding region where they are not affected. This helps identify which soils have been, and may be in future, prone to continued erosion, and to put them into a regional context with previous soil-type reporting for other purposes. In addition, the intention was to see whether surface soils are an adequate predictor of the distinctive patterns of subsoil materials and their characteristics.

Soil geomorphic assessment and mapping aims to assist with the characterisation and interpretation of soil materials within the eroded environment (including the deeper sediments and extent of the strata) for mapping and modelling; determining the potential behaviour of the materials for management; aid the determination of gully typology, and relate to the prediction of erosion rates, and to particularly support the planning and design of remediation methods as part of an innovative approach to alluvial gully management and sediment control.

Combined, both approaches assist with determining inherent soil erosion and erodibility relationships that can be interpolated and understood in the context of the overall alluvial sedimentary system.

Definition of 'Soil Materials' mapping: A multi-purpose layer approach to soil and regolith interpretation to assign greater significance to geomorphic processes and geoscientific principles (Pain et al., 1991; Atkinson, 1993; Thwaites, 2006).

- The approach recognizes the 'layer', which may be a soil horizon or a sedimentary stratum and is described independently of other layers.
- The approach is particularly suited to localised regions for mapping, and for areas of depositional materials.

- Erosion gully exposures offer unique opportunities that for soil material / substrate / alluvial sediments observation.
- The approach recognizes the relevance of substrate (regolith) materials, below that of the solum, to gully remediation and rehabilitation.

2.4.1 Methods

To serve most of the intent and requirements of both of these approaches, a coincident soils mapping and soil-geomorphic material assessment sub-project was undertaken for both the Crocodile and Strathalbyn Stations. Methods and materials used were:

- Conventional soil mapping with field sampling by soil coring with a vehicle-mounted hydraulic push tube corer to a maximum penetration of 1.5 m, using Australian Standard methods (NCST, 2009)
- Soil-geomorphological (soil materials) mapping with field sampling from the gully head, wall, and floor, and from streambank exposures to maximum exposure depths (4+ m below ground level in places), using techniques described elsewhere (Thwaites 2020, Thwaites 2018, Thwaites and Zund, 2018).
- Use of high resolution lidar digital elevation model (DEM) data: 1 m resolution airborne lidar (2009), and 10 cm resolution airborne lidar (2015-16).
- Absolute elevation of sample sites by terrestrial lidar DEM benchmark triangulation; UAV elevation data of sample point surface targeting; lidar DEM location.
- Aerial photo imagery 1: 25 000 scale (Qld Govt); SPOT 2010 satellite imagery; imagery acquired from in-field UAV surveys; and Google Maps online historical imagery.

Soil types were mapped using local soil profile classes (SPCs) from the Soils of Cape York (Cape York Peninsula Land Use Study: Biggs and Philip, 1995), the current extension of Lakeland Irrigation Area soils mapping (N. Enderlin, pers. comm.) and the SPCs of the Lower Burdekin Valley (Thompson and Reid, 1982) where available. Soils that did not correlate with published surveys (mainly in the Crocodile Station area) were defined as new soil profile classes. SPCs are a group of soil profiles that all meet the definition of the class of some soil classification system. The profiles are related by similarity of properties but are not necessarily related in space.

The assessment method for both research sites to identify soil materials for gully characterisation and interpretation purposes followed the brief outline below:

- Observations were made of geo-referenced exposures within gullies in irregular long- and cross-profile transects within selected gullies by the following method (see also the Field Protocols document in Appendix 2 that derived from these and other soil material assessments).
    - Identifying and recording the layers, which may be a soil horizon or a sedimentary stratum and describing them independently of other layers, numbered sequentially down the section using purpose-specific field data description sheets that relate directly to the requirements of the database for soil materials and erosion features.
    - Layers are observed both vertically and laterally: the sequence of difference layers vertically and the tracing of single layers laterally and numbered sequentially from the top for each observation site.

  - A single layer or grouping of related layers is then termed a Soil Material Unit (SMU) for both classification and mapping purposes.
  - Each layer was tested in the field for pH (Raupach test kit) and for aggregate stability using a Department of Environment and Science (DES), Queensland Government field method of observing the slaking and dispersion behaviour of an aggregate immersed in water immediately after immersion and after 10 minutes.
  - Samples were selected from representative layers for laboratory analysis, spatially duplicated where necessary. All samples are analysed for pH, EC, Cl-, P, base cations: Na+, K+, Mg++, Ca++, cation exchange capacity (CEC), particle size distribution. Exchangeable sodium percentage (ESP) and Ca:Mg ratio are calculated.
  - These were deemed the minimum data that was necessary for soil material and gully material characterisation and consequent management purposes. Top layers - whether intact, eroded, or absent A horizons – were further tested for nutrients using a standard agriculture suite of analyses.
- Broader groups of Soil Material Units (SMUs: major layers), distinguished by layer sequences of different soil material fabrics and colour (and maybe inclusions) were mapped out in a prior desktop exercise and verified in the field, where possible, as Soil Material Systems (SMS).

2.4.2 Crocodile Station

The soil materials assessment was restricted to the central gully complex of the study catchments and the vicinity between there and the Laura River, and onto the backplain of the severely eroded floodplain. For the conventional soil survey, a wider extent was taken, particularly to include the considerable expanse of gully erosion complexes further south bounding the Earl’s Creek and the old Peninsula road (Figure 17).

The elevation above Australian Height Datum (AHD) was determined for the surface of each observation site (see Figure 17) using data from lidar surveys. Soil material layer/horizon depths and sample depths were related to elevation above AHD for the purposes of correlating the soil material units from their morphology and analytical properties. To enable the tracing of eroded sediment, soil samples have been analysed for rare earth metals and the particle size has been determined using a laser diffraction methodology. As a result, a link can be determined between this site and suspended solids samples taken downstream.

All raw data for the soil survey part of the NESP 3.1.7 project is stored within the Queensland Government Soil and Land Information (SALI) database under the project code ‘GULLY’. This information will eventually be accessible via the Queensland Globe. There are no other prior or historical soil maps covering the Crocodile Gap area of the Laura River. The only relevant data is the 1:250,000 scale geology map sheet. Land systems and soils have been mapped by the CSIRO (Galloway, 1970) and the Queensland Government (Biggs and Philip,1995) and (Grundy, 1994).A soil survey mapping soils surrounding the Lakeland Downs area including Crocodile Station is still in progress (N. Enderlin, pers. comm.).

Surface soil materials were described and recorded to the Australian standards to a maximum depth of about 1.5 m. Field work involved describing 30 soil profile sites and 47 samples taken from eight gully systems (Figure 17). Samples were taken from key described soil profiles to characterise the chemistry of the representative dominant SPCs and distinct soil materials that were identified. Samples of soil and sedimentary materials were also taken from selected gully walls to characterise the chemical and physical characteristics of the distinct SMUs. An intensive sampling at the Control gullies, 1.1 and 2.1, was undertaken before rehabilitation works were initiated. This was accompanied by sampling the soil material at the heads of Gully 1.1 in the 'lobe' plots (Figure 18).

The soil material layers have been initially ascribed to Soil Material Systems that are further defined by soil material layers as a series of Soil Material Units. Groups of SMUs were identified for each soil material system by following the field protocols drawn up the investigation and sampling process (see Appendix 2).

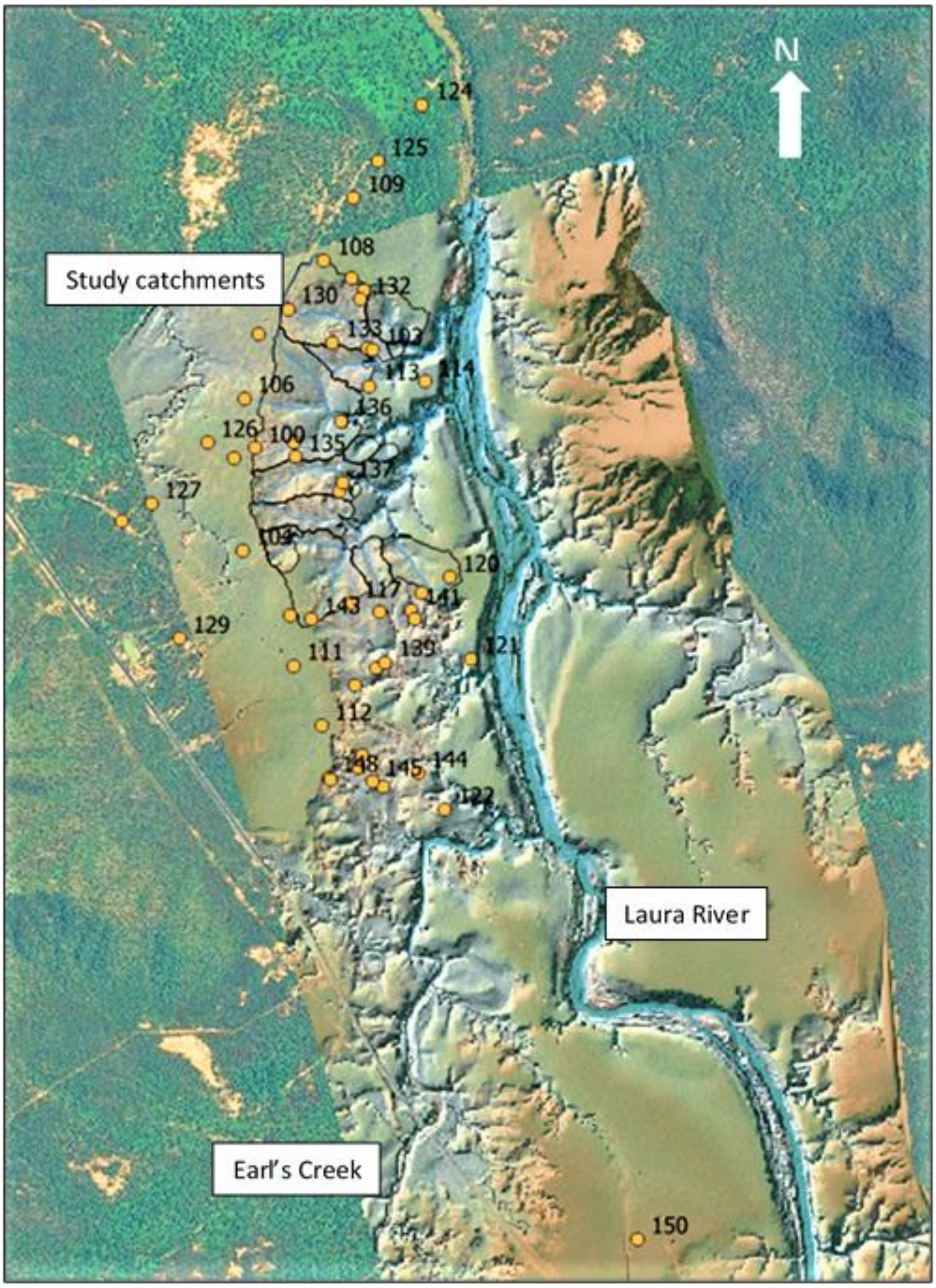

Figure 17. Physiography of the Crocodile study area, using a DEM from 2009 1 m LiDAR and satellite imagery, as a basis of the geomorphic and soil materials description in this section. Included are the soil survey and soil material assessment observation sites and IDs, and the outlines the gully catchments under investigation (in black)

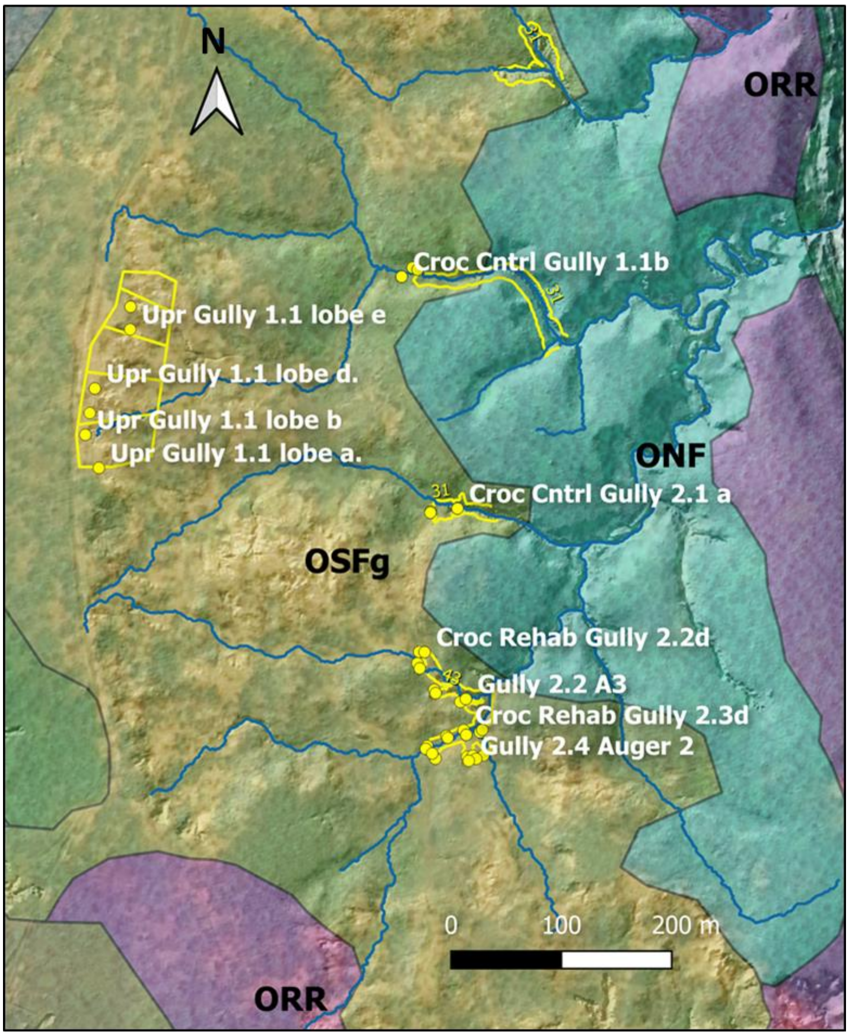

Figure 18. Soil material assessment observation sites and IDs for the assessment of pre-rehabilitation gully materials at the control and rehab. Sites. The outlines of the rehab. and control gullies under investigation are shown in yellow. The gully 'lobe' sites at the heads of the control gully 1.1 were also sampled within the five 'lobe' areas (shown in yellow). The background map is of the Soil Material Systems.

2.4.3 Strathalbyn Station

The survey was restricted to the alluvium of the Burdekin River on the south side of Bonnie Doon Creek, and including the Burdekin alluvium and basalt residual materials to the east of the S-N reach of Bonnie Doon Creek harbouring the Central and Southern gully systems, and bounded by surrounding low hills.

The elevation above Australian Height Datum (AHD) was determined for the surface of each observation site using data from LIDAR surveys. Soil layer/horizon depths and sample depths were related to elevation above AHD for the purposes of constructing a 3-D model of soil materials and analytical properties.

To enable the tracing of eroded sediment, soil samples have been analysed for rare earth metals and the particle size has been determined using a laser diffraction methodology. As a result, a link can be determined between this site and suspended solids samples taken downstream.

As for the Crocodile survey, all raw data for the soil survey part of the NESP 3.1.7 project is stored within the Queensland Government Soil and Land Information (SALI) database under the project code 'GULLY'. This information will eventually be accessible via the Queensland Globe.

Conventional soil survey

Dominant soil types, with dominant and minor soil profile classes (SPCs), were mapped based on an established SPC schema for the Lower Burdekin (Loi et al. 1994, Thompson and Reid 1982). Information from previous soil surveys (Hubble and Thompson 1953, McClurg 1997, Thompson et al. 1990) has been incorporated into this map. Soil materials and land surface conditions were described and recorded to the Australian standards (National Committee on Soil and Terrain, 2009, McKenzie et al., 2008) for soil and land survey, and to specific requirements for soil geomorphic assessment. These were taken by vehicle-mounted hydraulic push-tube corer coring to a maximum depth of 1.5 m. Samples were taken from a representative selection of these described soil material cores to characterise the chemical and physical properties of the dominant SPCs and the distinct soil materials that were identified. These were augmented by sampling and description of soil materials taken from gully walls in selected representative locations to characterise the chemical and physical characteristics of the distinct SMUs.

Soil materials survey

After further field investigations of the gullies an assessment of the soil material layers was converted into a simple classification of all the identified layers and their absolute positions in space.

The field procedures entailed locating each site observation by RTK GPS, rectified geo-referenced drone imagery, and 10 cm lidar DEM, or 1 m lidar DEM outside the 1cm lidar area. This was done so that accurate stratigraphical representations could be constructed of the identified layers (SMUs) through fence diagrams, cross-sections and mapping within gullies. A set of field protocols was developed through this process to aid further assessment of this kind for other specialists to undertake gully surveys. The field protocols are presented in Appendix 2.

The broader scale Soil Material Systems (the groupings of SMUs) were identified and mapped through desktop analysis from satellite imagery, previous mapping work, and lidar DEM analysis.

2.5 Cost-effectiveness of gully remediation

During 2017, 2018 and 2019, a total of 4 and 10 gullies of different sizes have been successfully treated on Crocodile Station (Case Study 1) and Strathalbyn Station (Case Study 2), respectively, using different remediation techniques. As part of this project, funding for the monitoring program has been allocated and results from monitored sites for the past two or three years have been analysed to produce treatment effectiveness estimates. This Chapter summarises gully remediation costs that have been incurred during 2017-2019 period across the two case studies. Using results on treatment effectiveness in reducing fine sediment export and the costs incurred, cost-effectiveness calculations have been undertaken for the following gully treatment sites:

- Crocodile Station: Treatments 2.234, 1.1, 0.1 and 0.2
- Strathalbyn Station: Treatments 1, 3, 4 and 6 using treatment effectiveness derived from monitoring data
- Strathalbyn Station: Remainder of the treatments (Treatments 2, 3-4 ext., 7, 8a and 8b) using treatment effectiveness estimates derived from repeat high resolution airborne lidar data.

Cost-effectiveness is a useful metric to use when comparing the performance of gully remediation at different sites within the same or across different catchments, as well as across projects or programs. As more fine sediment reduction projects under various programs are being funded to help achieve the GBR catchment water quality targets by 2025, consistent evaluation of their cost-effectiveness is becoming increasingly important to inform future project prioritisation and choice of cost-effective remediation techniques suited to the gully erosion problem. Information on the cost-effectiveness of gully remediation on these two case study areas would add to the pool of knowledge on cost-effective approaches to fine sediment abatement to improve water quality in the GBR.

2.5.1 Cost-effectiveness calculations

A cost-effectiveness (CE) metric reports a ratio of present value cost to pollution reduction load in biophysical unit at end of gully (EOG) or end of system (EOS). Information on the site-specific costs of remediation and the corresponding effectiveness of that remediation to reduce fine sediment reduction, measured in physical units, are required to produce cost-effectiveness estimate for each gully remediation sites.

All costs reported in this study are in current 2019 Australian dollars. As reported costs are incurred at the start of the project (i.e. Year 0), discounting of future costs is not required at this stage. However, if estimates of future costs are available (e.g. periodical maintenance costs, on-going monitoring costs) and public funding is made available to cover these costs for a foreseeable number of years into the future, then these costs will need to be discounted before they can be incorporated into subsequent cost-effectiveness evaluations.

Treatment effectiveness in the context of cost-effectiveness analysis simply refers to the fine sediment load reduction (in tonnes) delivered by the project either at treatment site i.e. end of gully (EOG) or at the Reef lagoon i.e. end-of-system (EOS). A percentage reduction is often applied to the fine sediment yield (i.e. baseline load) to obtain the load reduction. The baseline sediment yield is typically reported on an annual basis (Bartley et al. 2018; Rust and Star 2018; Wilkinson et al. 2019). Consequently, when applying the percentage load reduction to the baseline (annual) sediment yield, the resulting effectiveness of a gully remediation is also expressed as an annual load reduction.

Due to limited time series data on sediment reductions, annual load reduction (in tonnes per year) may be assumed to remain <u>constant</u> for the entire lifetime of the project. Variable annual load reduction is probably more realistic for most projects – reflecting changing effectiveness over the system's operational lifetime; however, this kind of information requires long term monitoring data which is not typically available for many Reef-related projects.

In this study, we apply a percentage reduction to the baseline sediment yield to obtain an annual load reduction at EOG, and then apply the catchment-specific delivery ratio (0.45 for gullies on Crocodile Station and 0.94 for gullies on Strathalbyn Station) to obtain annual load reduction at EOS. Load reductions at EOG and EOS are both assumed to be constant for the entire lifetime of each treated gully.

The CE metric is best reported in $/tonne (referred here as ‘Currency 1’); however, it is common to see CEs being reported in terms of $/tonne per year (referred here as ‘Currency 2’). In this study, both cost-effectiveness currencies are reported to enable easy comparison with the different cost-effectiveness metrics reported in other studies.

The CE metric expressed in terms of Currency 1 (i.e. $/tonne reduction) reports the ratio of the annualised present value cost to annual fine sediment reduction. The metric is based calculations used in business investment prioritisation and is widely used in a range of applications, such as evaluating different public health investments with the benefits realised at different time periods in the future (Tan-Torres Edejer et al., 2003). In this study, the annualise present value cost only include the upfront cost because other relevant costs are not yet available. The gully-specific upfront cost (i.e. total present value cost (in $), TPVC) is divided by an *annuity factor* to convert it into an annualised equivalent present value cost (APVC, in $/year):

$$APVC = \frac{TPVC}{Annuity\ Factor} \qquad (4)$$

The annuity factor is given by:

$$Annuity\ Factor = \frac{1-(1+r)^{-T}}{r} \qquad (5)$$

where r = real discount rate
T = assumed lifetime of the remediation works

Converting a total present value cost (TPVC) in absolute $ into an annualised equivalent present value (APVC) in $/year enables this annualised cost to be used alongside the yearly (assumed constant) sediment savings:

$$CE_1 = \frac{Annualised\ present\ value\ of\ upfront\ cost\ (APVC)}{Annual\ fine\ sediment\ load\ reduction} \qquad (6)$$

where CE_1 = cost-effectiveness expressed in $/tonne (Currency 1).

Expressing cost-effectiveness using Equation 6 produces a consistent cost-effectiveness metric (in $/tonne abated) that can be used to compare cost-effectiveness across all other sediment abatement interventions that have different lifetimes e.g. sediment retention basins, reductions in stocking density on grazing land, streambank repair etc. Another useful feature of CE_1 is that, when viewed from the perspective of an investor as the project proponent, the CE_1 metric indicates the payment required per tonne of sediment abated to achieve an internal rate of return that matches the discount rate (*r*) used in Equation 5[2]. In this study, cost-effectiveness is calculated using real discount rates of 2%, 5% and 7% per annum over 25-year and 30-year lifetimes.

For compatibility with other cost effectiveness metrics in the Reef literature (e.g. Wilkinson et al. 2015a, 2019; Rust and Star 2018; Alluvium 2019), another cost effectiveness metric is calculated as the ratio of total upfront cost (i.e. TPVC) to (assumed constant) annual fine sediment load reduction:

$$CE_2 = \frac{Total\ present\ value\ of\ upfront\ cost\ (TPVC)}{Annual\ fine\ sediment\ load\ reduction} \qquad (7)$$

where CE_2 = cost-effectiveness expressed in $/tonne per year (Currency 2). Both CE_1 and CE_2 are calculated for EOG and EOS.

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[2] This will only be true when the annual sediment abatement rate is assumed to remain constant over the lifetime of the gully remediation.

3.0 RESULTS

3.1 Case Study 1: Crocodile Station

3.1.1 Soil Material Characterisation

The Crocodile Gap study area was assessed for the characteristics of the soil materials and their spatial distribution, specifically for interpreting the soil and alluvial materials with respect to erosion susceptibility, gully analysis, relating to sediment yields, and for rehabilitation of the gullies and the eroding land. The detailed soil materials analysis results and summary interpretations are provided in Appendix 2. An overall conceptual model of the Crocodile floodplain materials association can be gained from both the soil survey and soil material assessment procedures. This is shown schematically in Figure 19.

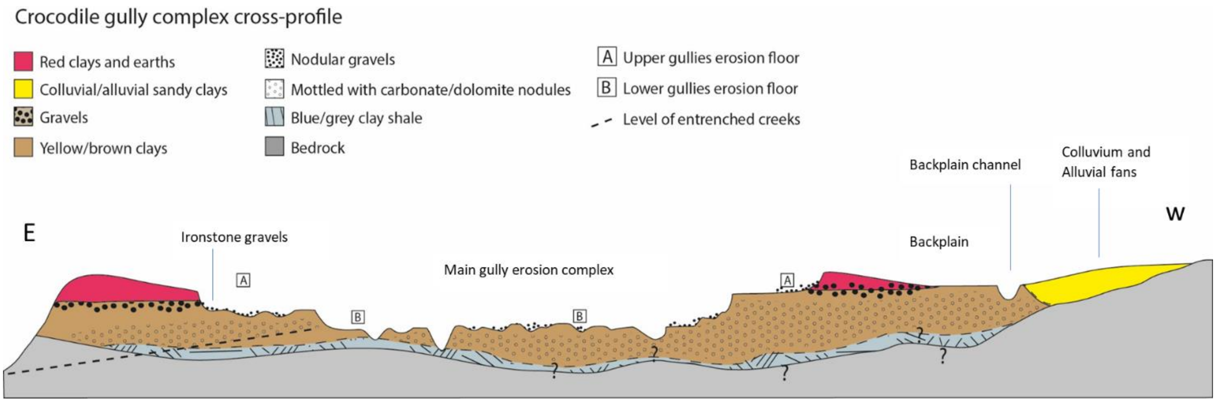


Figure 19. Schematic conceptualised cross-section of the main gully zone in the study area from east to west from The Laura River to the slopes of the Byerstown Range.

The resultant 'soil types' can be described in familiar terms, such as Sodosols, Dermosols, etc. as well as local soil names as Soil Profile Classes. Figure 20 shows the natural soil distribution when classified using the local SPC classification (Table 13). Within the study area, the soils have been characterised, mapped and correlated to soils of Cape York Peninsula Land Use Study (CYPLUS) The map incorporates SPCs from previous soil survey information from the CYPLUS work and the Lakeland Irrigation Area where applicable (Figure 20 and Table 13). Further details of the soil survey and resultant maps and classification can be found in Appendix 2.

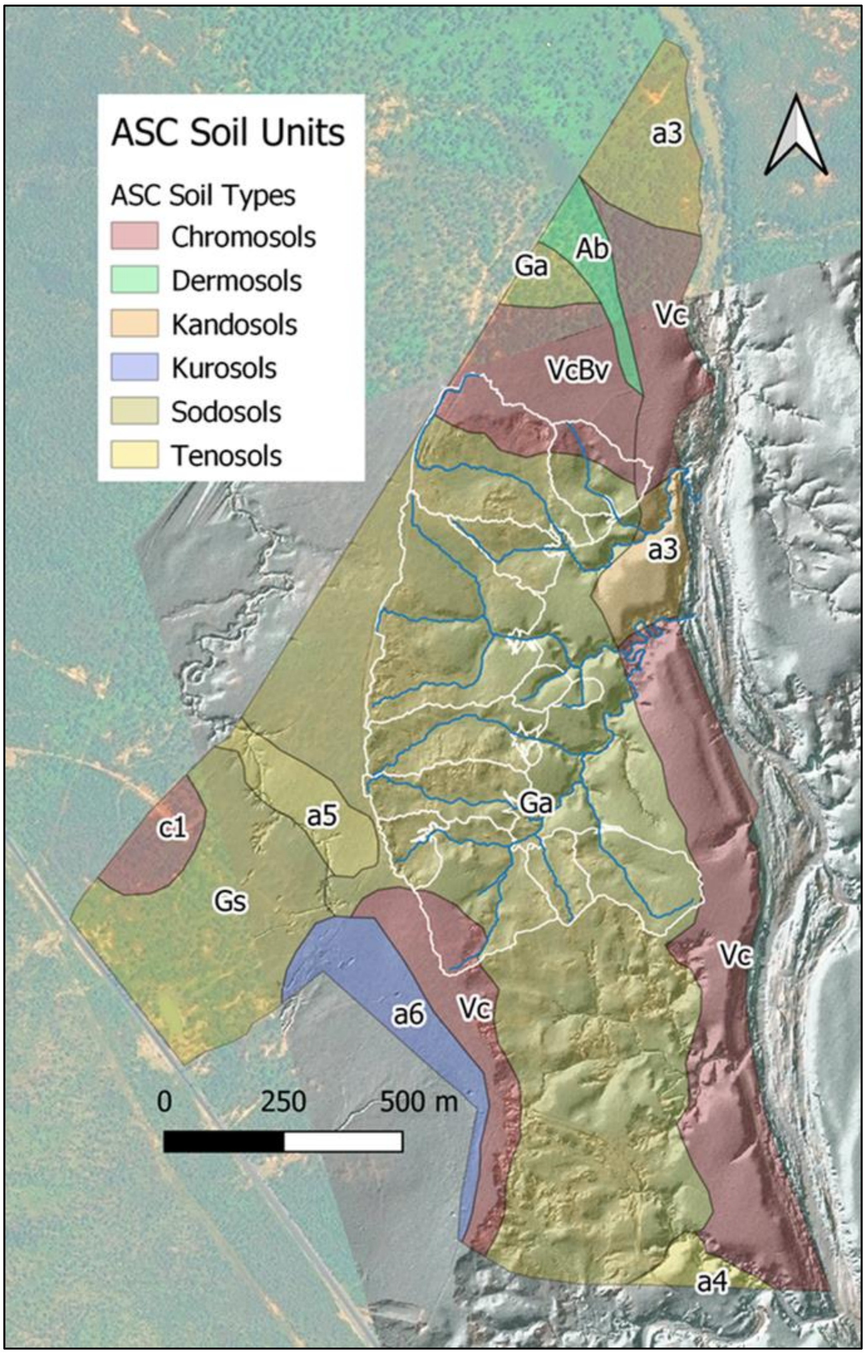


Figure 20. Map of soil types identified in the study area with outlines of the study gully catchments. Soil unit colours refer to the Australian Soil Classification (ASC) classes. The key to the SPC codes is in Table 13

Table 13. Identified Soil Profile Classes related to the Crocodile Station site and the Australian Soil Classification (ASC: Isbell & NCST, 2016) equivalents. Asterisk (*) indicates a new SPC derived for the Crocodile site. Italics indicated SPCs not mapped in Figure 20

Soil Profile Class	Australian Soil Classification Soil Order
A	Soils formed from older alluvial deposits
Victor (Vc)	Red Chromosol
Victor Brown variant (VcVb)	Brown Chromosol
Antbed (Ab)	Yellow, Brown to Grey Dermosol
*A3 / ?Mitchel	Red/Brown Orthic Tenosol or rarely Kandosol
*A4	Orthic Red or Brown Tenosol
*A5	Bleached-Orthic Tenosol
Greenant (Ga)	Yellow, Grey or Brown Sodosol
*A6	Yellow Kurosol
C	Colluvial/alluvial fan deposits from the Byerstown Range
Gibson (Gs)	Yellow or Grey Sodosol
C1	Yellow Chromosol
O	
Victor	Lower pH (slightly acid), D horizon encountered at a greater depth & non-saline
Victor Brown variant	
Antbed	
Ragvale	*LIA* SPC*
O3	*A3/?Mitchel*, sandier texture
O4	
O5	
Greenant (Ga)	
O6	
F	Colluvial fan deposits from the Byerstown Range made up of greywacke, slate, mudstones with sandstones and conglomerate
Gibson (Gs)	
F1	

The soil materials are briefly summarised here from the laboratory analysis data (see Supplementary Information for summary data interpretations) and the field observations. Of the six soil material systems (SMSs) identified in the region the OSF, OSB, and ORR are the most relevant to the major Crocodile gully systems (Figure 21 and Table 14).

The main gully erosion complex comprises several material layers of yellow brown to grey, mottled (with yellow, orange, red and grey) fine sandy clays and sandy clays (OSF SMS). An example of these is shown in Figure 22, with almost a full suite of the SMUs found in the OSF SMS. These are sometimes topped with recent surface wash deposition, deep in places (0.4-0.5 m), with evidence of several periods of depositional events (laminations), with erosion in between. These surface materials are both sodic and magnesic. The subsurface layers usually exhibit sparse to dense carbonate nodules, occasionally to depths over a metre. These nodules are often enriched with magnesium to form a much denser dolomite mineral than the usual calcite. It is this dolomitic nodulation that forms the characteristic ‘çoral’ of the southern gullies and Earl’s Creek from root channel mineralisation (Figure 23).

The red soil materials (Victor soil type and associations; ORR SMS) in the main gully complex are also sodic and magnesic with large amounts of both ferro-manganiferous (Fe-Mn) nodules and iron (Fe) nodules (ironstone), particularly in the ‘lateritic’ zone. This is indicative of an older land surface (pre-Quaternary in age) with evidence of advanced, strong weathering, possibly of earlier alluvial deposits of the palaeo-Earl's Creek / palaeo-Laura River system. Under these materials are 3-4 m of yellow brown sandy clay materials which are moderately to non-dispersive (ONF SMS) in which the main drainage from the erosion gully complex has entrenched in meandering gorges of alluvium, and bedrock near the outlets to the Laura River.

Underlying these soil material layers, above the bedrock, is a variable depth layer (SMU OSF5) of blue, dense clay, strongly mottled with grey and gley colours (indicative of 'waterlogging', anoxic, reducing conditions). This layer appears to be a weathered zone of the underlying Hodgkinson's Formation meta-shales and greywackes.

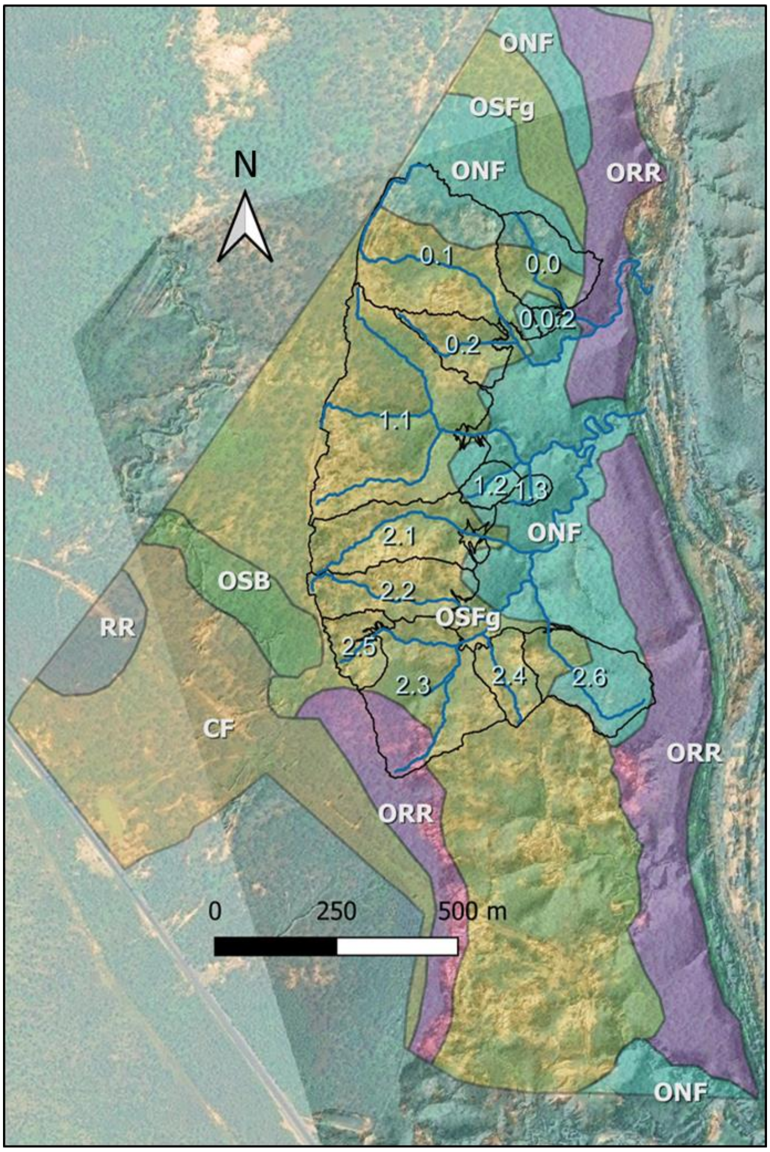


Figure 21. Map of the Soil Material Systems identified in the survey area on the soil map base also showing the study gullies catchment boundaries (in black) and the gully catchment IDs

Table 14. Description of the Soil Material Systems identified in the survey area

SMS Code	Description
OSF	Older Sodic Floodplain – alluvial floodplain with sodic soils and scalds (OSFs)
OSFg	Major gully systems with in the central alluvial valley – dominantly yellow/brown sodic soils
OSFb	Older alluvial floodplain with dominantly brown sodic soils
ONF	Older Non-sodic Floodplain – alluvial floodplain with sandier non-sodic soils
ORR	Old Red Rises – rises and low hills of older land surface – red soil materials
OSB	Older Sodic Backplain – backplain of alluvial floodplain with sodic soils and wetter backplain depressions
CF	Colluvial Fans - colluvial/alluvial deposits of soils
RR	Residual soils on bedrock

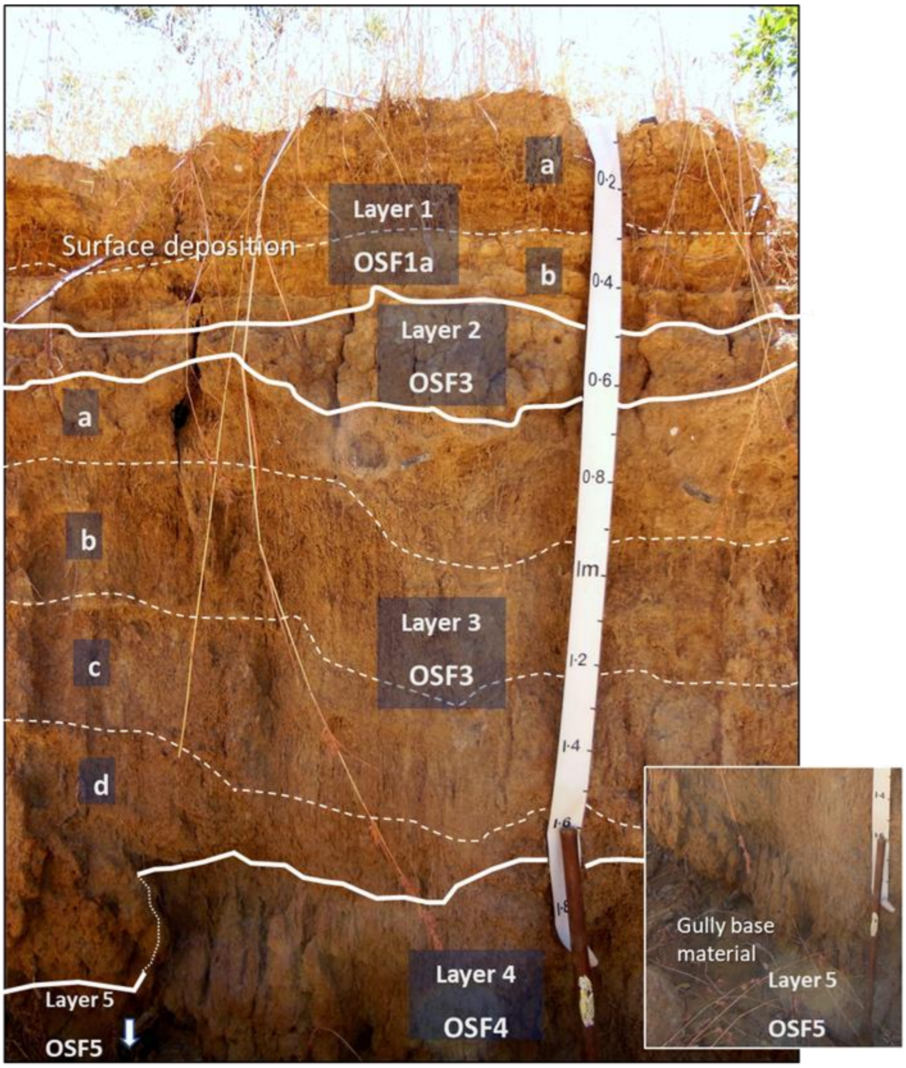


Figure 22. An example of the soil material layers at the down-gully head of the entrenched stream of Gully 0.1 in the OSFg SMS. The section illustrates the layer identification and coding of the soil material units (SMUs).

The soil materials in the main gully complex (Greenant and Victor soil types; OSFg SMU) show high dispersivity characteristics, although this is not all due to exchangeable sodium (sodicity) levels in the materials. The great majority of the soil materials appear to be also highly magnesic. High exchangeable Mg can also induce high levels of dispersion and slaking and therefore erosion. The exchangeable sodium percentage (ESP) values are, in fact, very variable, whereby in Gully 1.1 material at 2.2 m depth shows an ESP of 5.2% (non-sodic), an acidic pH of 4.2, but with an R1 dispersion ratio of 0.99 owing to an EMP (exchangeable magnesium percentage) of 54 % (extremely magnesic) – and a high fine sand, silt content (high slaking risk).

However, there are many sites where the ESP is over 40%, and in places is over 60%, with the highest recorded being 92.3% in the southern part of the gully complex. There are, in fact, 11 sites that are 80-90% range. These must rate as some of the highest ESP levels in Queensland, if not in Australia.

Summary analytical data indicate the averages for main chemical factors that are common to both the set of intensive sampling at the gully heads scarp and channel heads (OSFg SMS) and the soil survey / soil material assessment (see Supplementary Information).

From this it can be seen that:

Yellow/brown soil materials of OSF and OSFg SMSs:

- Field aggregate dispersion tests indicate high degree of slaking and dispersion in the subsoil and deeper layer materials and in the surface wash deposition materials;
- EMP levels generally in the magnesic to extremely magnesic range (Ca:Mg extremely low);
- Strong calcium carbonate nodulation from around 0.75 m depth;
- Salinity moderate to very high;
- pH levels predominantly strongly alkaline, with more acidic top layers (pH 5-6).

Red/Yellow soil materials of the ORR SMS (predominantly red weathered and lateritised materials)

- Dispersivity very high at shallow depths with slaking;
- pH levels in top layers are moderately acidic to around neutral (with some distinctively strongly acidic materials);
- ESP levels are generally in the sodic to very sodic range;
- EMP levels generally in the magnesic to very magnesic range (Ca:Mg very low to extremely low);
- High iron and manganese contents;
- Salinity low – non-saline;
- pH levels in sub-layers are predominantly alkaline

In the main gully erosion complex (OSFg) the subsurface materials are overwhelmingly fine sandy clays with commonly high proportions of silt-sized sediment. The representative site for the Greenant soil (OSFg SMS) at 1.2 m depth (Layer 3, i.e. OSF3), the proportions of fine sand : silt : clay sized material is 30 : 25 : 43 %.

The summary data has been split according to the topsoil/top layer materials, the 'sub-layer' materials, i.e. all that is below the topsoil/top layer. Any data gained from below normal augering or coring depth (approx. 1.2 m) is included as an indicator of what soil material conditions may have been missed by conventional soil survey.

For gullies 1.1, 2.1 and 2.2 (including gully floors) differences are evident between the top layer and the sub-layers:

- Top layers are distinctly acidic, but the lowest layers are only slightly alkaline
- Top layers can be moderately saline, and the deeper sub-layers can be only moderately saline. This has implications for the dispersibility of the materials, that is that they are not mitigated much by salinity.
- The materials below 1.2 m consistently show a distinct increase alkalinity and salinity from the upper sub-layers as well as higher CEC, which is reflecting the higher clay contents.
- All layers are sodic but they are generally extremely sodic. The median ESP value for the top layers is substantially lower than the mean, revealing the fact that a few gully floor samples in that group are skewing the mean to a substantial degree.
- Paralleling the sodicity is also the strength of magnesicity. Top layers are not so affected (but are still of no use for plant growth), and the sub-layers are very high in magnesium compared with calcium, because much of the calcium has precipitated out as nodules. It appears that the magnesium is doing that too, in the form of dolomitic nodules {the gully 'coral').

Taken as a whole, the sampled soil materials show similar trends (Table 15a) to the specific gully materials but the pH and the EC appear to be higher in the sub-layers below 1.2 m. This bolsters the argument that the conventional augering and coring of a soil survey is missing these valuable changes in sub-layer characteristics.

The most noteworthy aspect of the particle size distribution, or the textures, of the gully materials is the generally low silt contents and the dominance of the fine sands and clays (Table 15b). This puts the topsoils in to the silty loam to loam bracket, with the sub-layers tending towards clay loams. The higher clay contents in the deeper sub-layers, combined with their extreme ESP values and only moderate salinity, makes for a high risk of dispersion as well as readily slaking (from the dominance of the fine sand and silt still in these materials).

When viewed by relationship to the soil material systems in which the soil materials lie there are distinctive elements to the regional characteristic patterns:

- The top layers are generally sandier (at least 75 % fine sand) than the sub-layers throughout, except for the colluvial gullies (less clay; dominantly fine sand). These gullies are not significant the rehabilitation priorities, however.
- All have similar amounts of clay in the sublayers (25 – 35 %), again except for the colluvial gullies (substantially more sands in the sub-layers).
- Of the < 2 µm fraction, top layers contribute much less than the sub-layers; less than half for the ORR and a third less for the colluvial gullies (CF). The intensive sampling in study gullies comprised several gully beds of sorted, deposited materials, which is shown by the greater proportion of fines throughout with a corresponding lessening of fine sands.
- The sodicity is prevalent in the OSF SMS with the sub-layers averaging around the 40-45 % mark (extremely sodic). Even allowing for the gully floor top layers it appears that the top layers of the OSF soil materials are at least moderately sodic (>15 %). The other soil material systems show considerably less sodicity throughout, with only the

colluvial sub-layers being moderately to strongly sodic. The available magnesium, however, is high for all soil materials, especially so for the colluvial (CF) sub-layers. This tends to support the idea that the Hodgkinson's Formation (the underlying bedrock and source of colluvial material) is probably the source of the magnesium.

- For the availability of < 2 µm fraction, none of the soil material systems *per se* are a big supplier of the fines. The gully soil materials, which include the gully floors and eroded gully surfaces are the biggest, as expected, but are still only about 50 %, all that being considered. In general, the main gully-producing materials (in the OSF SMS) have 45 % fines, with less (34 %) in the top layers.
- The biggest supplier of fines appears to be the older red – yellow/red sub-layer soil materials of the ORR soil material system. A few large gullies do occur in this material.

Table 15.a) Chemical analysis averaged for all samples from the Crocodile site (EAL and DES lab analysis) categorised by the main Soil Material Systems. The results are split into those for the top layers only and the rest of the sub-layers, b) Particle size analysis averaged for all samples from the Crocodile site (EAL and DES lab analysis) categorised by the main Soil Material Systems. The results are split into those for the top layers only and the rest of the sub-layers.

a) Chemistry means by SMS

	pH	EC	Ca:Mg	ESP	EMP	CEC	Mg	Exch Al	ECEC	SMS	
Top Layers	6.3	0.4	0.8	16.2	38.1	2.1	3.9	0.5	3.3	**OSFg**	
Sub-Layers	7.1	0.7	0.5	38.7	32.0	3.0	6.3	0.3	4.6	Soil survey	
Top Layers	6.5	0.1	2.2	4.4	11.2	0.4	0.6	-	-	**ORR**	DES
Sub-Layers	6.0	0.2	0.7	7.1	53.4	3.3	5.2	0.4	5.3		
Top Layers	5.4	0.3	0.8	3.0	13.9	0.4	0.4	0.3	1.3	**CF**	
Sub-Layers	6.2	0.2	0.1	22.1	56.6	2.1	-	0.2	1.4		
	pH	**EC**	**Ca:Mg**	**ESP**	**EMP**	**Ca**	**Mg**	**K**	**ECEC**		
Top Layers	6.4	0.2	0.9	43.3	33.6	21.1	33.6	1.9	8.9	**OSFg**	EAL
Sub-Layers	7.3	0.4	0.6	49.9	30.8	20.3	30.8	1.7	9.5	Gullies	
Top Layers	6.3	0.3	0.8	29.8	35.8	-	18.7	-	6.1	**OSFg**	EAL+DES
Sub-Layers	7.2	0.5	0.5	44.3	31.4	-	18.5	-	7.0	All	

b) Particle size distribution means by SMS

	Sand	Silt	Clay	< 2 µm	SMS	
Averages for top layers	66.1	15.6	18.3	33.9	**OSFg**	
Averages for sub-layers	55.3	17.0	27.7	44.7	Soil survey	
Averages for top layers	71.9	13.5	14.6	28.1	**ORR**	DES
Averages for sub-layers	46.3	18.1	35.6	53.7		
Averages for top layers	77.5	13.6	8.9	22.5	**CF**	
Averages for sub-layers	64.8	12.6	22.6	35.2		
	Sand	**Silt**	**Clay**	**< 2 µm**		
Averages for top layers	50.5	27.1	22.4	49.5	**OSFg**	EAL
Averages for sub-layers	51.0	21.8	27.1	49.0	Gullies	
Averages for top layers	59.5	21.3	20.4	41.7	**OSFg**	EAL+DES
Averages for sub-layers	54.2	19.4	27.4	46.8	All	

Figure 23. Gully walls and Interfluves in the southern end of study area in the ORR SMS cutting into the yellow sodic and mottled grey sodic layers of the OSF SMS. Iron nodules evident from original, now eroded, ferricrete, and the ‘gully coral’ of the lower grey mottled layers (calcified/dolomitized root channels).

Figure 24. A typical example of the soil material layers in the OSF SMS, gully floors are semi-stable in places but most floor areas are reactivated.

Figure 25. A gully wall in the southern end of the lateritic ORR SMS, showing the laterisation and ferricrete formation, as well as the extensive iron nodule coverings of the lower soil material layers.

3.1.2 Water Quality Summary

Water quality of gully flow events was monitored via the collection of suspended sediment and the measurement of turbidity, using multiple monitoring methods, during two wet seasons (2017/18 and 2018/19). Samples were also collected for bioavailable nutrients from select gullies (control, 2.234, and 1.1) when possible. A total of 181 water quality samples were collected during the 2017/18 wet season, with >20 samples collected from each gully. Due to budgetary, logistical, and safety constraints, combined with two major flood events, there were a limited number of water quality samples collected (n=40) during the 2018/19 wet season. Gullies 1.1 and 0.1 only had 1 PASS sample from each gully to account for the SSC of flow events from November to mid December 2018 and gully 0.2 only had one RSS sample from the first flush event in October 2018. Flooding from backwater events destroyed or disabled most of the sampling equipment during January and February 2019. Water quality monitoring data from the 2019/20 wet season was not able to be retrieved due to complications associated with the Covid-19 Pandemic.

3.1.3 Meteorology and hydrology

Rainfall totals, measured between October and May each year, were not significantly different from the regional wet season average (average total of 855 mm ±402 mm) of the permanent rain gauge (1990-ongoing) operated by the Queensland Department of Natural Resources, Mines and Energy (DNRME), located at Coal Seam Creek, ~13 km from the study site (DNRME 2020). This suggests rainfall conditions observed during the monitoring period were representative of usual climatic conditions. There were 52 and 80 rainstorms (> 0.2 mm rainfall over a 6-hour period) that occurred during the 2017/18 and 2018/19 wet seasons respectively. Two major flooding events occurred during the 2018-19 wet season, that were generated by high-intensity rainfall in the Laura River catchment, surrounding the study site, that caused the Laura River to backwater. The study site was inundated with approximately 1 to 4 m of water during these events. Historical water level data of the Laura River, measured at the DNRME Coal Seam Creek stream gauge, indicate these backwater events occur on a ~3 year frequency (DNRME 2020).

3.1.4 Backwater Events

During the course of the study all gullies experienced a number of episodes of backwatering from the Laura River, with the largest event inundating the gully by more than 4m (Figure 26-Figure 28). It has now become apparent that these gullies are regularly inundated by backwater events, to the extent that this will have to be considered as a major driver of the gully erosion process, and therefore needs to be considered in the design for all alluvial gully remediation projects. We believe there is evidence that an increase in the magnitude of floods in the Laura River since the 1990s is responsible for the initiation and progression of these gullies (Figure 29). The backwatering is also a major complicating factor for water quality monitoring, and was responsible for the contamination or loss of a large number of water quality samples collected during the study (given that any sample collected while under backwater flow conditions is not representative of what is being delivered from the gully itself).

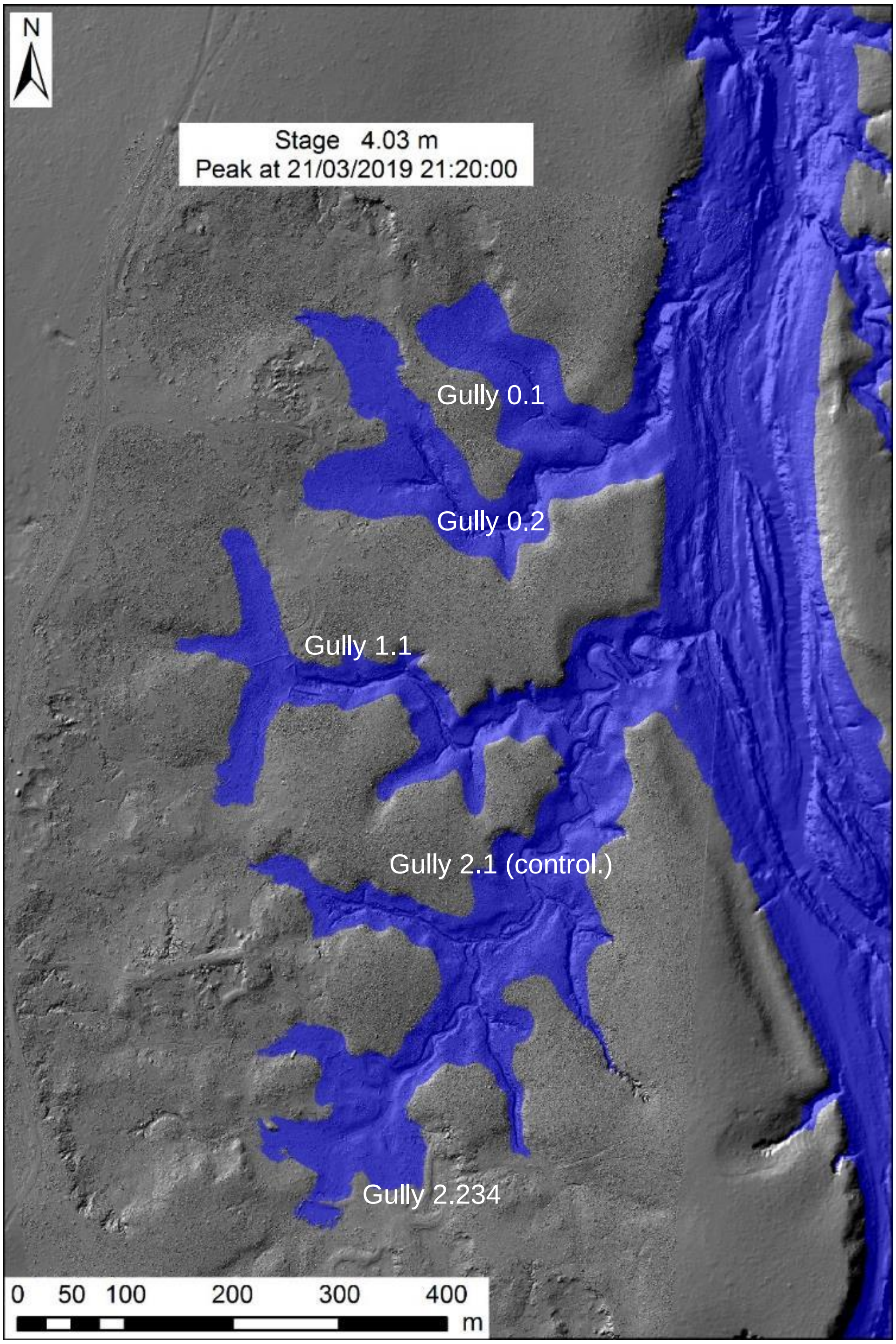


Figure 26. Map showing the maximum extent of gully backwatering during the flood of March 2019, in which the gully was inundated to a depth of around 4m.

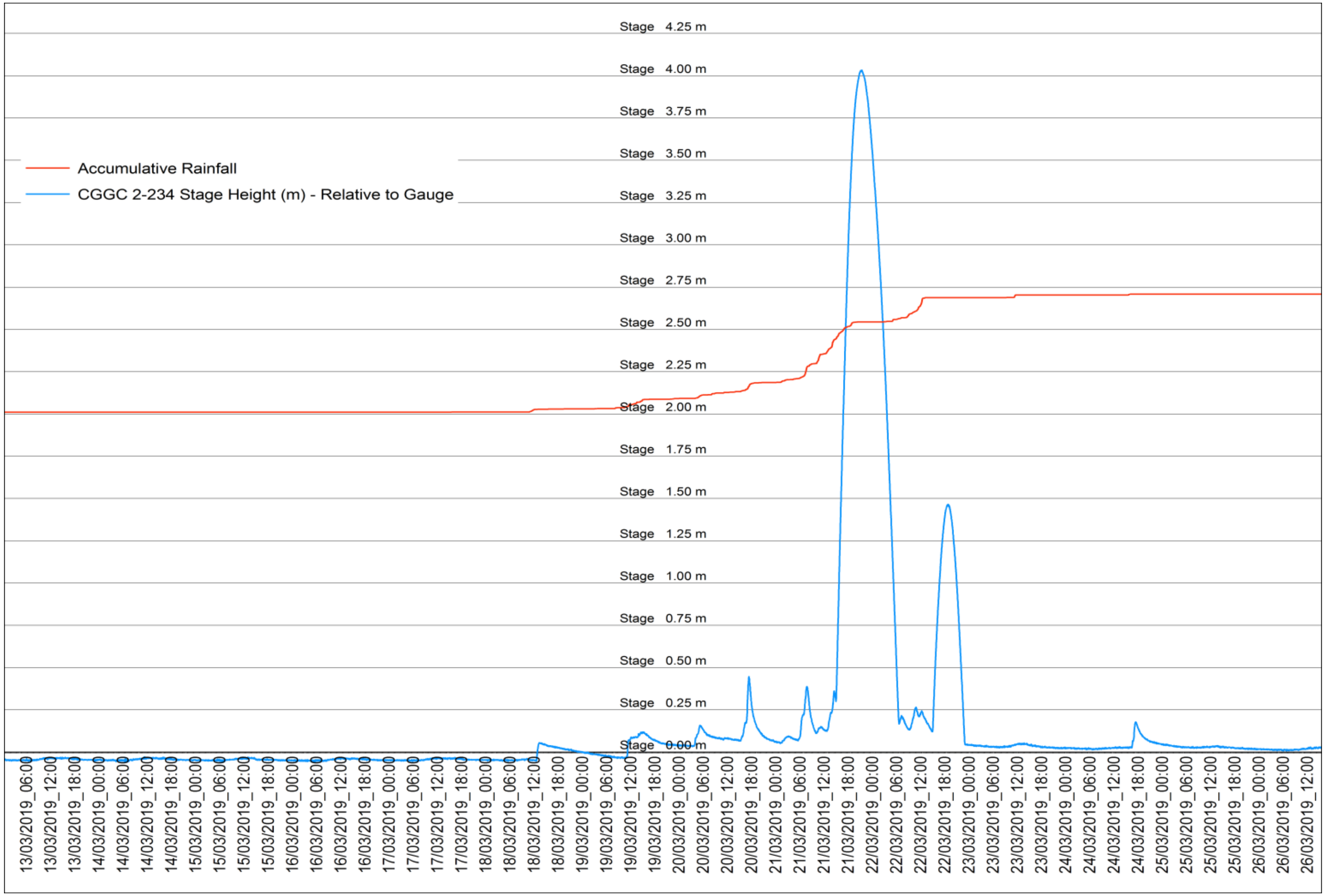


Figure 27. Hydrograph as recorded on the stage recorder at the outlet to gully 2.234 during the March 2019 backwater event from the Laura River.


Feb 2017


Early Jan 2018


Late Jan 2018


Mid March2018

Figure 28. Sequence of post-construction rehabilitation of Crocodile Gully 2.234. Note the backwater event experienced in March 2019.

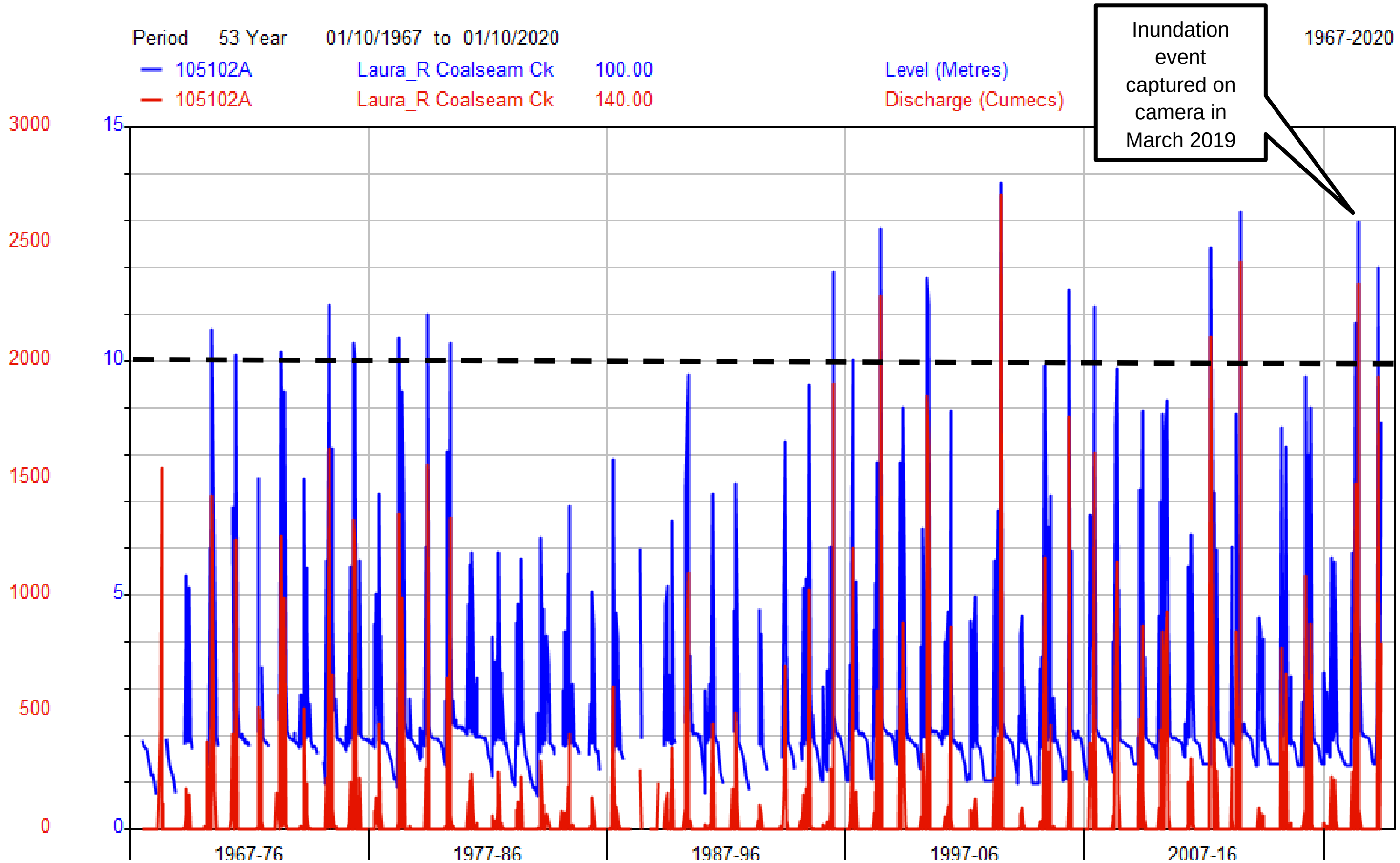


Figure 29. Flow record for the Coal Seam Creek gauge on the Laura River, 13km downstream of the Crocodile Station study site. The dashed line represents the approximate flow stage on the river at which the study site gullies begin to be inundated by river backwater.

3.1.5 Suspended sediment concentration and particle size

Gullies Control and 2.234 were used as part of a study that evaluated suspended sediment monitoring methods for gullies, during the 2017-18 and 2018-19 wet seasons (Doriean et al., 2020a). As a result, a much higher number of samples were collected from these gullies, compared to gullies 1.1, 0.1 and 0.2, for the 2017/18 and 2018/19 wet seasons. SSC data, from samples collected using different monitoring methods over the monitoring period (2017-2019), indicate all remediated gullies, except gully 2.234, did not differ with the control gully (Table 16) (Figure 30). SSCs of samples collected from gully 2.234, remediated during the 2016 dry season, indicate the gully soil erosion has been significantly reduced compared to the control for both wet seasons monitored (2017-2019). The remediation measures installed at other gullies (1.1, 0.1, and 0.2) occurred late in the dry season of 2017 during which time the site was impacted by a late dry season storm event (60mm in less than 1 hr). As a result, a substantial amount of sediment was generated by the storm while remediation activities were still underway. This first flush event explains the generally higher SSCs observed in these gullies during the 2017/18 wet season. Repairs were made to the soil erosion controls on these gullies during the 2018 dry season and initial water quality data suggest they were effective at reducing gully soil erosion (Table 16).

Table 16. Descriptive statistics of sample suspended sediment SSC for all gullies during the 2017-2019 monitoring period.

	Control		2.234		1.1		0.1		0.2	
Wet season	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19
Number of samples	62	14	51	23	1810	1	21	1	23	1
Minimum (mg/L)	4146	1012	378	364	3397	NA	975	NA	608	NA
25% Percentile (mg/L)	5058	4829	850	682	4250	NA	1549	NA	2551	NA
Median (mg/L)	6082	5920	1451	1034	6915	NA	8223	NA	6228	NA
75% Percentile (mg/L)	8107	7214	2000	1082	38384	NA	11953	NA	11485	NA
Maximum (mg/L)	15612	20240	5278	1428	36574	NA	48373	NA	20566	NA
Range (mg/L)	11465	19228	4900	1064	1810	NA	47398	NA	19958	NA
Mean (mg/L)	6806	6752	1561	908	6574	3304	10493	3658	7571	6,228
Std. Deviation (mg/L)	2370	4321	946	310	6987	NA	12368	NA	5734	NA
Std. Error of Mean (mg/L)	301	1155	132	65	1276	NA	2699	NA	1196	NA
Geometric mean	6471	5723	1327	844	5001	NA	5639	NA	5255	NA
Geometric SD factor	1.4	1.9	1.8	1.5	1.9	NA	3.3	NA	2.7	NA
Lower 95% CI of mean (mg/L)	6204	4257	1295	774	3965	NA	4864	NA	5091	NA
Upper 95% CI of mean (mg/L)	7407	9247	1827	1042	9183	NA	16123	NA	10050	NA
Coefficient of variation	35%	64%	61%	34%	106%	NA	118%	NA	76%	NA

Table 17. Descriptive statistics of sample suspended sediment d50 particle size measurement for all gullies during the 2017-2020 monitoring period.

	Control		***2.234***		***1.1***		***0.1***		***0.2***	
Wet season	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19	2017/18	2018/19
Number of samples	62	14	51	23	1810	1	21	1	23	1
Minimum (mg/L)	5.9	6.1	3.4	2.6	6.8	NA	6.3	NA	7.3	NA
25% Percentile (mg/L)	6.8	7.3	4.4	4.1	7.6	NA	7.3	NA	8.8	NA
Median (mg/L)	7.5	8.2	5.3	4.4	8.9	NA	7.9	NA	9.7	NA
75% Percentile (mg/L)	8.6	9.4	6.1	6.6	10	NA	8.6	NA	10	NA
Maximum (mg/L)	16	15	7.9	13	12	NA	12	NA	12	NA
Range (mg/L)	10	9.1	4.6	10	5.2	NA	5.6	NA	4.2	NA
Mean (mg/L)	8.7	8.7	5.3	5.3	9	6.3	8.3	7.4	9.6	12
Std. Deviation (mg/L)	2.2	2.2	1.1	2.3	1.5	NA	1.5	NA	1.1	NA
Std. Error of Mean (mg/L)	0.54	0.54	0.16	0.47	0.33	NA	0.42	NA	0.28	NA
Geometric mean	8.5	8.5	5.2	4.9	8.9	NA	8.1	NA	9.6	NA
Geometric SD factor	1.3	1.3	1.2	1.4	1.2	NA	1.2	NA	1.1	NA
Lower 95% CI of mean (mg/L)	7.6	7.6	5	4.3	8.3	NA	7.3	NA	9	NA
Upper 95% CI of mean (mg/L)	9.8	9.8	5.6	6.3	9.7	NA	9.2	NA	10	NA
Coefficient of variation	26%	26%	22%	43%	17%	NA	19%	NA	12%	NA

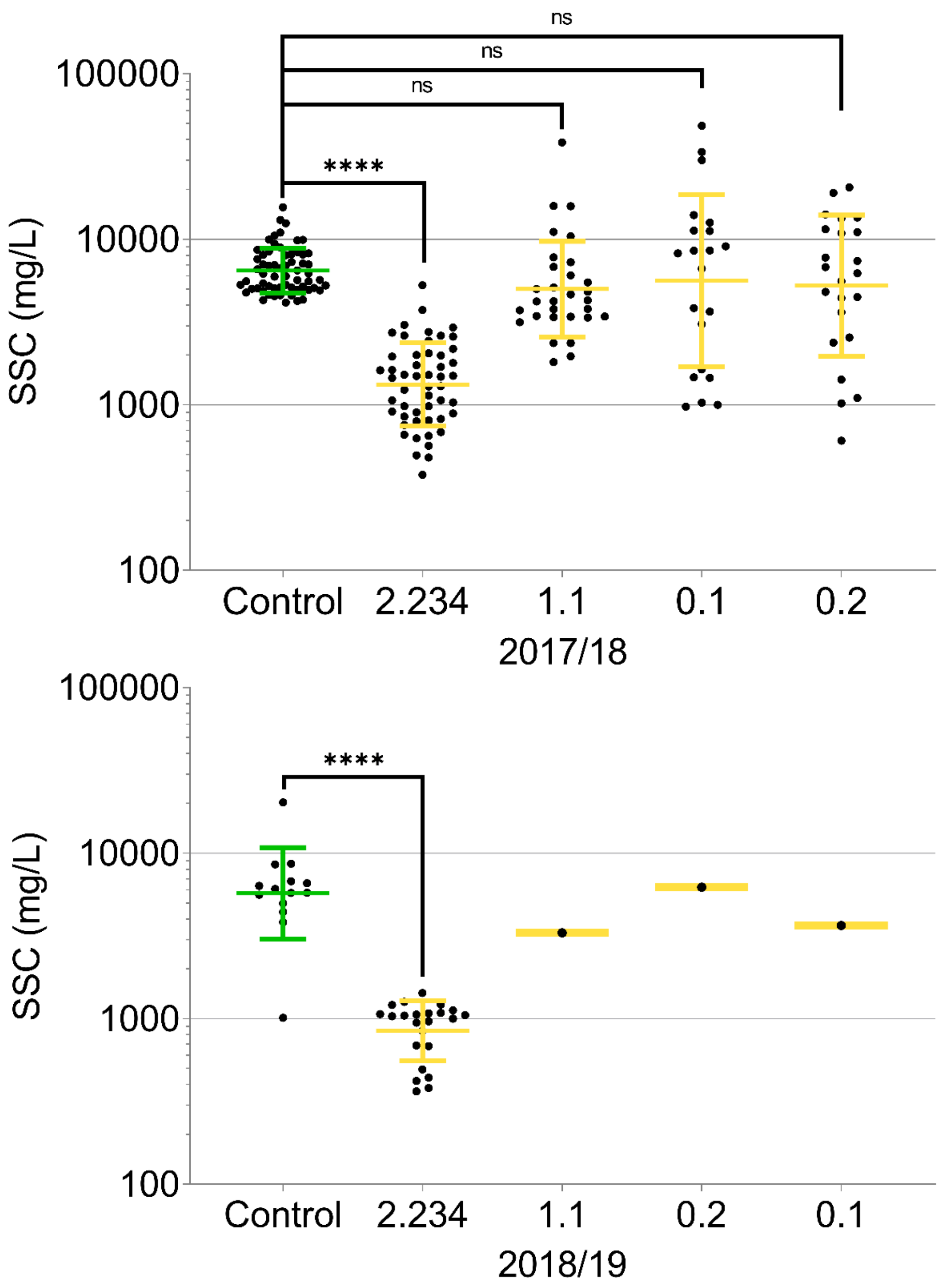


Figure 30. SSC of samples collected from the Control (green) and remediated (yellow) gullies during the study period (2017-2019). Long lines and error bars represent the geometric mean and standard deviation of samples collected. The black markers represent individual samples collected. Brackets represent the results of unpaired t-tests, where p < 0.001 (***), or p > 0.05 (ns). Statistical comparison of gullies Control, 1.1, 0.2, and 0.1 were not possible for the 2018/19 samples as they represent only one sample per site. Note, the two samples collected from gullies 1.1 and 0.1 during the 2018/19 wet season are single PASS samples that collected sediment from flow events that occurred between October 2018 and December 16th, 2018. The sample collected from gully 0.2 during the 2018/19 wet season represents a single RSS sampler from the first flow event of the 2018/19 wet season.

The gully suspended sediment sampling method evaluation study conducted using gullies 2.234 and Control, determined that the recently developed PASS sampler method collected the samples that were more representative of gully suspended sediment dynamics, compared to the other methods. This was due to the ability of the PASS sampler to collect time-integrated samples (i.e., continuously sample suspended sediment during from one or multiple flow events) during a deployment and the method had the least sampling bias (Doriean et al. 2020a). Comparison of PASS sample time weighted-average SSC data, collected from the control and remediated gullies, best represents the measured approximation of suspended sediment dynamics occurring in these gullies throughout the monitoring period (Figure 31). PASS samples collected from the control gully indicate the gully was actively eroding during the monitoring period (2017-2019) with SSCs generally above 5000 mg/L. In contrast the remediated gully 2.234 shows consistently low SSCs (<2000 mg/L), whereas the erosion control failures (2017/18 only) and first flush effect associated with gullies 1.1, 0.1, and 0.2 are also evident. Further suspended sediment monitoring results for each gully are described in the following sections. Note, much of the sample data collected was not normally distributed, rather it was log-normally distributed. In these instances, comparisons of data refer to the geometric mean (GM) of sample SSCs rather than the more commonly used arithmetic mean. The GM calculates a more representative average for log-normal distributions. The standard deviation is not added or subtracted from the GM, as it is with the arithmetic mean, because it is a unitless factor. Thus, the GM standard deviation is a factor that is multiplied or divided by the GM (e.g. GM = X *÷ the standard deviation factor) (Kirkwood, 1979).

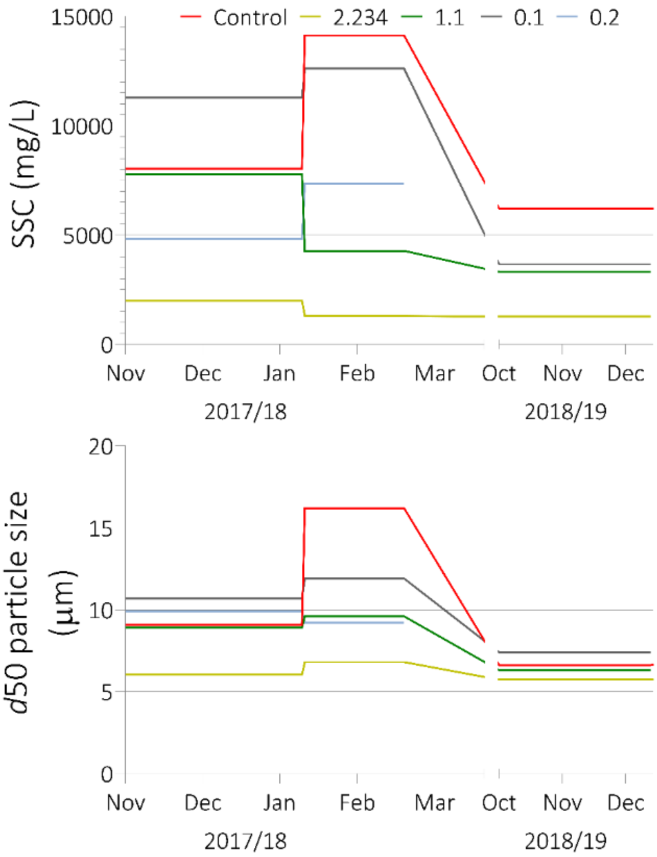


Figure 31. Approximation of gully suspended sediment dynamics during the study period using data from PASS samples collected during the monitoring period (2017-2019). Note the horizontal lines represent the time-weighted average SSC (top panel) and median (*d*50) sediment particle size (bottom panel) of a PASS sampler for the time it was deployed (e.g. one PASS sample represents the SSC for November 2017 to January 2018).

Gully Catchments

Visual observations made, during the 2018/17 wet season (Figure 32) of the water flowing from the catchments of gullies 2.234 and Control indicated that suspended sediment sourced from the catchments was being transported through the gullies. This meant that the SSC measurements of samples collected at the outlet of the gullies were likely measuring gully and catchment sourced suspended sediment together, thus biasing the measurement of sediment contribution form the gully. To confirm this several PASS samplers were deployed, during the 2018/19 wet season, in natural depressions throughout the catchments of gullies 2.234 (three PASS samplers) and Control (one PASS sampler) (
Figure 3 and Figure 33).

Only two samples from each sampler were collected during the 2018/19 wet season. However, the PASS samples collected provided a time-integrated suspended sediment sample representative of the runoff flow events that occurred during the periods of October 10th to December 16th, 2018 and December 17th, 2018 to February 5th, 2019. Sample time-weighted average SSCs ranged between 336-3556 mg/L and 485-2709 mg/L for the catchments of 2.234 and Control gullies respectively (Table 18). Comparison of SSC and PSD of samples collected from the catchments and gully outlets indicate the catchments are contributing a substantial amount of the suspended sediment through gullies Control and 2.234. Based on these observations, and the similarity of catchment features between gullies, it is likely that the catchments of the other remediated gullies are also contributing to a portion of the suspended sediment measured at the gully outlets. This assumption needs to be confirmed by water quality monitoring data from the catchments of those gullies (1.1, 0.1, 0.2).

Table 18. Time-weighted average SSC and PSD data of samples collected, using PASS samplers, from gullies Control and 2.234 during the 2017/2018 and 2018/2019 wet seasons. Note catchment samples (n=2 per sampling location) were only collected during the 2018/2019 wet season.

Sampling location	*TWA SSC (mg/L)*	*PSD (µm)*		
		d10	*d50*	*d90*
Control gully	7123 (± 2670)	1.79	10.80	175
Control catchment	485-2709	1.04	4.29	26
Gully 2.234	1429 (± 419)	1.40	5.84	27
2.234 sub-catchment 2.2	337-563	1.71	8.11	36
2.234 sub-catchment 2.3	461-1517	1.27	5.52	30
2.234 sub-catchment 2.4	808-3556	1.27	5.06	24

Note, each catchment PASS sample TWA SSC represents the average SSC of several flow events.

Figure 32. Catchment runoff flowing into gullies 2.234 (left) and Control (right). The brown colour of the water suggests fine sediment is being transported in the catchment runoff. Note, the left picture is facing upstream at the top of a remediated lobe on gully 2.234, whereas the right picture is facing up stream at water flowing into the head cut of the Control gully.

Figure 33. PASS sampler deployed in catchment upstream of remediated gully 2.234.

Gully 2.1 (Control):

SSC of water flowing through the gully was generally consistent for both 2017/18 and 2018/19 wet seasons with GMs of 6471 *÷ 1.4 and 5723 *÷1.9 respectively. Suspended samples collected from the control gully catchment indicate erosion processes within the catchment are contributing to the total suspended sediment export from the control gully (Table 18), although it appears to be much less compared to erosion of the gully itself (Doriean et al. 2020b). Suspended sediment PSD of the catchment and gully outlet samples had similar amounts of fine sediment (i.e., <63 µm), however, the gully outlet samples generally had a higher amount of coarser sediments (63-2000 µm) compared to the catchment samples. This is likely due to the erosion of coarser subsoils at the gully face and the greater carrying capacity of concentrated water flows within the gully head and channel, compared to the overland flows of the catchment. The PSD of sediment that flowed through the gully during the monitoring period remained relatively stable (*d*50 of 8.0 and 8.6 µm for the 2017/18 and 2018/19 wet seasons respectively) (Figure 35). There was also a notable contribution of very fine sand (63-100 µm) in most samples, likely sourced from the erodible subsoils of the gully (Doriean et al 2020b).

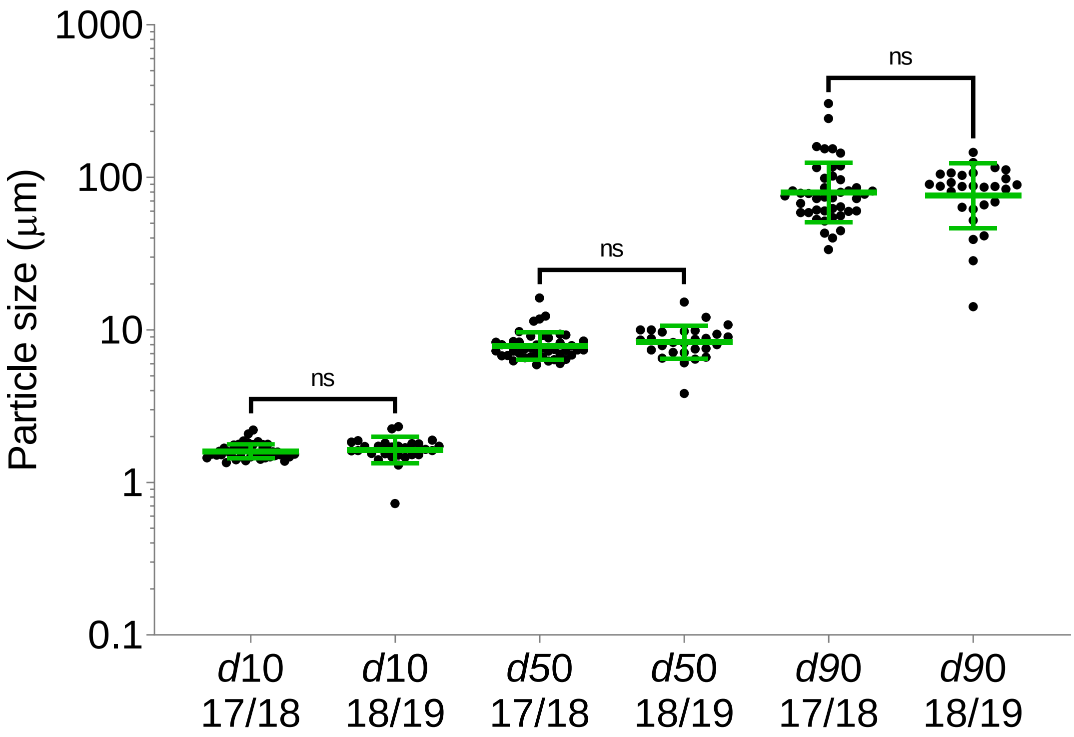


Figure 34. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from the Control gully across the monitoring period. Bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of paired t-tests, where p > 0.05 (ns).

Turbidity measurements were collected from gullies Control and 2.234 as part of the gully suspended sediment monitoring method evaluation conducted by Doriean and co-workers (Doriean et al., 2020a). There was no significant difference between turbidity measurements collected from the two gullies, despite corresponding SSCs differing by almost one order of magnitude (Figure 35). There was good correlation ($R^2 > 0.9$) between sample SSC and corresponding turbidity measurements in the control gully, however, there was little correlation for samples/measurements collected from the remediated gully ($R^2 < 0.2$). This meant the turbidity measurements could not be used as a surrogate suspended sediment concentration, for the purpose of comparing gully suspended sediment dynamics (Doriean et al., 2020a).

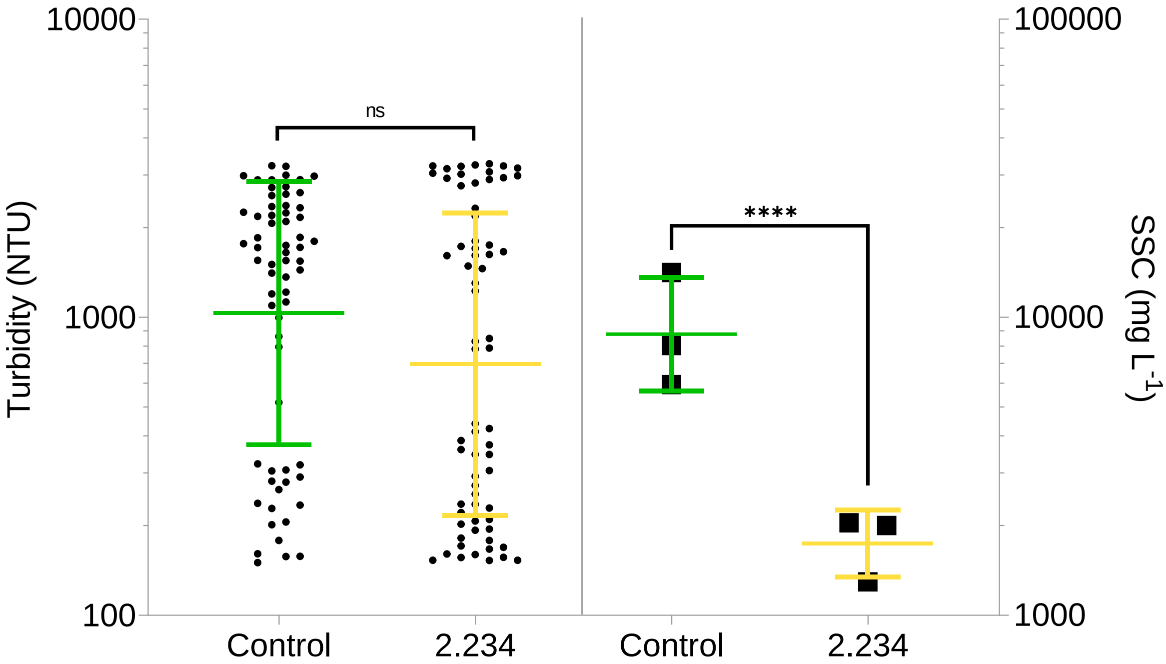


Figure 35. Comparison of turbidity measurements (left panel) and PASS sample time-weighted average SSC (right panel) collected, during comparable time periods, from gullies 2.234 (yellow) and Control (green). Long horizontal lines and error bars represent the geometric mean and standard deviation of samples collected. Black round and square markers represent individual turbidity and PASS sample SSC concentrations respectively. Brackets represent the results of unpaired t-tests, where $p < 0.0001$ (****), or $p > 0.05$ (ns).

Gully 2.234:

Gully 2.234 was remediated during the 2016 dry season, thus, there is no water quality monitoring data from this gully during the first year of water flows post remediation. However, visual observations and terrain analysis from the 2016/17 wet season indicate there were no major failures to the erosion mitigation measures. SSC and particle size data of the samples collected from gully 2.234 suggest the subsoil sediment source from the gully has been mitigated and the majority of sediment measured flowing through the gully was likely sourced from the catchments draining into the gully (Doriean et al. 2020b). SSC of samples collected during the monitoring period were significantly lower compared to the control gully and contained generally finer sediment (Table 16, Figure 30 and Figure 36).

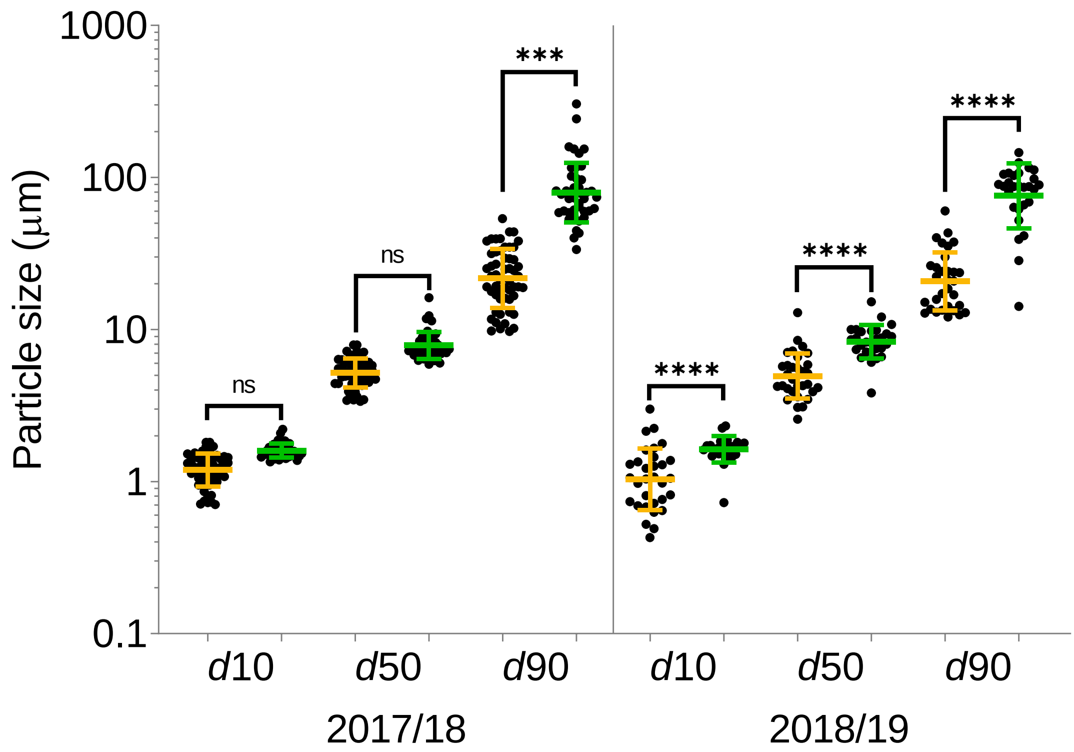


Figure 36. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from gullies 2.234 (yellow) and Control (green) across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where $p < 0.0001$ (****), $p < 0.001$ (***), or $p > 0.05$ (ns).

Gullies 1.1, 0.2 and 0.1:

Comparison of SSCs and particle size data of samples collected from the gullies 1.1, 0.1, 0.2 with the sample data collected from Control gully during the 2017/18 wet season indicate the soil erosion mitigation measures applied during remediation did not significantly reduce gully suspended sediment contributions (Table 16). Visual observations of the gully erosion control structures conducted during the 2017/18 wet season confirmed that several remediation components had failed and were allowing soil erosion to occur. Due to the damage to equipment from repeated backwater events, only one PASS sample, per gully, was collected from gullies 1.1 and 0.1 and only one RSS sample was collected from gully 0.2 for the 2018/19 wet season. The PASS samples collected from gullies 1.1 and 0.1 do provide a representative measure of suspended sediment from the flow events that occurred during the October to December 2018 period. However, the single RSS sample from gully 0.2 is only representative of the initial flow event of the wet season that occurred in October 2018. The SSC and particle size data of the PASS samples collected indicate the repairs made to the erosion mitigation measures, during the 2018 dry season, may have reduced the contribution of gully sourced suspended sediment (Table 2) (Figure 37, Figure 38, and Figure 39). More monitoring data is needed from these gullies to determine if the remediation measures have reduced SSCs in these gullies.

Table 19. SSC trends throughout monitoring period (2017-2019) for gullies 1.1, 0.1, and 0.2.

Gully	Month	Average (mg/L)	Standard Deviation (mg/L)	Number of samples	Average (mg/L)	Number of samples
1.1	Oct	NS	NS	NS	3304	1
	Nov	13265	3419.001	2		
	Dec	10332	12745	4		
	Jan	3642.61	1279	20	NS	NS
	Feb					
	Mar					
	Apr					
	May					
	Jun	NS	NS	NS		
0.1	Oct	NS	NS	NS	3073	1
	Nov	27477	15201	5		
	Dec	11294	NA	1		
	Jan	8937	1983	6	NS	NS
	Feb					
	Mar					
	Apr					
	May					
	Jun	NS	NS	NS		
0.2	Oct	NS	NS	NS	6228	1
	Nov	13394	4230	6	NS	NS
	Dec	4808	NA	1		
	Jan	7137	3316	6		
	Feb					
	Mar					
	Apr					
	May					
	Jun	NS	NS	NS		

Note, arithmetic averages, rather than geometric averages, are used because the individual flow events were normally distributed. NS = no samples were collected from this period.

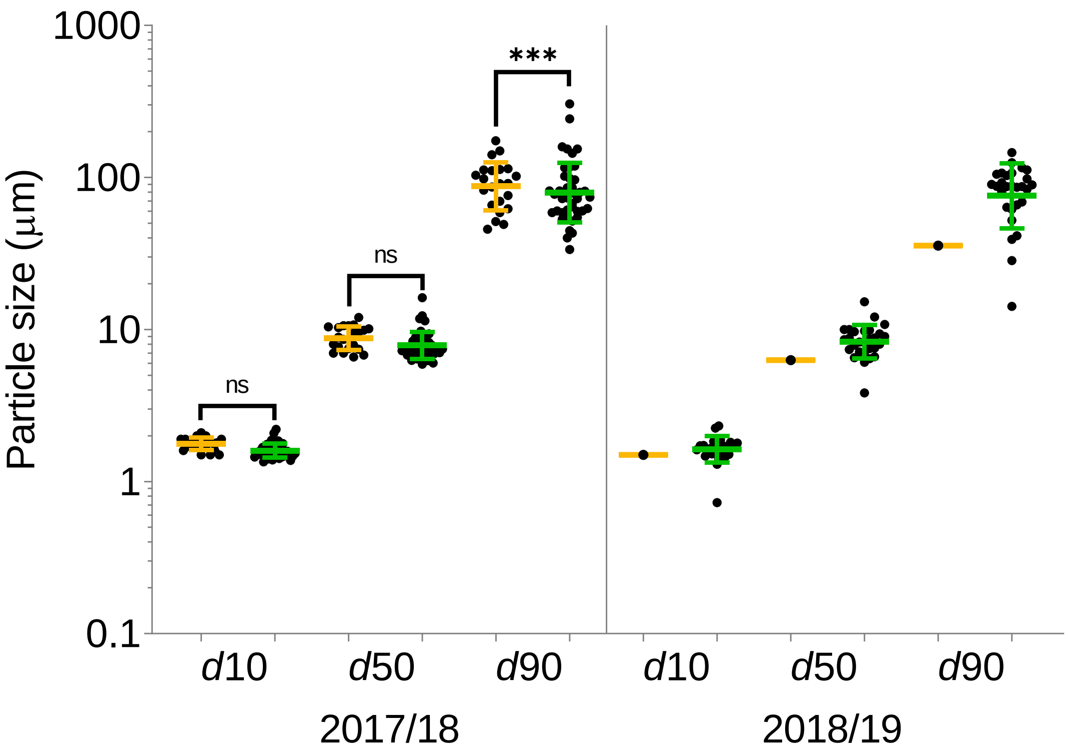


Figure 37. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from gullies 1.1 (yellow) and Control (green) across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where $p < 0.001$ (***) or $p > 0.05$ (ns). Note, statistical comparison of samples collected from Control and 1.1 were not possible for the 2018/19 wet season because only one sample was collected from gully 1.1.

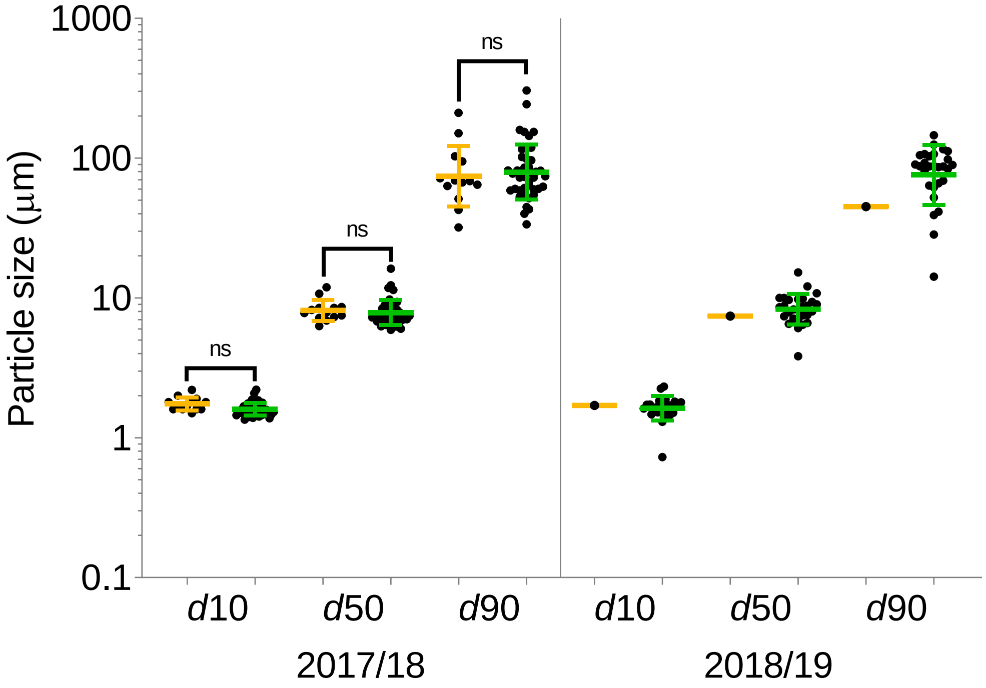


Figure 38. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from gullies 0.1 (yellow) and Control (green) across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where p > 0.05 (ns). Note, statistical comparison of samples collected from Control and 0.1 were not possible for the 2018/19 wet season because only one sample was collected from gully 0.1.

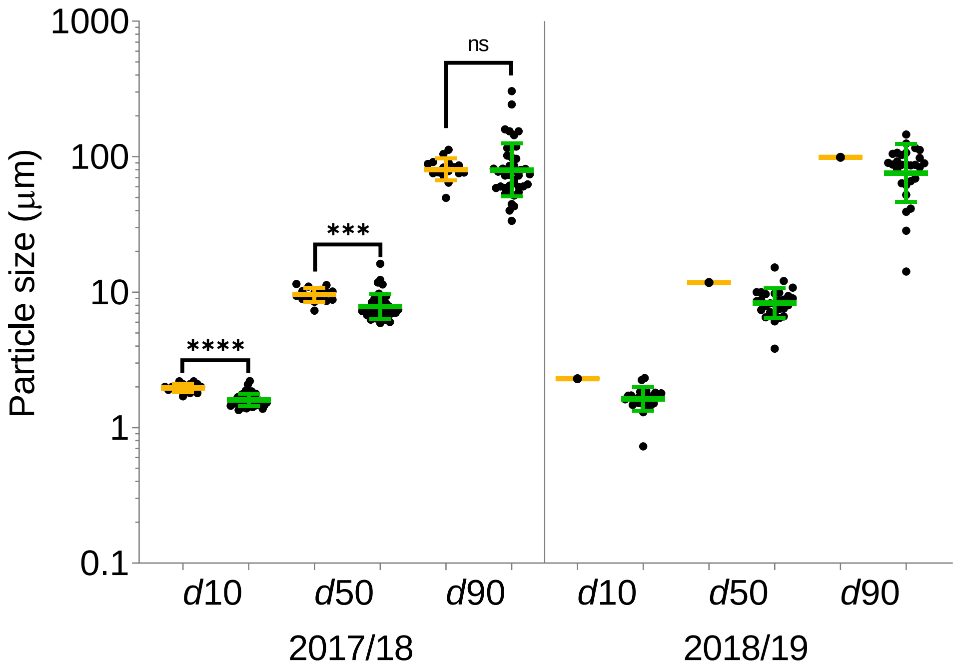


Figure 39. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from gullies 0.2 (yellow) and Control (green) across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests where p < 0.0001 (****), p < 0.001 (***), or p > 0.05 (ns). Note, statistical comparison of samples collected from Control and 0.2 were not possible for the 2018/19 wet season because only one sample was collected from gully 0.2.

3.1.6 Gully suspended sediment yield estimates

Due to logistical and budgetary constraints it was not feasible to obtain discharge measurements from the control and remediated gullies during the monitoring period. Because of this, high-resolution rainfall data (rainfall totals of 1-min intervals) collected on-site paired with high-resolution (10cm resolution) lidar data was used to model the water runoff discharged from each gully and their corresponding catchments. Without empirical stream flow velocity measurements and associated gully discharge estimates it is not possible to calibrate the HEC-HMS model. Calibration of the model was achieved by reverse calculating modelled stream flow discharge into gully stream water levels during flow events. These estimated water levels were compared to the gully flow event water level measurements collected at each gully and model parameters (i.e., curve numbers) were corrected accordingly. These uncertainties are significant, however, even if there was a 50% uncertainty associated with the estimated suspended sediment yield of a remediated gully it would make a negligible change when compared to high magnitude of difference between load estimates of the Control and remediated gullies.

Each gully monitored discharged more than 100 tons of suspended sediment during the 2017/18 wet season (Figure 40), with a significant proportion of this sourced from the gully catchment. The erosion mitigation control measure failures that occurred at gullies 1.1, 0.1, and 0.2, during the 2017/18 wet season (due to them being installed too late in the dry season and being impacted by early wet season rains), resulted in the gullies discharging more suspended sediment than the control gully, when normalised for catchment area or water yield. The total SSY from gullies 1.1 and 0.1 were ~2.5 times greater than the total yield of the Control gully. In contrast, gully 2.234 had significantly lower SSYs, when normalised for catchment area, compared to the Control gully for the duration of the monitoring period (2017-2019). Comparison of the SSY from each gully for each cubic metre of water discharged shows gully 2.234 had very little sediment (0.0002 t/m^3), whereas gullies 1.1, 0.1, 0.2, and Control all had much higher yields (>0.049 t/m^3). The focused gully water quality monitoring study conducted at gullies Control and 2.234 concluded that it is highly likely that gully 2.234 is no longer acting as a significant source of suspended sediment (Doriean et al., 2020b). The estimated total SSY for the catchments of gullies Control and 2.234 was 45 ± 42 t and 135 ± 125 t respectively. Note, these estimates are highly variable and are mentioned only to demonstrate that the catchments were a likely source of suspended sediment flowing through the gully outlet. However, the estimated SSY of only gullies 2.234 and Control (i.e., without their respective catchment SSY estimates included) indicate gully 2.234 is not acting as a source of sediment. Rather, it acting as a suspended sediment sink (i.e. it may be accumulating suspended sediment) (Figure 40).

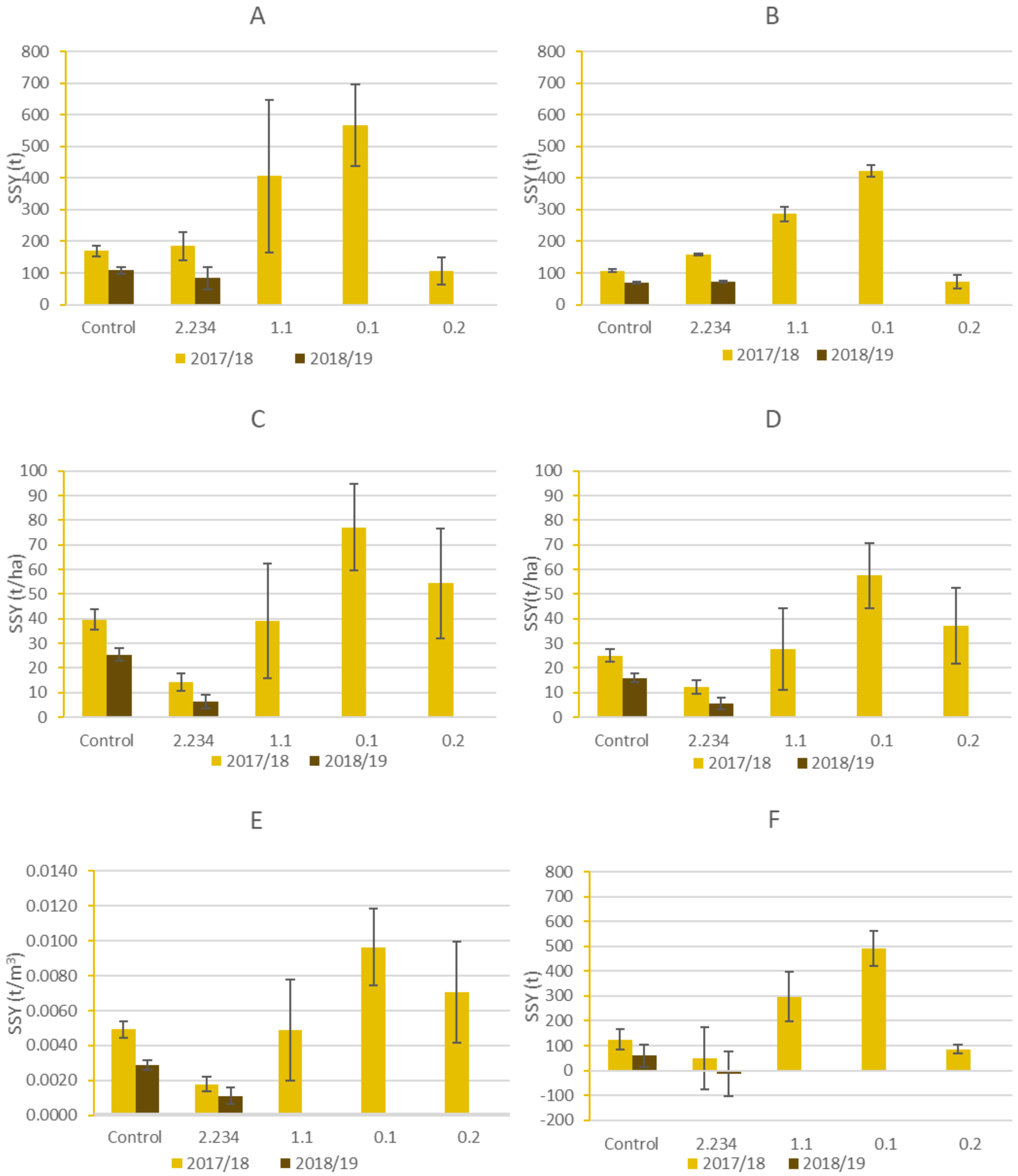


Figure 40. Suspended sediment yield estimates from gullies monitored at Crocodile Station for the 2017-2019 monitoring period. A = Total gully suspended sediment yield, B = gully total fine suspended sediment (<20 µm) yield, C = gully suspended sediment yield normalised for catchment area, D = gully total fine suspended sediment (<µm) yield normalised for catchment area, E = gully suspended sediment yield normalised for rainfall runoff discharged, and F = estimate of gully suspended sediment yield normalised for rainfall runoff discharged minus the estimated suspended sediment yield of the gully catchments without catchment sediment contribution. Error bars represent the standard deviation associated with the estimated SSY derived from SSC GM values.

3.1.7 Lidar terrain monitoring

Terrain monitoring at each of the five gullies was undertaken annually over the study period, twice annually in the initial years to capture the changes associated with construction. Surveys were undertaken using a Leica C10 Terrestrial laser scanner, at a minimum point density of ~ 100pts/m^2. The scanner has a beam footprint of ~ 5 cm^2 at a distance of 30m from the scanner. The limit of detection for the DoD analysis was around 5-10 cm but varied for each scan depending on the vegetation density.

The following figures show both the net three year annual erosion and deposition (Figure 41) and the annual changes over the study period (Figure 42) for the treatment 2.234 The overall erosion rates derived from these data are summarised in Table 21 - Table 24. For the main gully system (gully 2.234), that was treated using a combination of reshaping, gypsum treatment, rock capping and rock check dams, sediment reduction from the active gully itself has been 100% effective - i.e. trapping sediment delivered from its catchment as well as having no net erosion from the gully. This result was achieved within one year post construction. It should be pointed out that sediment is still being delivered from the gully, but it is sourced from the sizeable catchment area that feeds into the previously actively incising portion of the gully. While the lidar data clearly shows there was net deposition within the treated gully from the first year after remediation, this predominantly consists of coarser bedload material. As time has progressed and more vegetation has grown within these depositional zones, a greater proportion of fines have been deposited. For the purposes of loads calculations only 20% of this deposition was included in the fine sediment yield remediation effectiveness calculations. The gullies treated using rock chutes alone, were less effective in the first year (due to being caught out in early wet season storms), but by year two the sediment yield at these three sites was in the order of 80% below baseline (before) and control (Figure 45, Figure 46, Table 21 - Table 24).

The elevated sediment yield from sites 0.1, 0.2, 1.1 in the first wet season was exacerbated by the fact that construction occurred late in the dry season, and the site experienced some major rainfall events in late October, prior to the remediation being completed. This was a major setback for the sediment savings from this site, as the sediment yields from these three gullies are shown to be approximately double baseline for the first-year post treatment. Unfortunately, all water quality samples for the 2018/19 wet season were lost in the major backwater events that occurred that year, but lidar data indicates that the gullies were effectively stabilised the second year after treatment.

The risk of losing monitoring samples due to backwater contamination and/or damage to sampling equipment, highlights the need for having multiple monitoring methods sources when undertaking long term post-remediation monitoring to measure the effectiveness of alluvial gully treatments.

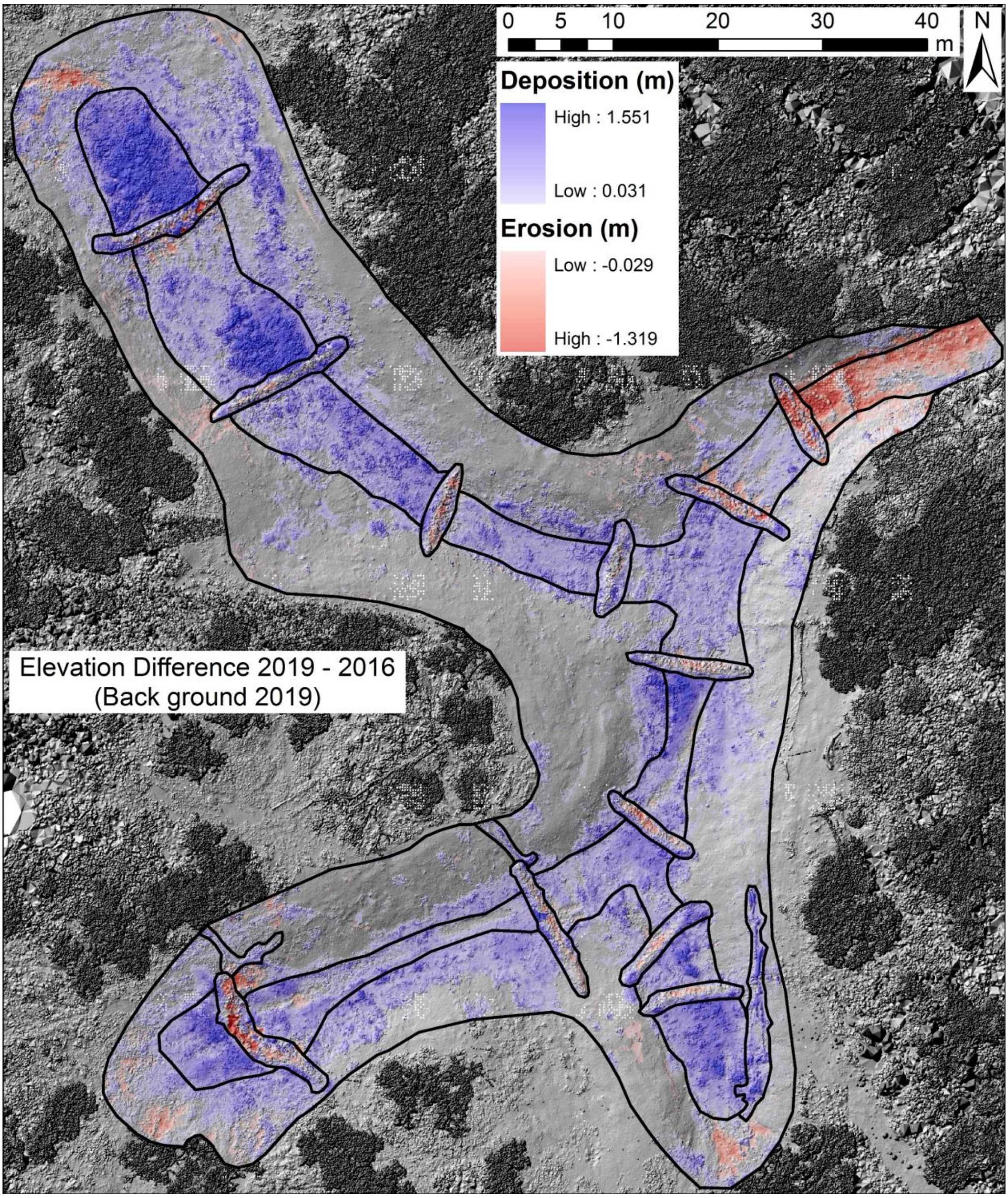


Figure 41. Lidar DoD showing the net topographic change at gully 2.234 over the study period – indicating net deposition within the gully over the 4 years of the study.

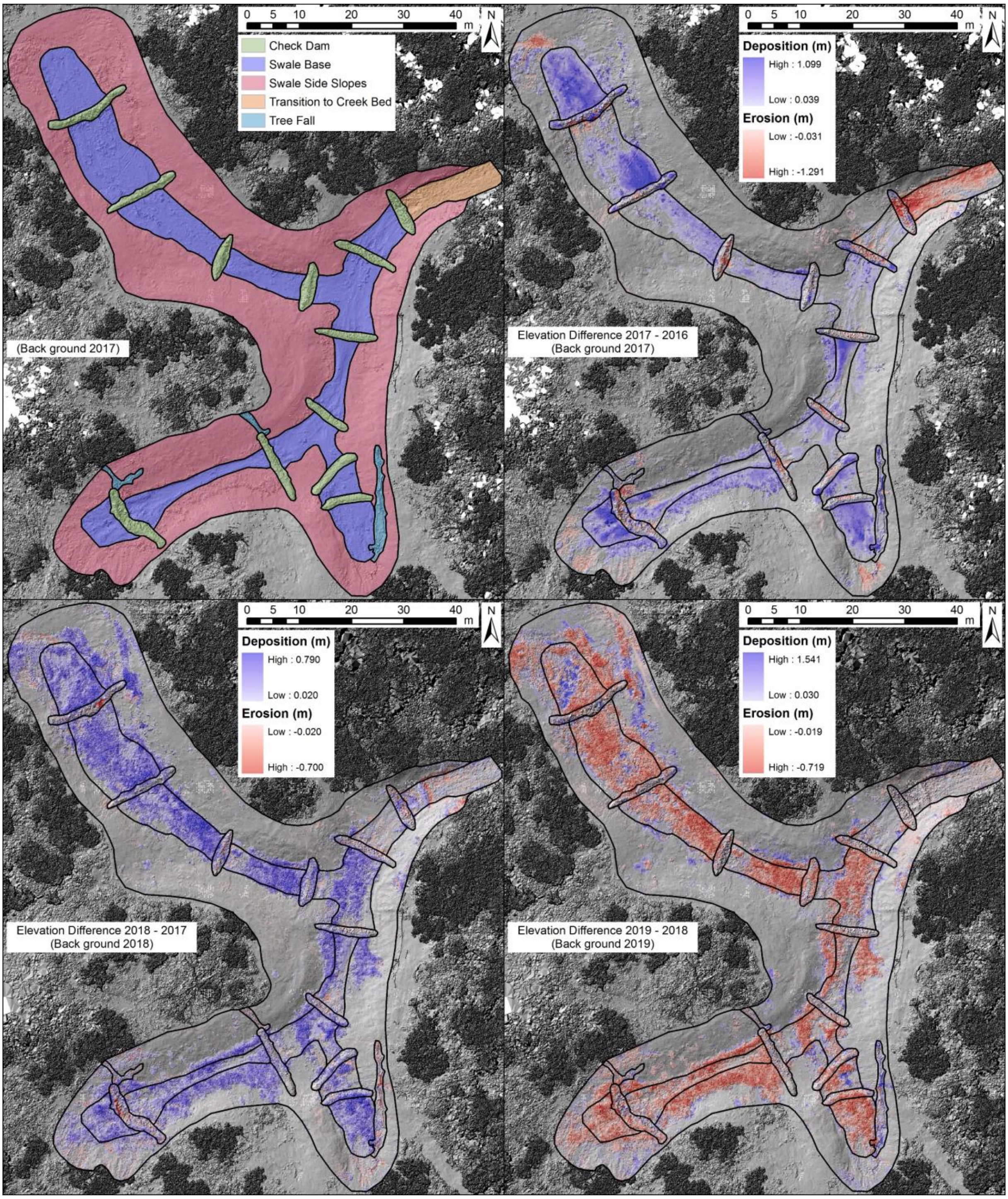


Figure 42. Lidar DoD changes at gully 2.234 across the study period. Image on the top left shows how the data was processed in different process zones. Erosion of the check dams was not counted in the sediment yield figures, as this was all coarse rock. Note that the apparent erosion shown in 2018/19 is largely due to changes in grass cover that could not be accounted for in the T lidar processing.

Gully 2.1 (Control)

The following figures show both the net three year annual erosion and deposition (Figure 43) and the annual changes over the study period (Figure 44) for the control gully. The overall erosion rates derived from these data are summarised in Table 21 - Table 24.

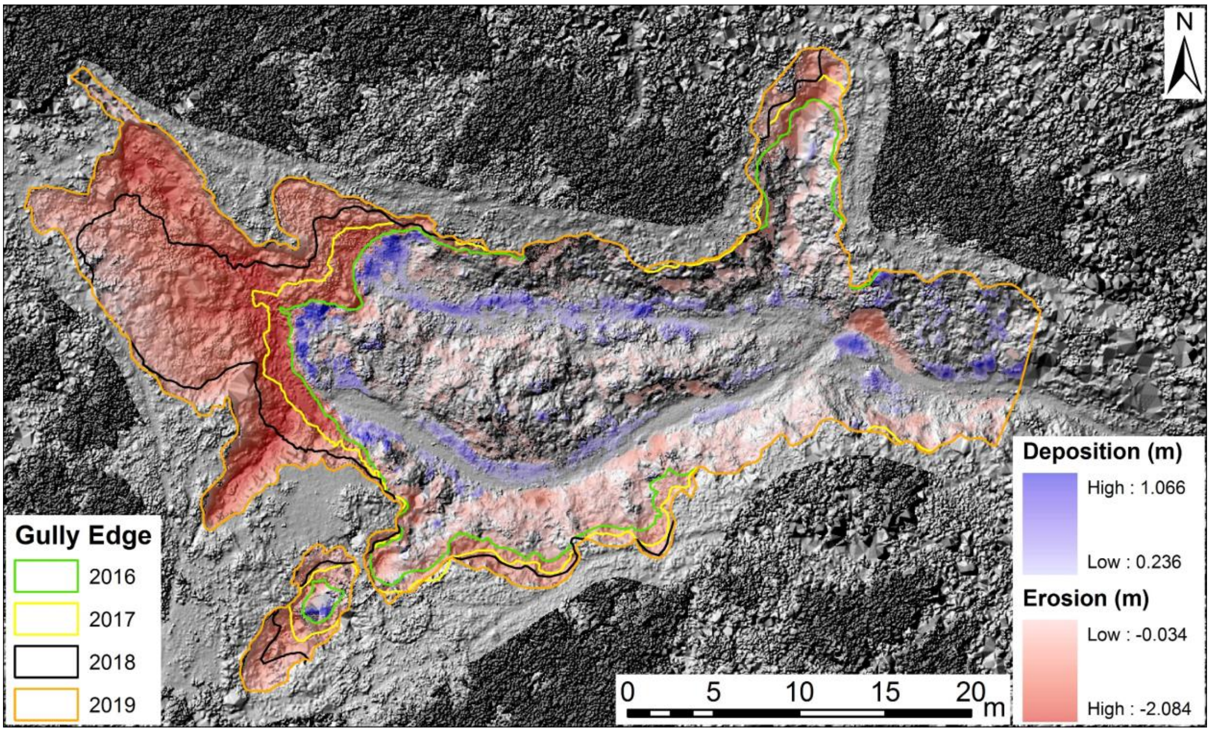


Figure 43. Lidar DoD showing the net topographic change at gully 2.1 (control) over the study period (2016-2019).

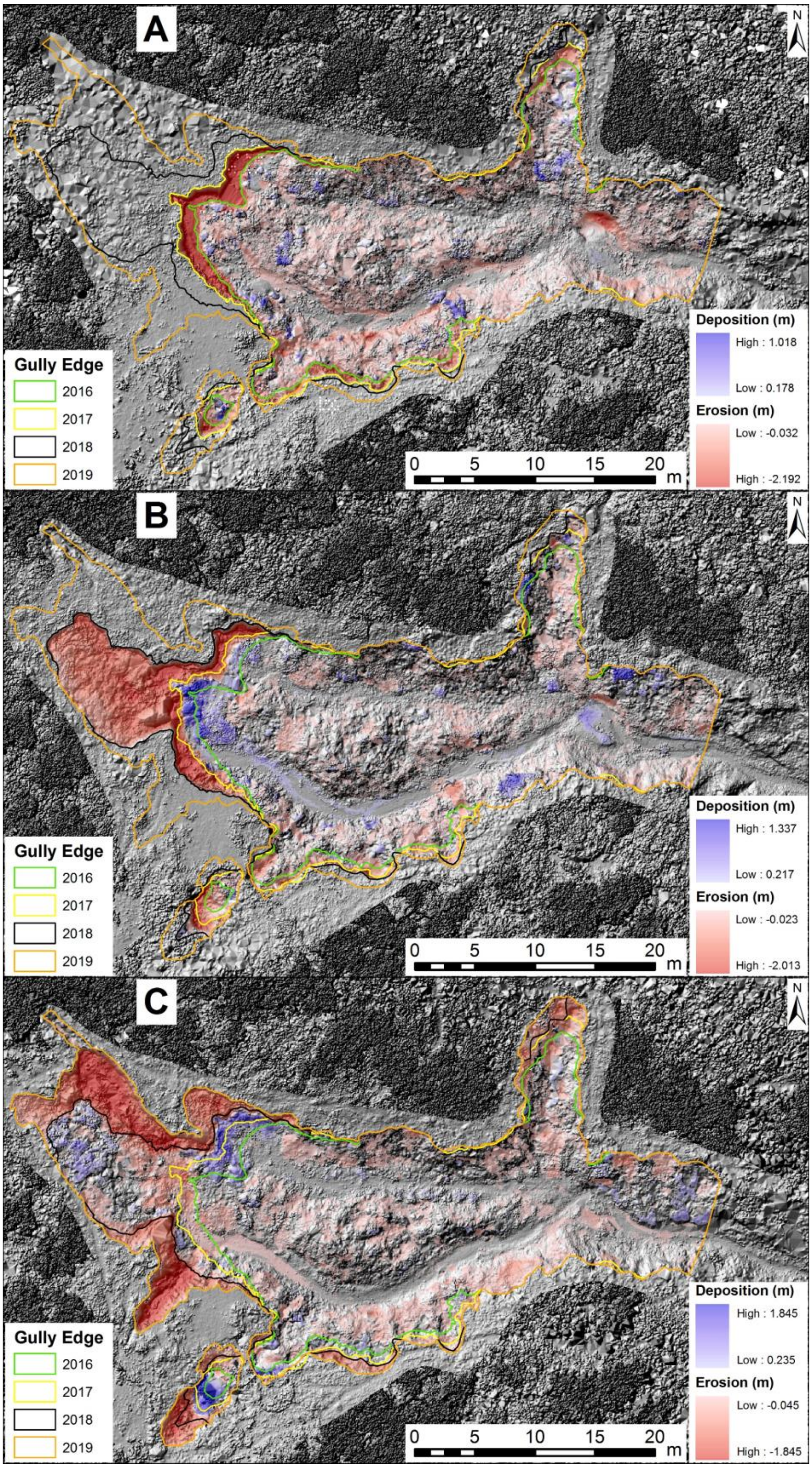


Figure 44. Annual lidar DoD changes at gully 2.1 (control) across the study period. All surveys except the last one captured in 2019 were terrestrial lidar, whereas the 2019 survey was high resolution airborne lidar. A) = 2016-17; B) = 2017-2018; C) = 2018-2019

Gully 1.1

The following figures show the annual erosion and deposition over the study period (Figure 45) for gully 1.1. The overall erosion rates derived from these data are summarised in Table 21 - Table 24.

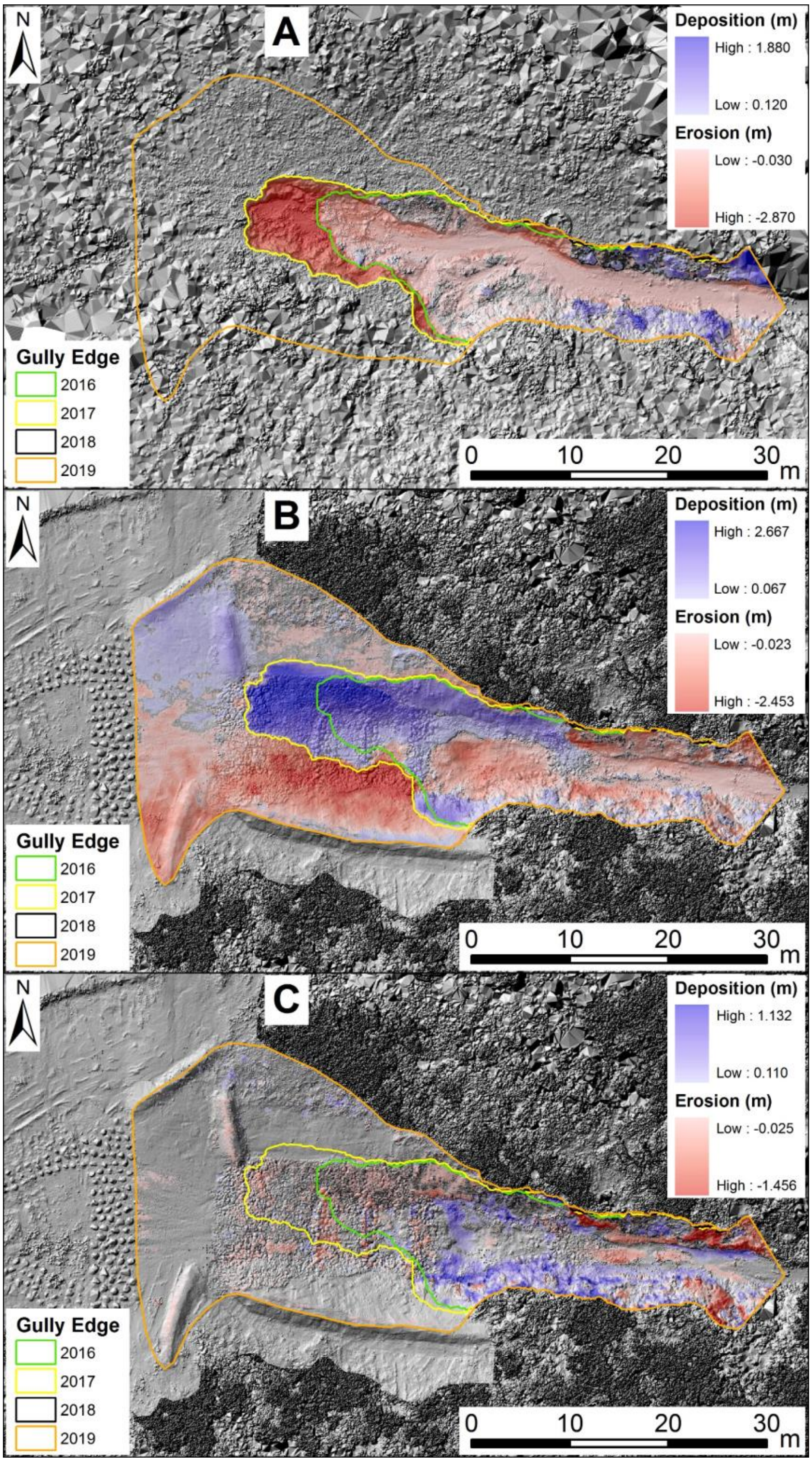


Figure 45. Annual lidar DoD changes at gully 1.1 across the study period.

Gully 0.1 & 0.2

The following figures show the annual erosion and deposition (Figure 46) and the annual changes over the study period (Figure 45) for gullies 0.1 and 0.2. The overall erosion rates derived from these data are summarised in Table 21 - Table 24.

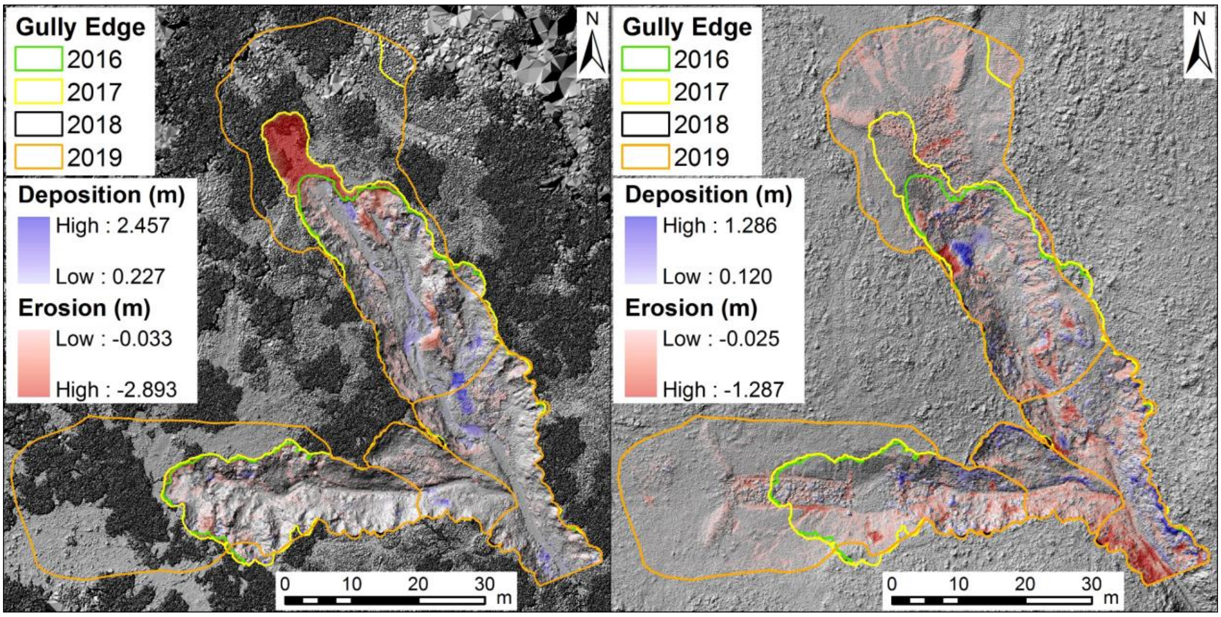


Figure 46. Annual lidar DoD changes at gully 0.1 and 0.2 across the study period.

3.1.8 Remediation Effectiveness Ratios

The remediation effectiveness for each of the treated gullies is calculated using equation 1 and 2 based on the before and after treatment lidar DoD data and water quality monitoring data. These results are also presented in Table 21 - Table 24 for 2016/17 at gully 2.234 and for the four Crocodile treatment sites in 2017/18 and 2018/19. For each year the CI comparisons use an adjusted control yield to account for the variation in baseline yield at the outset, ensuring that the control/impact comparisons are as unbiased as possible.

Table 20. Start and end dates of gullies from Airphoto analysis and Baseline sediment yields calculated using the PSE method (Stout et al., 2019) corrected with recent lidar DoD data 2009-2015

Gully ID	Gully Area_m^2	Catchment Area	Start year	Finish year	Quantity eroded (t)	EOG FSS yield (t/yr)	SSY (t/yr/ha)
2.1 (control)	0.166	4.2	2000	2019	2990 ± 400	119 ± 18	28.4 ± 4.24
0.1**	0.067	7.4	1992	2017	2890 ± 390	69 ± 10	9.3 ± 1.38
0.2**	0.064	1.9	1992	2017	1940 ± 260	47 ± 7	24 ± 3.64
1.1	0.287	10.4	1995	2017	6070 ± 810	182 ± 27	17.5 ± 2.61
2.2-2.4	0.306	12.1	2000	2015	4610 ± 620	184 ± 27	15.2 ± 2.27
2.6	0.132	3.5	1988	2015	2310 ± 310	50 ± 7.6	14 ± 2.15
Total	**1.022**	**39.6**	**-**	**-**	**20800 ± 2800**	**652 ± 97**	**16.5 ± 2.46**

*Assumes a fine sediment proportion of 60% BD of 1.8

** Erosion data adjusted to 2017 using terrestrial lidar DoD analysis

Table 21. Site baseline sediment yield data and effectiveness for first year (2016/17) at site 2.234

Sept 2017 - Sept 2016 (baseline rates)	an RF (mm) =				951	2016/17 effectiveness (2.234)		
Treatment	Area (ha)	t	t/ha	t/ha/mm	baseline ratio cf control	t #	t/ha/mm	(lidar)
2.1 Control	4.2	89.6	21.3	0.02	100%	89.6	0.02	
2.234*	13.5	184.0	13.6	0.014	64%	-1.7	-0.002	108%
1.1	10.4	248.8	23.9	0.03	112%			
0.1	7.4	199.5	27.0	0.03	126%			
0.2	1.9	26.8	14.1	0.01	66%			
	37.4	**749**	**20**	**0.02**				

* pre 2015 baseline data

assume sediment deposited in 2.234 is 20% fine

Table 22. Effectiveness data for all sites for the 2017/18 wet season

Sept 2018 - Sept 2017			annual RF (mm) =		1089			
Treatment	area (ha)	t	t/ha	t/ha/mm	adjusted load cf baseline (t/ha/mm)	RER_{CI} (lidar & WQ)	RER_{BA} (lidar & WQ)	diff.
2.1 - Control	4.2	115.2	27.4	0.03	0.025			
2.234	13.5	-2.1	-0.2	-0.0001	0.0002	101%	101%	0%
1.1	10.4	298.0	28.7	0.026	0.023	7%	7%	0%
0.1	7.4	490.0	66.2	0.061	0.048	-91%	-70%	21%
0.2	1.9	86.0	45.3	0.042	0.063	-149%	-322%	173%
	37.4	**987**	**26**	**0.03**				

Note: pale blue shading represents lidar data and darker blue shading represents water quality monitoring data.

Table 23. Effectiveness data for all sites for the 2018/19 wet season

Sept 2019 - Sept 2018			annual RF (mm) =		929			
Treatment	**area (ha)**	**t (lidar)**	**t/ha**	**t/ha/mm**	**adjusted load cf baseline (t/ha/mm)**	RER_{CI} **(lidar)**	RER_{BA} **(lidar)**	**diff.**
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%
	37.4	**214.3**	**44.2**	**0.05**				

Table 24. Effectiveness data for sites 2.234 across 3 wet seasons - 2016/19

Sept 2019 - Sept 2016			3 yr RF (mm) =		2969			
Treatment	**area (ha)**	**t (lidar)**	**t/ha**	**t/ha/mm**	**adjusted load cf baseline (t/ha/mm)**	RER_{CI} **(lidar)**	RER_{BA} **(lidar)**	**diff.**
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%
	17.7	**335.7**	**80.1**	**0.03**				

3.1.9 Sediment Abatement Achieved to date at Crocodile Station

Based on the observed treatment effectiveness ratios (RERs) at the monitored sites, total fine sediment abatement at the end of gully (EOG) up to 2019 was 328t/yr or 148t/yr end of system (EOS) (after applying the 0.45 Normanby sediment delivery ratio). This was significantly offset by the 470t increase in fine sediment production from the site in 2017/18, due to the late dry season rains that occurred mid-construction at gully 0.1, 0.2 and 1.1. Estimates of the additional abatement from the 2019/20 wet season (not assessed due to COVID-19) based on the 2018/19 data, suggest that the collective EOS abatement from the 4 treated gullies would be in the order of 165 t/yr at the present time. Had the late dry season disturbance at gullies 0.1, 0.2 and 1.1 not happened in 2017, and similar results been recorded in 2017/18 as in the following year, EOS abatement would be around 319 t/yr now. This highlights the need to avoid working on such sites, late in the dry season, when there is a high risk of remediation works being interrupted by early wet season rains.

3.1.10 Nutrient monitoring

Due to logistical and safety constraints it was very difficult to gain access to the site within the short timeframe required (samples must be processed within <48 hours of sample collection) to be analysed for bioavailable nutrients. However, despite these challenges, 46 samples for various nutrient fractions (including some bioavailable fractions) were collected from the Control (n=26), 2.234 (n=14), and 1.1 (n= 6) gullies during the monitoring period (Sample dates were: 24/01/2018, 15/12/18, and 05/02/2019). Most of the nutrients (nitrogen and phosphorus) and total organic carbon measured in the collected samples consisted of particulate (i.e., nutrients or carbon adsorbed to sediment or associated with other suspended solids, e.g., vegetation litter) rather than dissolved fractions (Figure 47) (Doriean et al., 2020b). Sample nutrient and carbon concentrations from gullies 2.234 and 1.1 (in particular, particulate fractions) were both significantly lower compared to samples collected from the Control gully (Doriean et al., 2020b). These preliminary results indicate the erosion of gully subsoil has been virtually eliminated (gully 2.234) or greatly reduced (gully 1.1) in the remediated gullies. It is also evident that the remediation works completed at gully 1.1 were still effective at reducing the contribution of nutrients from the gully when compared to the control gully, despite of the occurrence of some erosion control failures.

Most of the dissolved nutrient and carbon concentration data did not indicate any apparent correlations with SSC except for dissolved phosphorus. Dissolved phosphorus had very weak to no relationship with SSC for the data collected from each individual gully. However, there was a moderate-strong relationship ($r = 0.82$, $p<0.0001$) between dissolved phosphorus and SSC when sample data from all of the gullies monitored was included. The variation in dissolved nitrogen and carbon concentrations were expected because these compounds are often influenced by different biogeochemical processes as they are transported during a flow event (Garzon-Garcia et al., 2015; Garzon-Garcia et al., 2016; Lloyd et al., 2019). Thus, the relatively small sample set collected is not enough to identify any subtle trends in the data. In contrast, there were very strong correlations between SSC and particulate nutrients (Figure 48). The strong relationship between suspended sediment and particulate nutrients ($r > 0.9$) in the samples collected from the outlet of gully 2.234 suggest suspended sediment from the gully catchment is sourced from soils of the same type/characteristics. It also suggests the suspended sediment sourced from both the catchments (clays and silts) and eroding gully subsoils (clays, silts, and fine sands) has on average similar particulate nutrient content. None-the-less, when having a closer look at these relationships, it is apparent that a better predictive power of the relationship would be obtained if regressions were developed separately for controls and treatments.

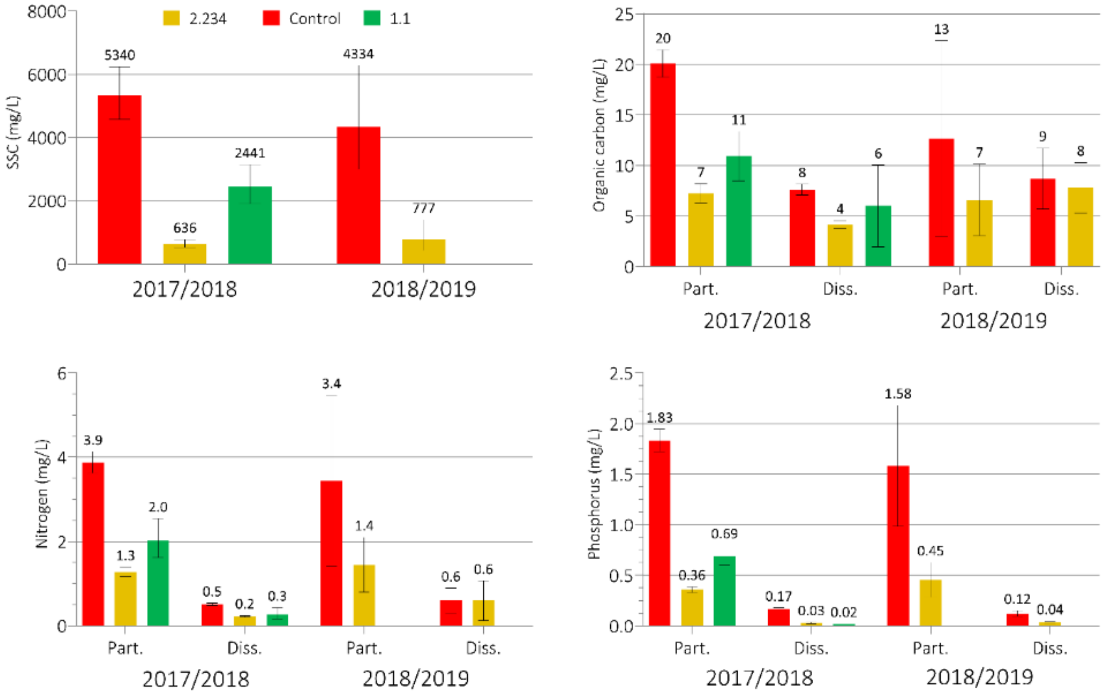


Figure 47. SSC and nutrient concentrations of samples collected from gullies Control (red), 2.234 (dark yellow) and 1.1 (light yellow) during flow events in the 2017/2018 and 2018/2019 wet seasons. Bars and error bars represent the geometric mean and standard deviation. Note, the 2017/2018 data represents a single flow event and the 2018/2019 data represent multiple flow events. Also, only one flow event was monitored for gully 1.1. Modified from Doriean et al. 2020b.

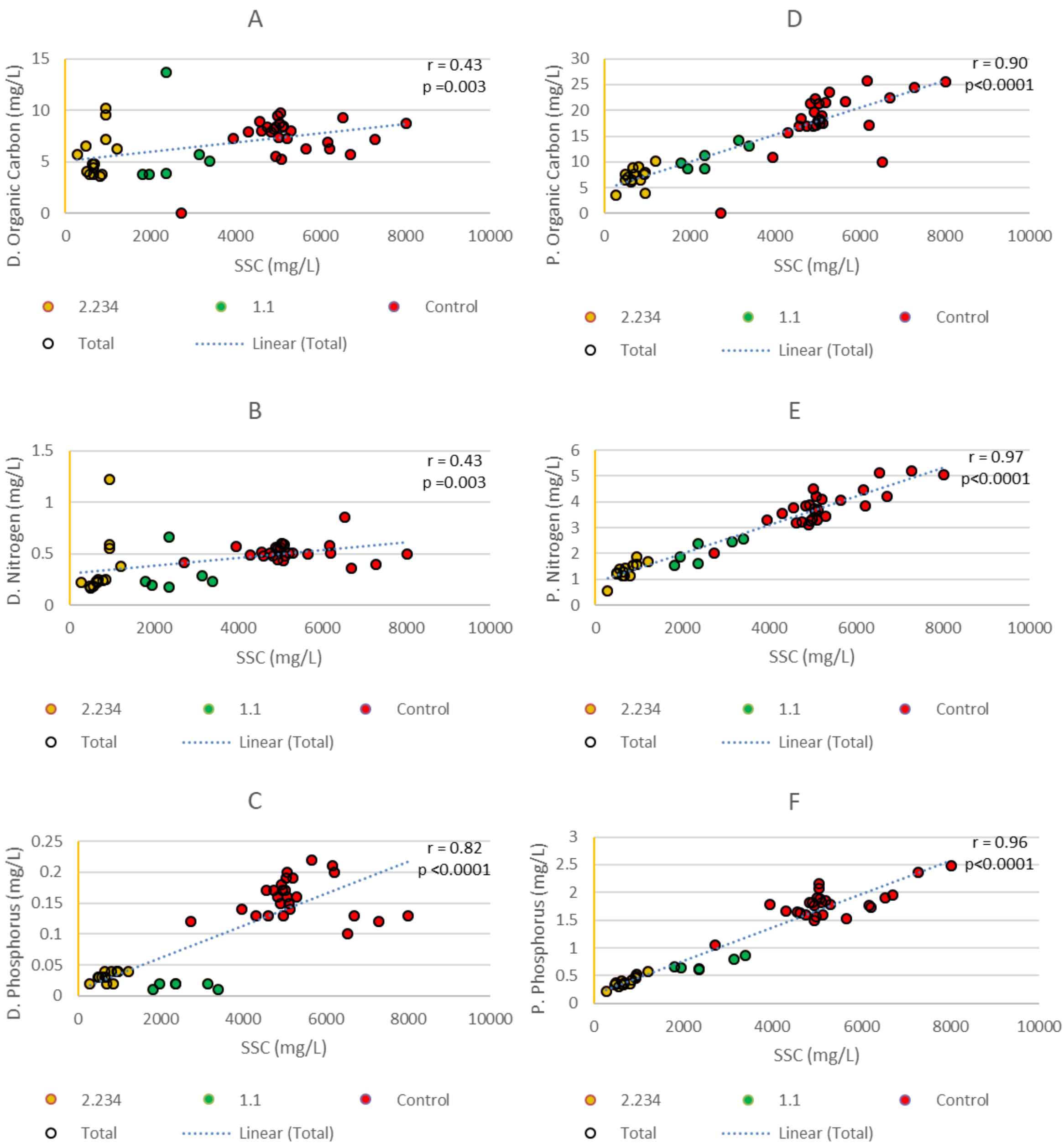


Figure 48. Relationships between SSC, organic carbon, and nutrient concentrations in the control (red) and remediated gullies 1.1 (green) and 2.2.3.4 (yellow) from single multiple flow events on during the monitoring period (2017-2019). D. = dissolved and P. = particulate. Modified from Doriean et al. 2020b.

3.2 Case Study 2: Strathalbyn Station

3.2.1 Soil Material Characterisation

An overall conceptual model of the Strathalbyn floodplain materials association can be gained from both the soil survey and soil material assessment procedures undertaken at Strathalbyn. This is shown schematically in Figure 49 - Figure 51. The results of the laboratory analysis of the sampled soil materials and summary interpretations are provided in Supplementary Information.

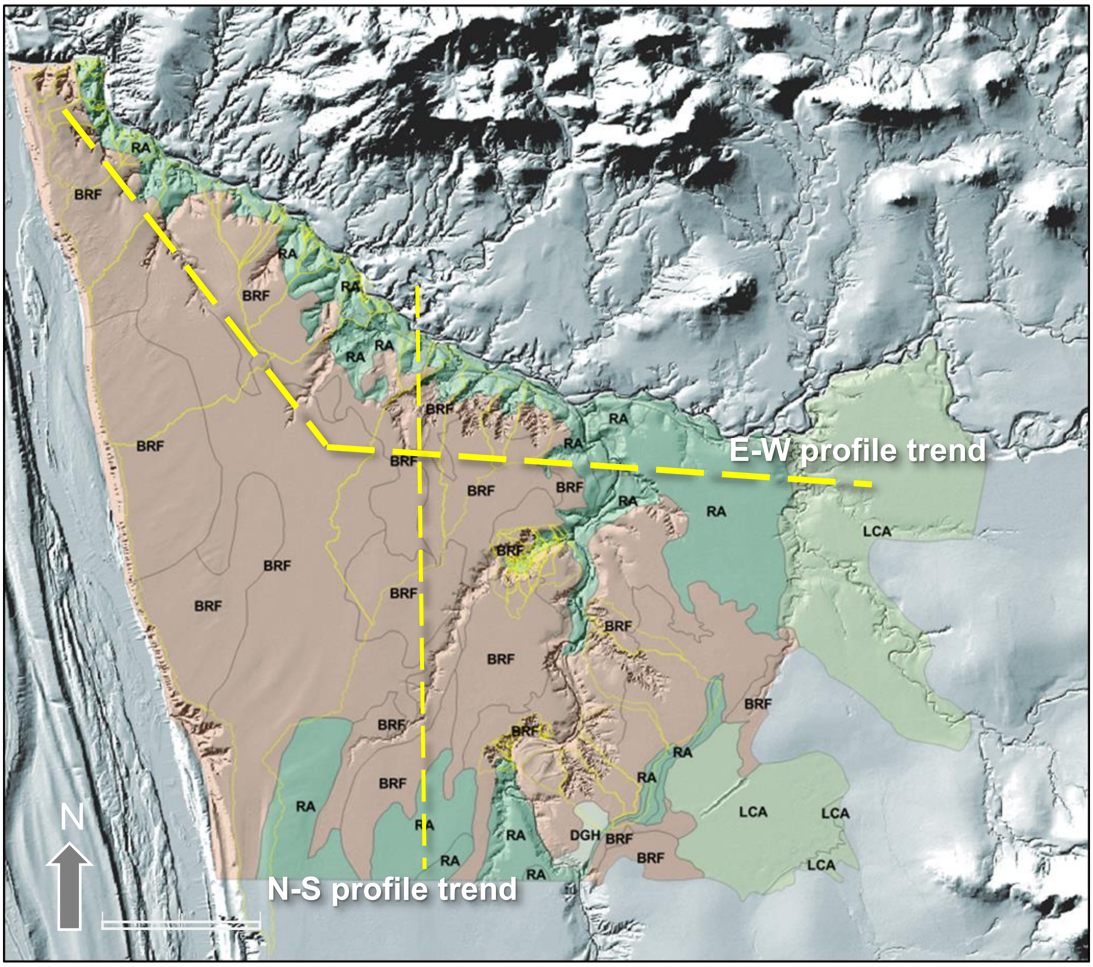


Figure 49. A generalised indication of the trends of the cross-sections of the conceptual models in Figure 50 and Figure 51. The base map shows the mapping of broad Soil Material Systems identified through the soil material assessment and the outlines of the gully catchments (in yellow).

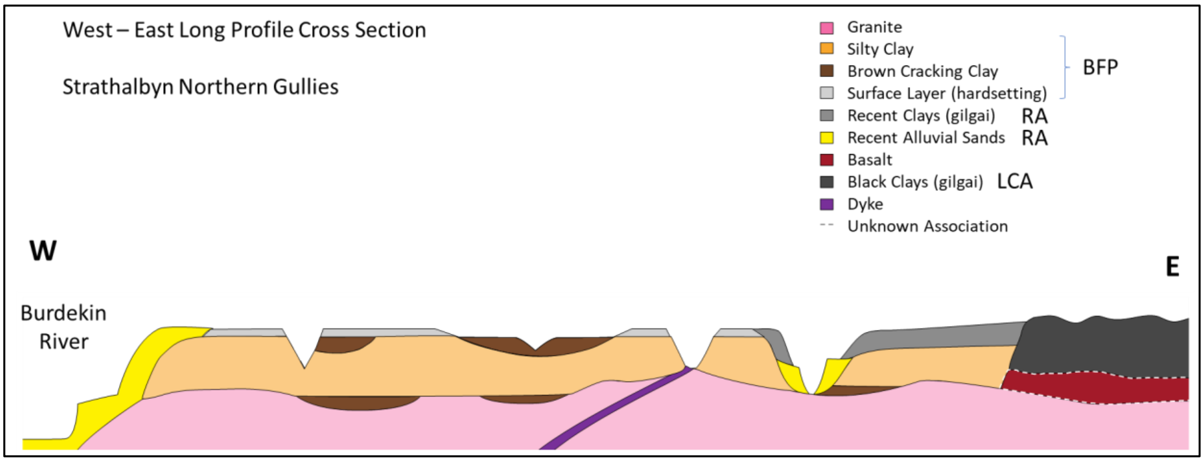


Figure 50. A schematic cross-section of the Strathalbyn floodplain/terrace as a west – east transect through the 'Northern' gullied region: illustrating the relationships of the various sedimentary and hard rock material, with the Soil Material Systems

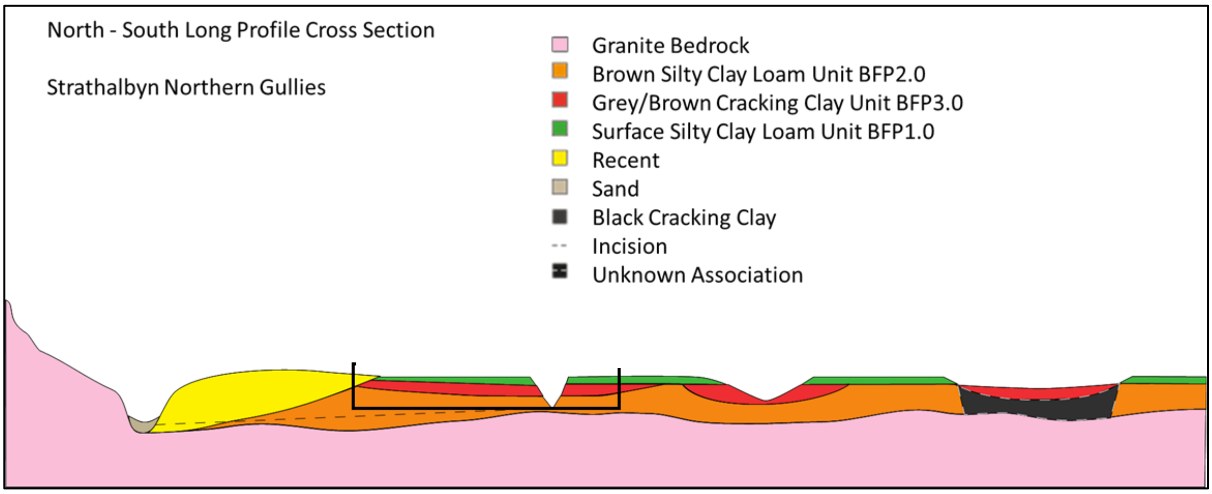


Figure 51. A schematic cross-section of the Strathalbyn floodplain/terrace as a north – south transect through the 'Northern' gullied region: illustrating the relationships of the various sedimentary and hard rock material, with the Soil Material Systems.

The broad-scale characterisation of the floodplain alluvial surface soils is presented here (Table 2 in Appendix 2) as SPCs (Thompson and Reid, 1982), modified from the outcomes of the conventional soil survey (Figure 52), and as the ASC generic soil classes (Figure 53). The soil material observation and sampling sites from the different surveys are shown in Figure 53. Further information and details about the results of the survey are provided in Appendix 2. Although this information is detailed and comprehensive about the soil types it has limited value for a rehabilitation planning and design point of view. It is more informative for land use management as a natural resource.

The resulting map of Soil Material Systems (SMSs) largely followed the soil landscape groupings of the individual soil mapping units of Thompson and Reid (1982). This represented the only conventional mapping able to be undertaken for the soil materials assessment. Following the field protocols drawn up the investigation and sampling process groups of soil material units were identified for each soil material system.

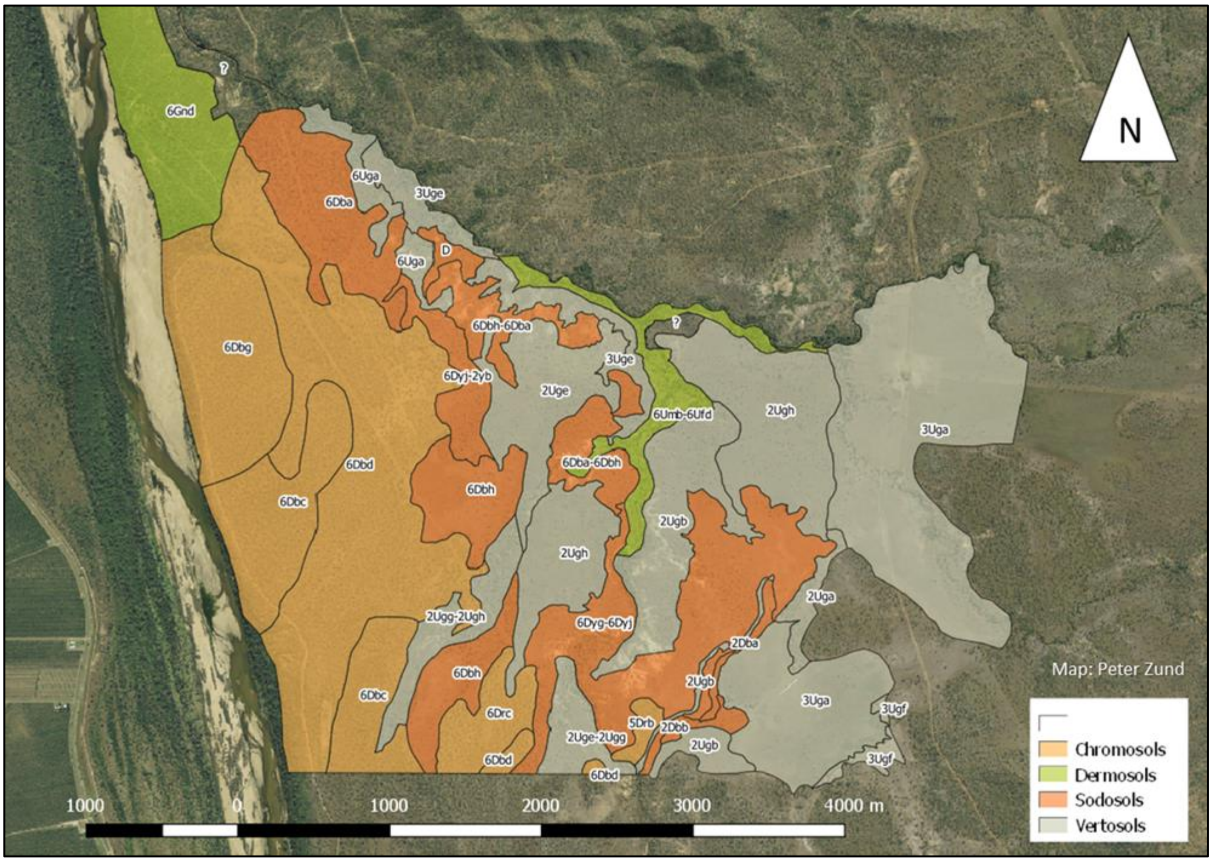
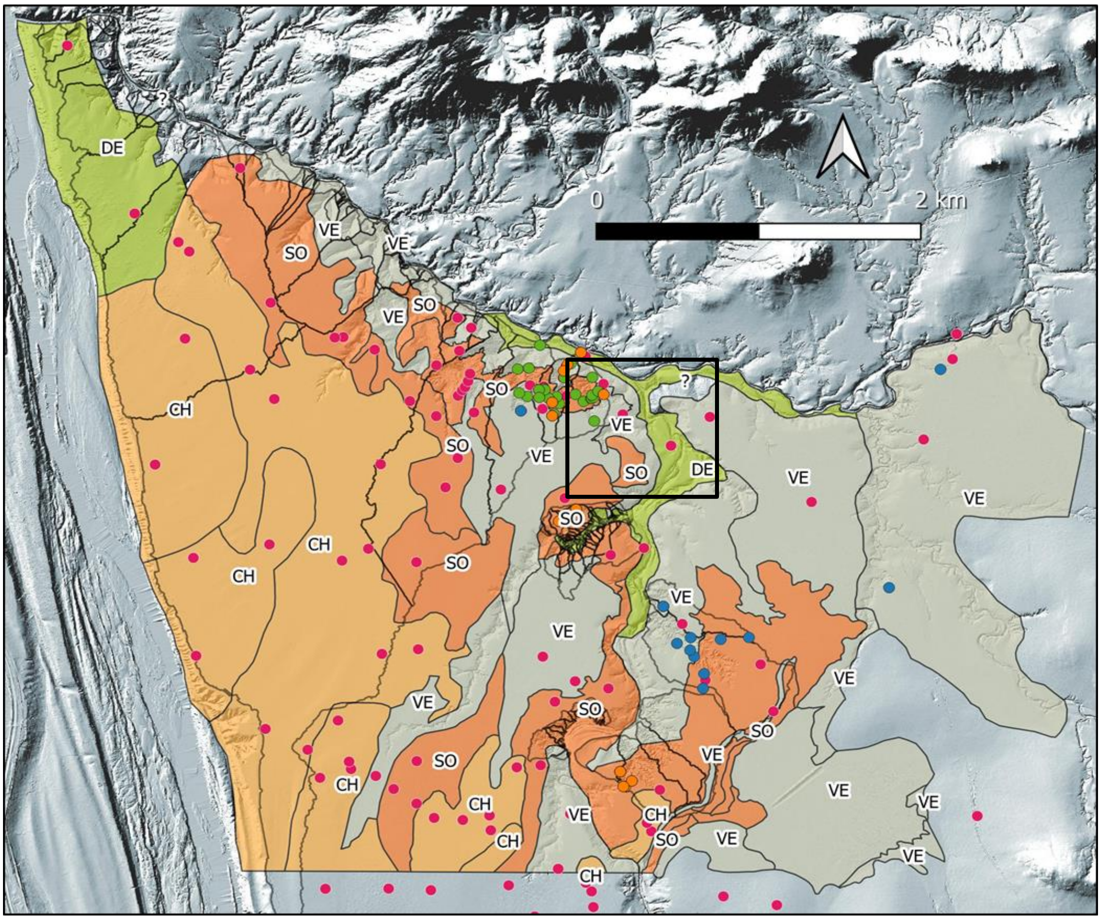


Figure 52. The map of modified and augmented Soil Profile Classes of Thompson and Reid (1982) and the ASC as illustrated by the fill colours (legend) from the conventional soil survey by normal augering (to 1.2 m) and coring (to 1.5 m) and in-gully observations.



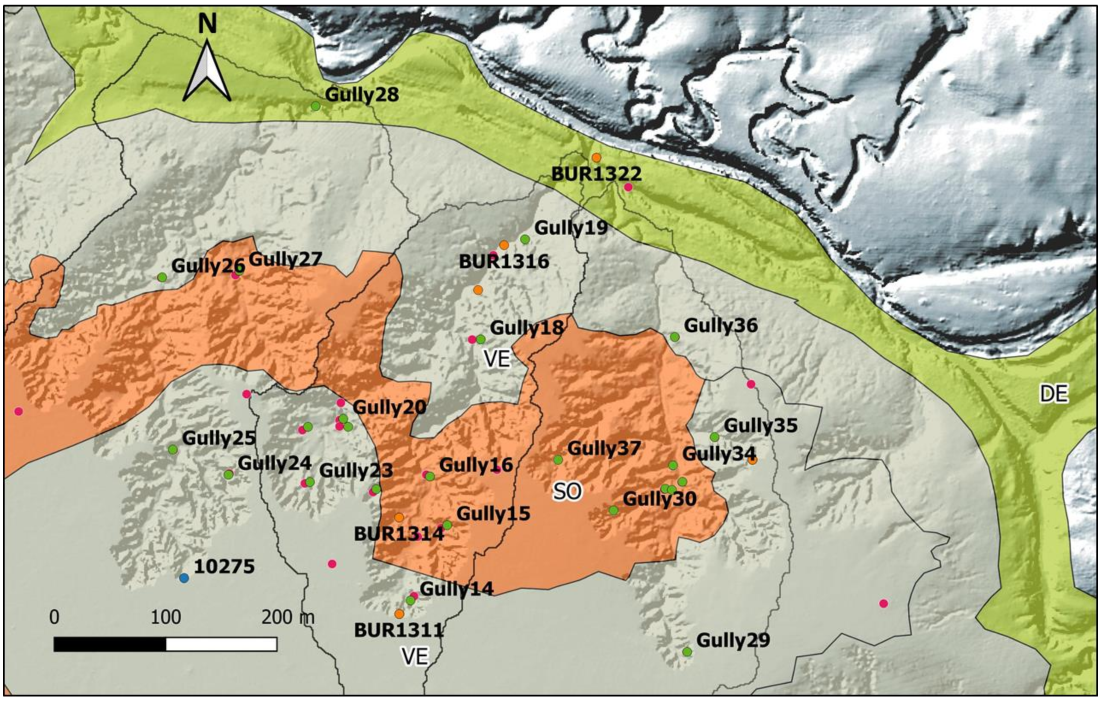


Figure 53. The sites of soil material observations and sampling in (A) the northern gullies (see inset) and (B) the northern floodplain region of Bonnie Doon Creek. Red – soil survey site observations by coring, and in-gully recording; Green – soil material assessment site observations in and around the Northern gully cluster; Blue – later, augmenting observations in gullies other soil material systems and other gully locations matching the BRF SMS. Background map is of ASC soil map units.

The soil materials are briefly summarised here from the laboratory analysis data (see supplementary material) and the field observations. Of the five soil material systems identified in the region the BRF, Local Clay Alluvium (LCA), and RA are the most relevant to the major Strathalbyn gully systems around Bonnie Doon Creek. Table 25 gives an example of the soil material units descriptions found in the BRF and LCA and BRL SMSs. An example of the SMUs in the BRF (Burdekin River Floodplain) soil material system is shown in Table 25 and identified as layers in Figure 54.

Overall, the soil materials on the flood plain are dominated by high silt and fine sand contents with comparatively low clay contents, typically 5 – 15%. This changes for the 'blacksoil' cracking clays (Vertosols and Vertic Dermosols) of the Local Clay Alluvium SMS, where clay contents can commonly reach 60+ %. Top layers vary from hardsetting sandy loams in the BRF SMS to clay loams in the LCA SMS. Silty loam top layers are also common, generally where topsoils have been completely eroded. Organic contents are commonly low but, again, higher in the LCA cracking clays. Carbonate nodules are common at depths below 0.75 m in both SMSs.

Summaries of the key analytical characteristics for the representative sample sites of each SMS are provided in Table 26. Chemical values of importance are the measures for salinity (electro-conductivity – EC; along with the chloride – Cl^- – content) and for sodicity (exchangeable sodium percentage – ESP). These give an indication of erodibility hazard for each soil material layer.

Top layer values for sodicity can be variable -depending on whether there is a surface wash of sodic materials or if topsoils are intact – giving lower ESP values. Sodicity can indicate susceptibility to clay dispersion, as can high magnesium levels (indicated by calcium:magnesium ratios less than about 0.8 (making the material magnesic and adding to the dispersion hazard). Salinity at depth can mitigate dispersibility by providing more structure to the material and encouraging flocculation of fine materials in suspension.

In general, the soil materials in which the gullies have developed are sodic to very strongly sodic in the lower layers (some surface layers can also show mild to strong sodicity). Values of over 50% exchangeable sodium have been recorded here in the BRF materials. The LCA Vertosols tend to be less sodic and magnesic.

Of significance in the particle size distribution is the proportion of 'fines' (particles of less than 20 microns (0.02 mm), i.e clay- and silt-sized particles) being overwhelmingly high for all of the soil material systems except for the very recent alluvial material. A very high proportion of the sand-sized particles are fine sands (commonly over 75%), so the soil material on the Strathalbyn floodplain are dominated by high silt and fine sand material sizes. These are precisely the most erodible of the particle sizes and are very prone to slaking, (mechanical disaggregation). They can be highly sodic / magnesic at all depths and then are possibly prone to dispersion if clay percentages are significant (i.e. > ~15%).

Table 25. General description table for the main soil material units identified in three of the soil material systems at Strathalbyn.

SMU	Description	Sites
BRF – Burdekin River Floodplain (BRF-interior)		
BRF1.1	Dark grey, clay loam fine sandy, hardsetting, massive or weakly structured	60, 61, 73-74, 80-81
BRF1.2	Bleached to grey, massive fine sandy loam to loam fine sand	54-55, 57-58, 62-65
BRF2	Brown, light medium clay, lenticular structure	54-55, 58, 60-61, 64, 73-74
BRF3.1	Brown, prismatic breaking to angular blocky, light to light medium clay with calcium carbonate segregations, slightly saline, strongly sodic, highly dispersible	54-56, 58, 60-67, 73-74, 80
BRF3.2	Saline and solonized facies of BRF3.1, highly saline, very strongly sodic and highly dispersible	81-82
BRF4	Brown, structured light medium clay with manganese nodules, saline, strongly sodic, magnesic, highly dispersible	54, 56, 60, 62-67, 73-74
BRF5	Dark, finely structured light medium to medium clay with manganese nodules, non-saline, sodic, moderately dispersible	56
BRF6	Dark, lenticular structured medium to medium-heavy clay	
BRF7	Grey-brown, fine structured silty clay loam to silty medium clay, non-saline, non-sodic, non-dispersive	66-67, 73
BRL – Burdekin River Levee (BRF-west)		
BRL1	Bleached to brown, massive, clayey fine sand to fine sandy loam	51
BRL2	Brown, strong prismatic parting to moderate fine structured, fine sandy clay loam	51-52
BRL3	Brown, prismatic structure, sandy light clay	51-52
LCA - Local Clay Alluvia (Lacustrine and/or palustrine plains)		
LCA1	Dark, self-mulching cracking finely structured medium clay, non-saline, non-sodic, non-dispersive dispersive	59
LCA2	Dark, lenticular structured medium clay, slightly saline, sodic, non-dispersive	59
RA - Recent Alluvia (Bonnie Doon Creek)		
RA1	Dark, self-mulching cracking finely structured medium clay, non-saline, non-sodic, non-dispersive dispersive	59
RA2	Dark, lenticular structured medium clay, slightly saline, sodic, non-dispersive	59

Table 26. Summary table of the key analytical characteristics of the top layers and sub-layers for the soil material systems and regions within them.

Averages	ESP	EC	Sand	Silt	Clay	< 2 µm	SMS	
Top Layers	31.5	1.06	32.3	31.5	39.2	70.6	BRF	Burdekin River Floodplain
Sub-layers	36.0	0.91	25.6	30.1	42.4	72.6		Northern gullies
Top Layers	20.4	0.21	39.7	36.1	27.5	63.5	BRF	Burdekin River Floodplain
Sub-layers	42.9	2.29	34.4	39.3	27.3	66.6		Southern gullies
Top Layers	1.4	0.11	51.8	31.2	21.7	52.8	BRF	Burdekin River Floodplain
Sub-layers	25.1	0.46	28.8	22.6	52.8	75.4		Central gullies
Top Layers	18.4	0.73	18.0	74.5	6.4	80.9	LCA	Local Clay Alluvium
Sub-layers	14.4	0.59	16.4	23.2	63.6	86.8		Blacksoil cracking clays
Top Layers	-	0.07	55.7	11.2	34.9	46.1	RA	Recent Alluvium (Bonnie Doon Creek)
Sub-layers	3.3	0.03	62.2	10.3	27.1	37.4		Very recent alluvium (upper bench)
Top Layers	21.4	0.92	41.7	28.4	32.8	61.2	BRL	Burdekin River Levee
Sub-layers	37.0	0.67	30.0	30.0	40.4	70.4		
Top Layers	38.8	0.14	15.6	27.8	57.7	85.5	RA	Recent Alluvium (Bonnie Doon Creek)
Sub-layers	19.4	0.88	18.9	24.6	55.9	80.5		Recent alluvium and modified BRF material

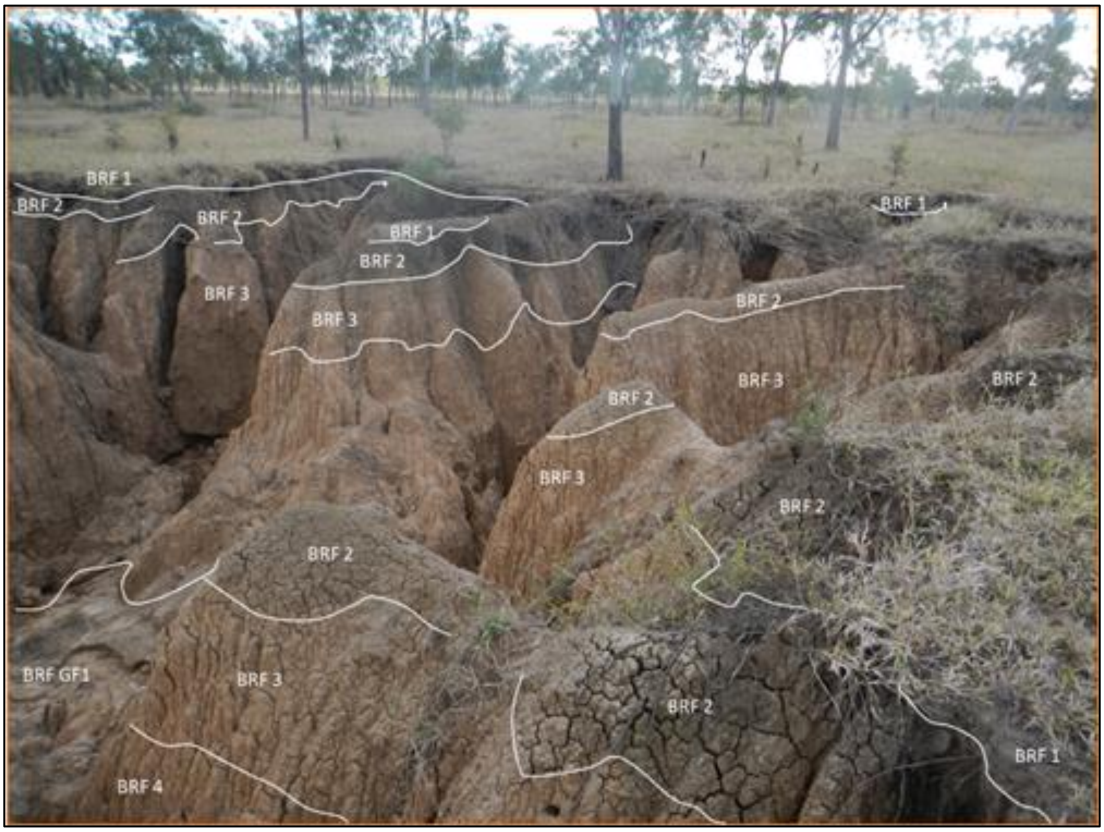


Figure 54. Soil-geomorphic layers (as SMUs) identified in Gully 7 at Strathalbyn Northern Gullies. As can be seen from this photograph the soil material layers vary, well below the depth of normal augering (1.2 m) and coring (1.5 m).

The dominant erosion process for the BRF and similar soil materials on the floodplain is slaking (by saturation, rainsplash-sheetflow, and soil piping). For the cracking clays of the LCA SMS the dominant process is dispersion and mechanical (flowing water) erosion of fine clay aggregates.

Fence diagrams and stratigraphic section (as shown in Figure 55 and Figure 56) indicate that the soil material layers are fairly consistent throughout the Bowen River Floodplain Soil Material Systems (BRF SMS) at least, although the BRF 2 and lower BRF 4 SMUs can show inconsistent presence and thicknesses.

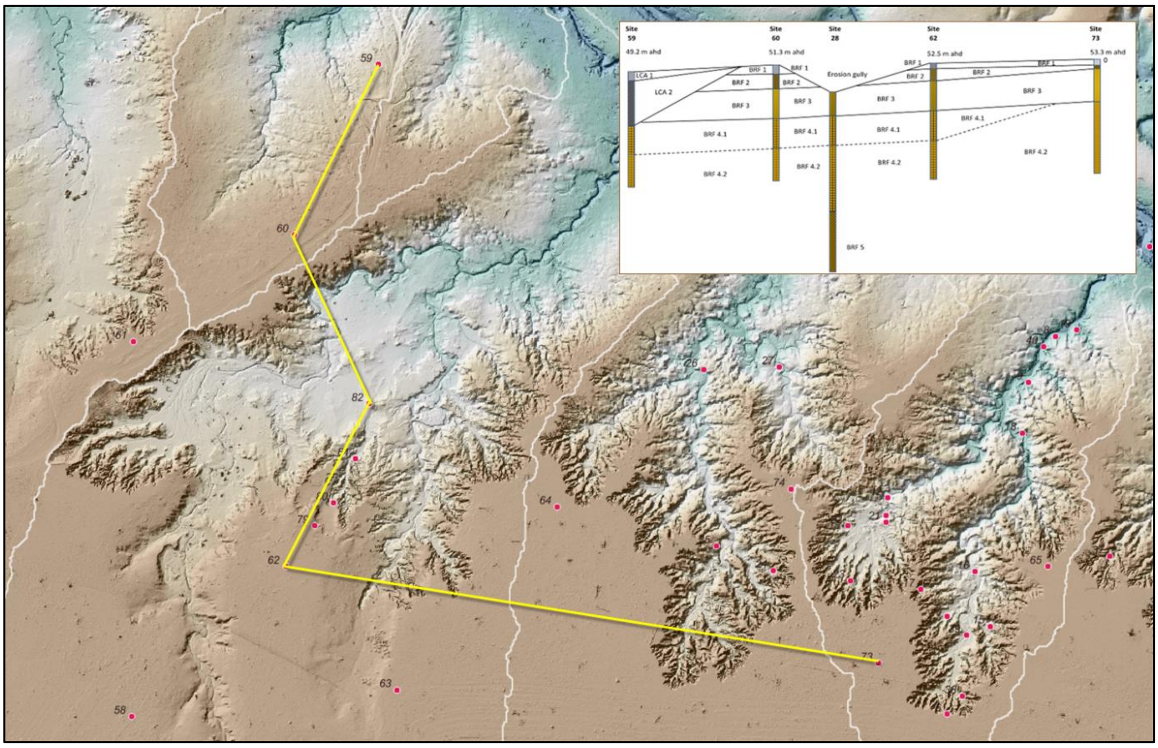


Figure 55. A stratigraphic cross-section path of part of the Strathalbyn 'Northern' gullied region from detailed coring and gully wall descriptions of soil material layers: the arrangement and interpretation of distinct Soil Material Units (classified and coded). Inset shows the stratigraphic cross-section SMUs grouped by Soil Material System (i.e. LCA and BRF), correlated by elevation above AHD (by lidar and UAV photogrammetry) from both gully exposure and soil core observations.

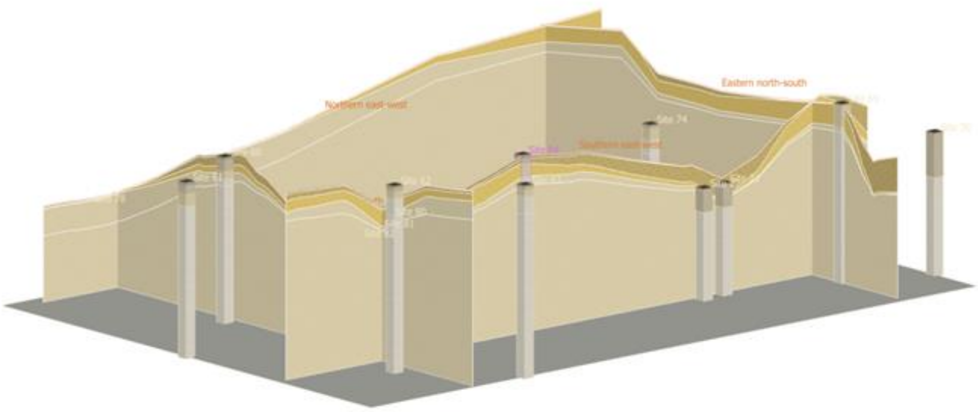


Figure 56. A stratigraphic fence diagram in pseudo-3D across the northern gullies showing precise elevations and layer depths from gully observations tied in with some soil cores. Layers are largely consistently present but can vary in their depths and thicknesses.

3.2.2 Meteorological and hydrological monitoring

A broad array of monitoring equipment was deployed at the northern gully sites, as outlined in Telfer (2018) and summarised in Table 29. Two tipping bucket rain gauges (Hydrological Services tipping bucket design - 0.2 mm/tip with Hobo data logger and Campbell Scientific datalogger CR1000) were deployed in the catchment of Gully-13 (southern gullies) and the Control gully and remediated area adjacent to the confluence of Treatment-1 and the Control gully outlets.

Water level flowing through the gullies was measured and recorded every 10 minutes using pressure transducers with built in dataloggers (in-situ rugged troll 100, Onset HOBO U20L, and Campbell Scientific CS451/CS456). The majority of water level loggers used (in-situ rugged troll 100 and Onset HOBO U20L) were non-vented and required barometric pressure correction using data measured and recorded every 10 minutes from a barometric transducer datalogger (In-situ barotroll®) located ~1 m above the ground surface in the control and T1 gully catchment.

Gully water velocity was measured and recorded every 10 minutes using Doppler instruments (Unidata, Starflow) connected to dataloggers (Campbell Scientific Cr1000). The Doppler instruments were deployed, facing downstream, attached to a steel post at a height of ~15 cm above the channel bed in the centre of the channel cross section. Unfortunately, due to turbulence and the very short duration of flows, and the lack of flows of suitable depth, no usable velocity data was collected from any of the gauge sites. Consequently, water yield and hence gully discharge has been modelled at selected gullies using the HEC HMS (USACE) with the timing and relative magnitude of peaks calibrated against the stage record for each gully. Water yields were only derived for the gullies with sufficient SSC and BAN data to warrant annual and event loads being calculated.

3.2.3 Gully Water Yields

The high degree of flatness of the alluvial terrace into which the gullies are eroding coupled with the high resolution of the lidar posed considerable challenges to modelling the water yield. Subtle variations in topography between consecutive lidar surveys resulted in changes to modelled flow paths and ambiguous areas of the catchment in which it is unclear exactly where the water would flow (Figure 57). Consequently, the runoff from these areas have been divided equally into the treatment areas as indicated in Table 27.

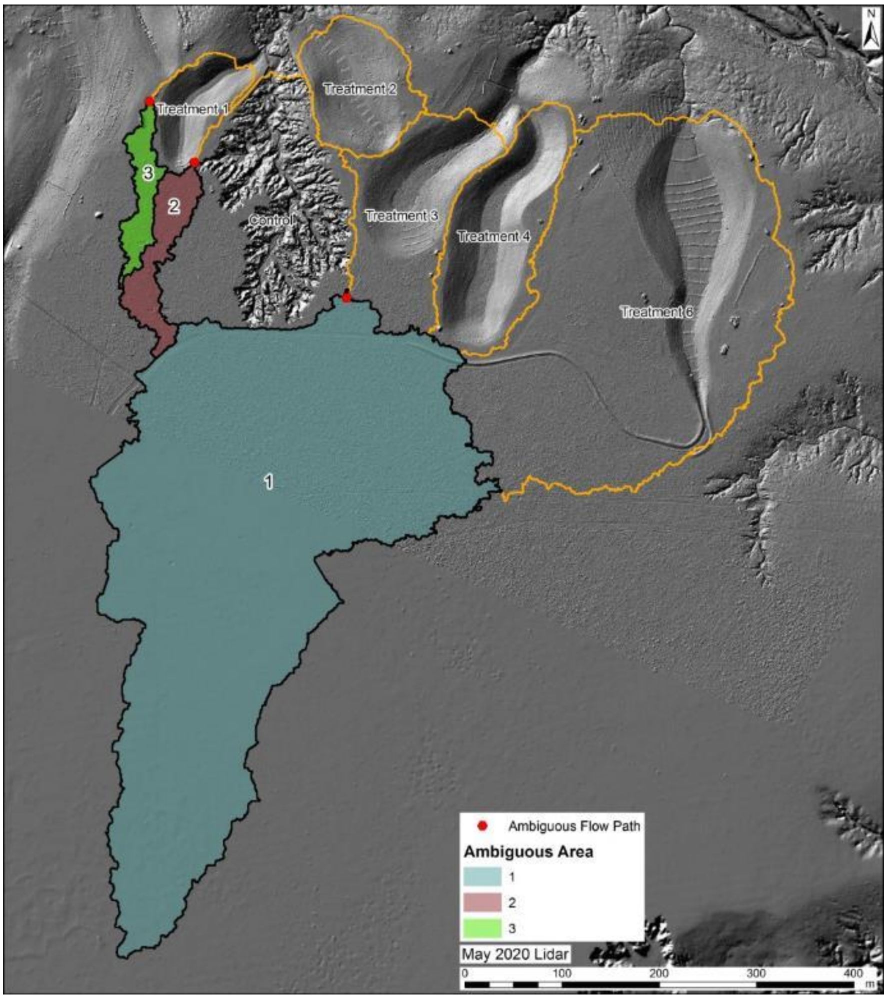


Figure 57. Derived catchment areas for monitored gully treatment areas. Relative contributions from the shaded areas are shown in Table

Table 27. Gully catchment areas derived from lidar hydrologic analysis. These areas are used for the water yield modelling for the suspended sediment load estimates.

	Based on lidar from 2018 - 2019		
Treatment	**Contributing area**	**Area m^2**	**Hectares**
Treatment 1	T1 +0.5 x area 2 + 0.5x area 3	12631	1.26
Control	Control + 0.5 x area1 + 0.5 x area2	110549	11.05
Treatment 2	T2	13005	1.30
Treatment 3	T3 + 0.5 x area 1	90761	9.08
Treatment 4	T4	21691	2.17
Treatment 6	T6	93598	9.36

Table 28. Annual water yields for the Control gully along with Treatment gullies 1, 3, 4 and 6 derived from the water yield of the respective gully catchments

Water year Gully	2018/19 Water discharge (m^3)	2019/20 Water discharge (m^3)
Control	75336	26811
T1	8445	3070
T3	61941	22012
T4	14633	5208
T6	55742	19807

Table 29. Summary statistics for the type of water quality monitoring undertaken at each site, along with the number of *usable* samples in bold collected according to type of monitoring equipment (note more samples were collected than are shown here; some were not able to be used due to QA/QC from things such as backwater contamination).

Monitoring Equipment	Treatment sites at which samplers deployed	Number of usable samples per Water Year (July-June)		
		2017/18	2018/19	2019/20
ISCO Autosampler	*Control, T1, T2, T3, T4, T6*	Not installed-	T4/**32**;	Control/**10**;T1/**1**; T6/**6**
PASS sampler*	*Control, T1, T2, T3, T4, T6*	damaged	Backwatered – not usable	T1/**1**;T4/**2**
Rising Stage Samplers (RSS)	*Control, T1, T2, T3, T4, T6*	Control/**23**; T2 /**1**;T3/**13**; T4/**9**;	Control/**2**; T/**2**; T4/**10**;	Control/**1**; T1/**3**; T2/**1**;T3/**4**; T4/**4**; T6/**4**
Stage Recorder (1 at each site)	*Control, T1, T2, T3, T4, T6*	Control, T1, T2, T3, T4, T6	Control, T1, T2, T3, T4, T6	Control, T1, T2, T3, T4, T6
Tipping Bucket Rain gauge # 1 (telemetered)	*Control*	NA	Hourly Intensity data only + hourly & daily totals – full wet season	Hourly Intensity data only + hourly & daily totals – full wet season
Tipping Bucket Rain gauge GU (0.2 mm tips)	*Top T3/T4*	Part wet season	Full wet season	G13 record used for Northern gullies
Velocity Meter	*Control, T1, T2, T3, T4, T6*	0	Control, G8, T1, T4	-
***Overland Flow PASS**[a]*	*T5 inlet, T6 inlet*	Not developed	Not developed	T5/**1**; T6/**1**

* See Dorien et al (2019) for PASS sampler specifications and performance analysis. [a] Note - a single sample for a PASS sampler represents an integrated sample across the entire wet season; overland flow only installed 2019.

3.2.4 Backwater Events

The northern gully site experienced a major backwater event on January 10th in 2019 (event A Figure 58) associated with a localised rainfall event in the headwaters of Bonnie Doon Creek. This event had the effect of contaminating a number of the samples collected during the event, which can be seen to change significantly either up or down depending on whether the site was a treatment or control (see Figure 10). A further small backwater event was also experienced on January 31st 2019 (event B Figure 58) which was only experienced at the Treatment 3 gauge. The plots in Figure 58 show the relative stage height above gauge zero at each monitoring point, and the maps in Figure 59 show the maximum inundation extent in the flood of January 10th.

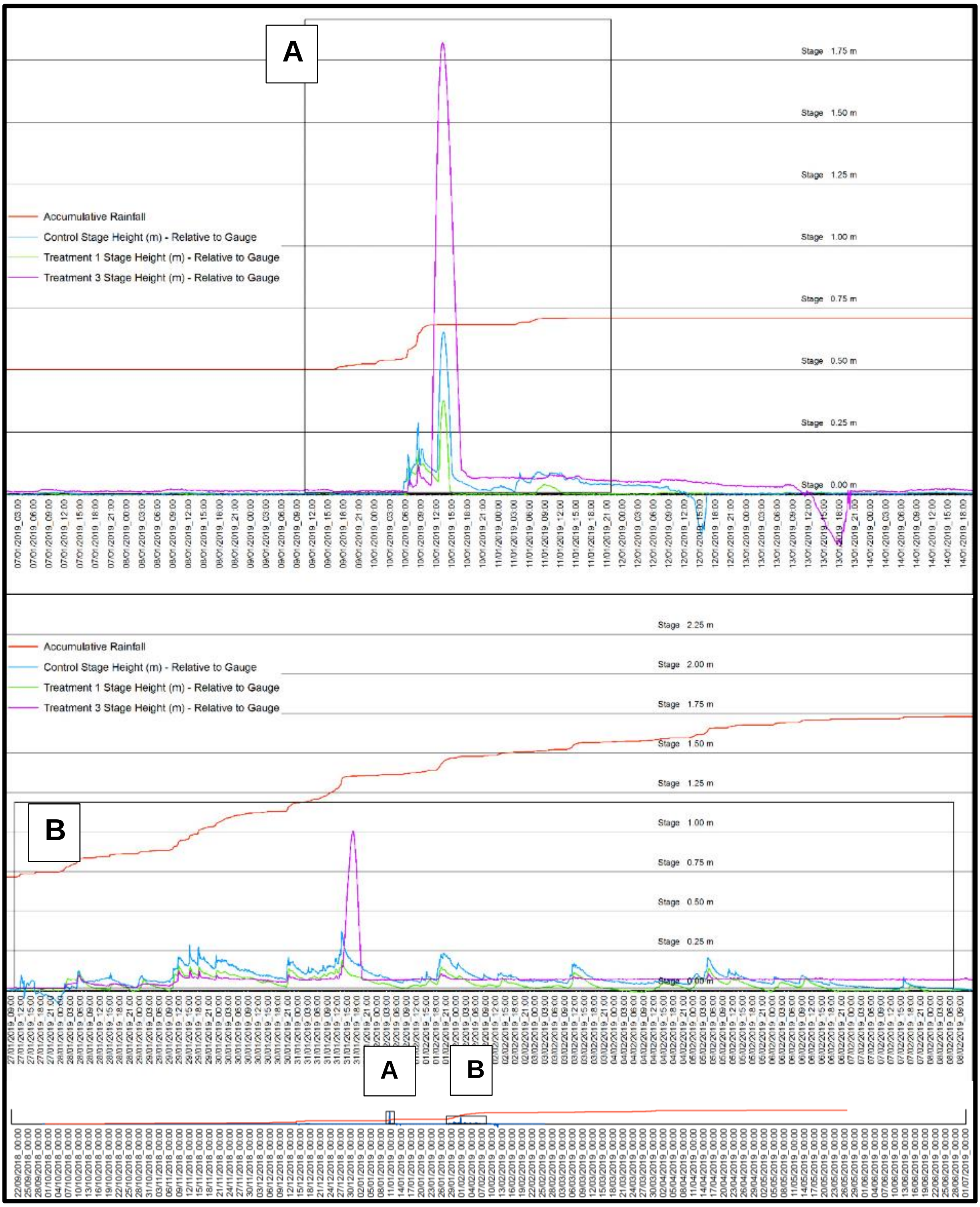


Figure 58. Stage height at the Control & treatment 1 and 3 – normalised to the gauge zero for each site, showing the clear signature of the hydrographs associated with the backwater event in January 2019. The timeline at the bottom extends from September 2018 to July 2019.

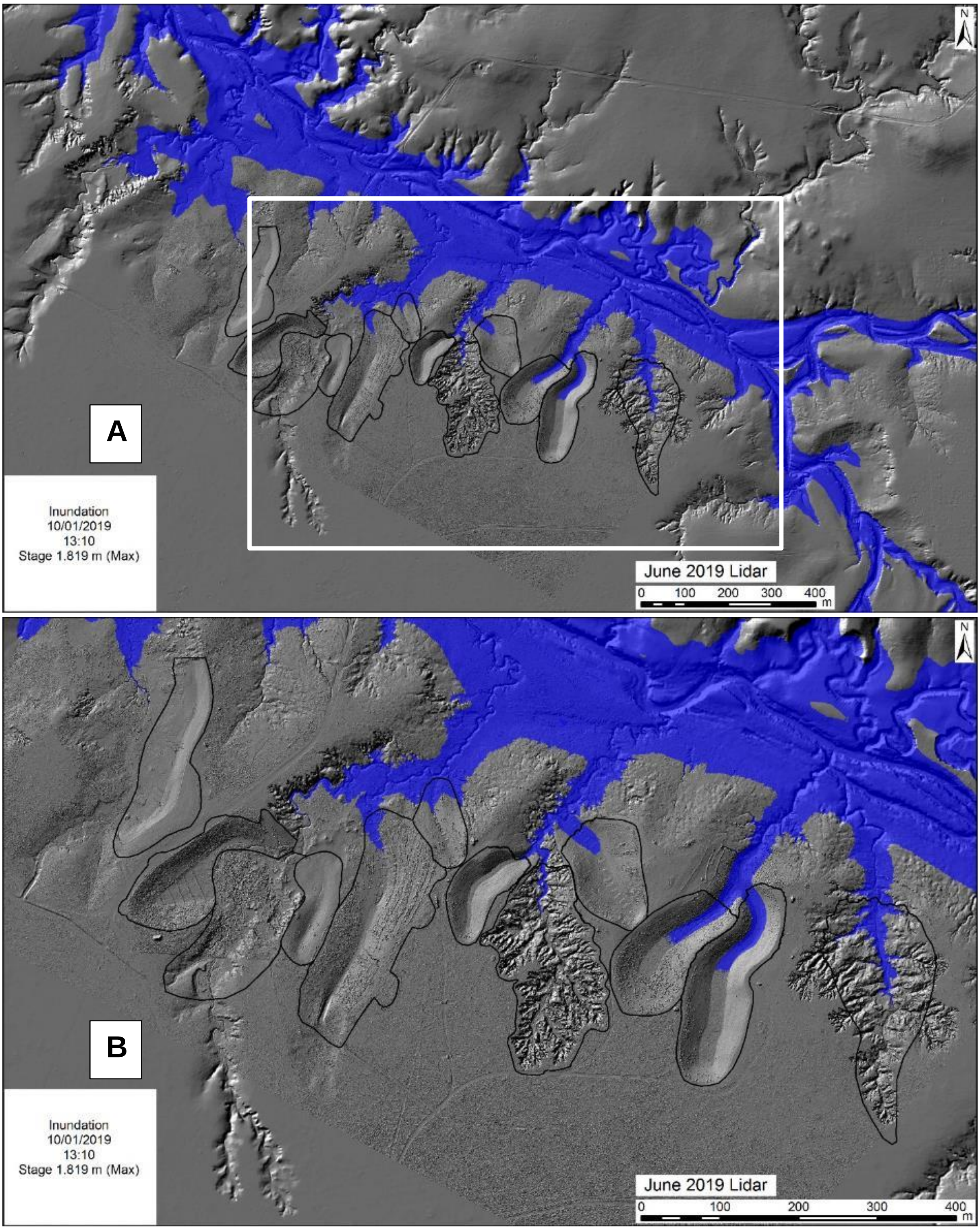


Figure 59. Maps showing the maximum extent of inundation associated with the flood in Bonnie Doon Creek on 10th January 2019. Magnified box on A shows the extent of the map in B.

3.2.5 Suspended sediment monitoring

Suspended sediment dynamics in the control and remediated gullies were primarily monitored using RS samplers and autosamplers deployed at the gully outlets (Table 29). A total of 174 samples were collected from the control and five remediated gullies (Table 30). The SSC of the samples collected from the control gully was consistent for the three wet seasons (2017-2020) monitored. The GM SSC of the samples collected for each of the three years monitored (2017-2020), 57925, 69451, and 66192 mg/L respectively, only varied by 9.5% (5941 SSC mg/L). This indicated there was a steady supply of readily erodible soil throughout the gully during the monitoring period. Comparison of SSC data trends between the control and remediated gullies are shown in Figure 60- Figure 69.

Gully Control

The control gully had consistently high sample SSCs for the three wet seasons that were monitored (2017-2020) (Figure 60). The GM of sample SSCs collected each wet season varied by <10% from each wet season to the next. This indicates gully erosion and subsequent suspended sediment transport in the Control Gully was consistent throughout the monitoring period (2017-2020). Sediment particle size analysis show that sample suspended sediment PSD parameters (i.e., 10^{th} (*d*10), 50^{th} (*d*50 or median), and 90^{th} (*d*90) percentiles) of suspended sediment measured were also consistent throughout the monitoring period. This indicates there was a steady supply of sediment, likely from the same source area, eroding from sections of the gully during most flow events (Figure 61).

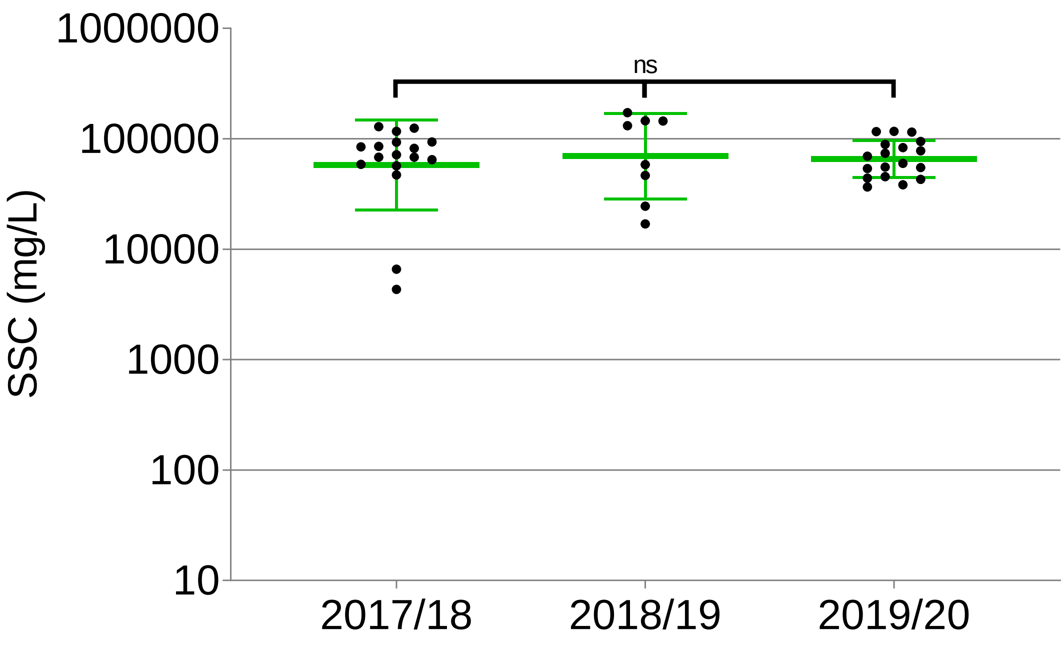


Figure 60. Geometric mean (long green horizontal bars) and standard deviation factor (green error T bars) of sample SSCs (black markers) collected from the Control Gully for wet seasons 2017/18, 2018/19, and 2019/20. Brackets represent the results of a repeated measures ANOVA, where p > 0.05 (ns).

Table 30. Descriptive statistics of sample suspended sediment SSC for all gullies during the 2017-2020 monitoring period. Highlighted columns represent untreated gullies.

	Control			***Treatment-1***			***Treatment-3***			***Treatment-4***			***Treatment-6***	
Wet season	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2018/19**	**2019/20**
Number of samples	17	8	20	7	8	4	10	6	3	9	39	5	16	10
Minimum (mg/L)	4,320	16,974	36,597	440	29	172	1,900	732	1,137	73,551	266	98	37,998	6,301
25% Percentile (mg/L)	57,784	30,050	47,496	770	379	202	76,261	1,397	1,137	80,741	408	260	45,388	7,101
Median (mg/L)	71,784	94,980	64,733	859	604	374	102,383	3,071	1,739	105,381	741	769	60,124	8,934
75% Percentile (mg/L)	93,398	145,510	93,275	1,781	1,002	572	160,557	5,086	2,030	130,801	1,399	5,571	75,978	13,566
Maximum (mg/L)	128,975	172,176	116,800	1,948	3,191	610	420,148	6,504	2,030	164,148	2,578	9,680	87,826	44,484
Range (mg/L)	124,655	155,202	80,203	1,508	3,162	437	418,248	5,772	893	90,597	2,312	9,582	49,828	38,183
Mean (mg/L)	73,818	92,580	70,773	1,086	892	383	134,405	3,268	1,635	108,881	933	2,486	61,495	13,192
Std. Deviation (mg/L)	34,708	62,137	26,543	558	980	192	115,775	2,121	455	29,743	632	4,053	16,395	11,571
Std. Error of Mean (mg/L)	8,418	21,969	5,935	211	347	96	36,611	866	263	9,914	101	1,813	4,099	3,659
Geometric mean	57,925	69,451	66,192	972	511	344	82,265	2,613	1,589	105,436	762	852	59,377	10,755
Geometric SD factor	2.6	2.4	1.5	1.7	3.8	1.7	4.2	2.2	1.3	1.3	1.9	5.4	1.3	1.8
Lower 95% CI of mean (mg/L)	55,973	40,632	58,351	570	72	77	51,584	1,043	504	86,019	728	- 2,547	52,758	4,915
Upper 95% CI of mean (mg/L)	91,663	144,528	83,195	1,602	1,711	688	217,226	5,494	2,766	131,744	1,138	7,519	70,231	21,469
Coefficient of variation	47%	67%	38%	51%	110%	50%	86%	65%	28%	27%	68%	163%	27%	88%

Table 31. Descriptive statistics of sample suspended sediment *d*50 particle size measurement for all gullies during the 2017-2020 monitoring period. Highlighted columns represent untreated gullies.

	Control			***Treatment-1***			***Treatment-3***			***Treatment-4***			***Treatment-6***	
Wet season	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2017/18**	**2018/19**	**2019/20**	**2018/19**	**2019/20**
Number of samples	10	13	19	4	10	4	7	10	4	7	30	5	18	11
Minimum (µm)	7.4	1.7	4.6	3.3	3.4	9.6	8.2	4.4	4.1	7.7	2.7	5.4	4.8	3.8
25% Percentile (µm)	7.6	4.7	7.3	3.4	4.4	9.7	9.6	6	4.5	8.1	3.9	6.1	6.7	4.4
Median (µm)	8.2	7.4	8.3	3.7	7.3	10	12	6.8	5.8	9.8	4.6	7.4	8.6	5.2
75% Percentile (µm)	9.8	8.1	11	4	11	13	13	7.8	13	10	5.1	11	9.6	5.8
Maximum (µm)	10	9.7	21	4.1	12	14	13	8.7	15	10	6.5	13	13	11
Range (µm)	2.6	8	16	0.85	9	4.6	4.5	4.4	11	2.6	3.8	7.8	7.8	7.3
Mean (µm)	8.6	6.6	9.2	3.7	7.6	11	11	6.8	7.7	9.1	4.6	8.5	8.3	5.5
Std. Deviation (µm)	1.1	2.5	3.6	0.35	3.2	2.1	1.8	1.3	5	1.1	0.94	3	1.9	2
Std. Error of Mean (µm)	0.35	0.7	0.82	0.17	1	1.1	0.67	0.42	2.5	0.43	0.17	1.4	0.45	0.6
Geometric mean	8.6	5.9	8.6	3.7	7	11	11	6.7	6.7	9.1	4.5	8.1	8.1	5.2
Geometric SD factor	1.1	1.8	1.4	1.1	1.6	1.2	1.2	1.2	1.8	1.1	1.2	1.4	1.3	1.3
Lower 95% CI of mean (µm)	7.8	5	7.5	3.1	5.3	7.7	9.8	5.9	-0.31	8.1	4.2	4.7	7.3	4.1
Upper 95% CI of mean (µm)	9.4	8.1	11	4.2	10	14	13	7.8	16	10	4.9	12	9.2	6.8
Coefficient of variation	13%	38%	39%	9.4%	42%	19%	16%	19%	65%	12%	21%	36%	23%	37%

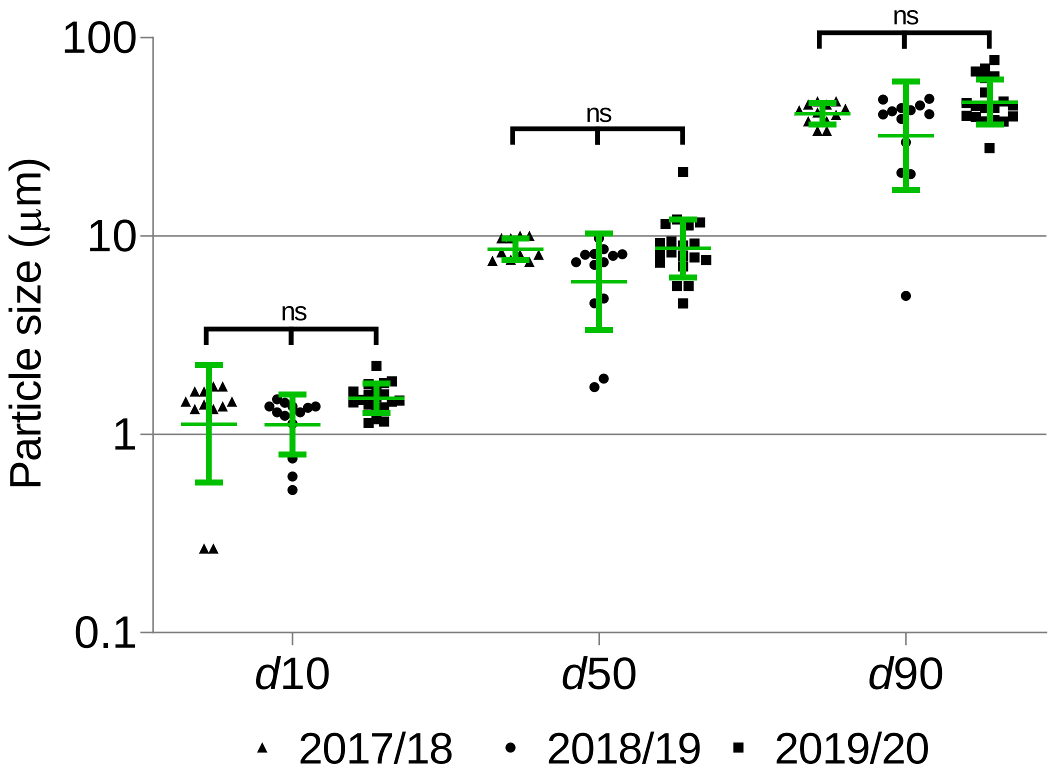


Figure 61. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from the control gully site across the study period. Bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of repeated measures ANOVA, where $p > 0.05$ (ns).

Gully Treatment-1

Baseline SSC data was not collected from Treatment-1 because the gully was remediated, during the 2016 dry season, prior to water monitoring began. However, sediment yields estimated by terrain analysis suggest the gully had comparable annual SSYs to the control gully. Comparison of SSC sample data collected from Treatment-1 and the control gully for the monitoring period (2017-2020) indicate that the gully remediation measures used have significantly reduced SSC, by approximately two orders of magnitude (Figure 62). Consistently low SSC trends from Treatment-1 across wet seasons (2017-2020) also suggest the remediation measures have potential for mitigating gully erosion over long periods (i.e., decades). Monitoring data collected over a greater time scale (i.e., 10 years) is needed to validate this observation.

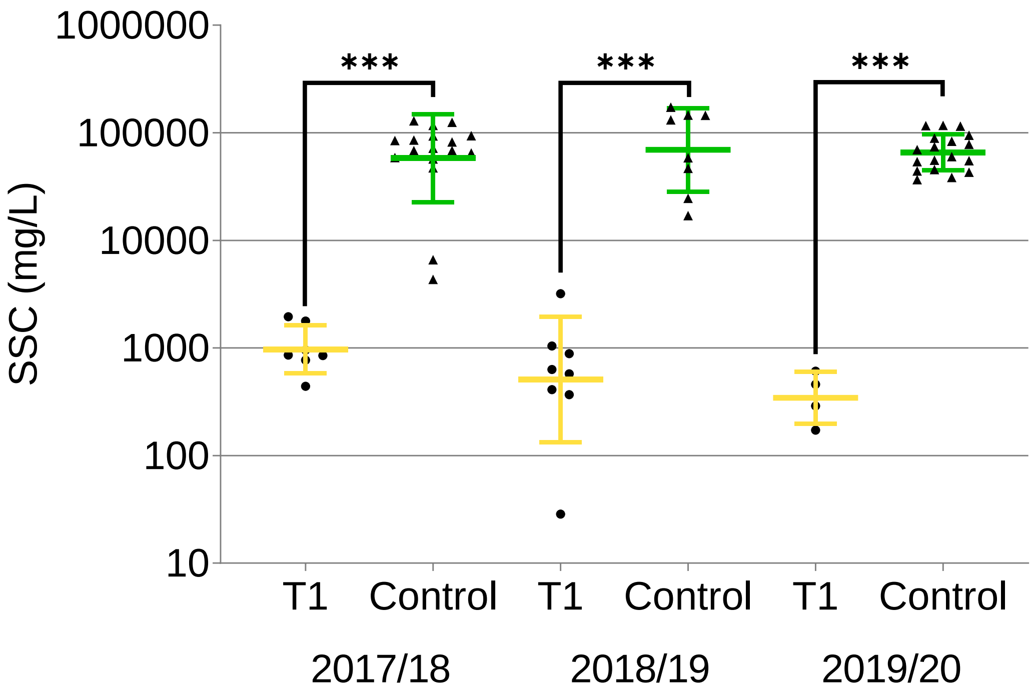


Figure 62. Geometric mean (long horizontal bars) and standard deviation factor (T bars) of sample SSCs (black markers) collected from Treatment-1 (yellow) and Control (Green) gullies for wet seasons 2017/18, 2018/19, and 2019/20. Brackets represent the results of unpaired t-tests, where $p < 0.001$ (***), or $p > 0.05$ (ns).

Sample PSD data collected from Treatment-1 indicate the suspended sediment flowing through the gully is generally very fine (90% of sediment <36 µm). Comparison of Treatment-1 sample PSD with Control gully sample mean PSD measurements show that the sediment flowing through Treatment-1 is significantly finer than the Control sediment. This suggests the relatively coarser gully subsoils (coarse silt and very fine sand) are not eroding from Treatment 1 as they are in the control gully.

There was no apparent trend in suspended sediment particle size over the study period, except for a slight increase in particle size for each wet season monitored (Figure 63). This trend was also observed in PSD data of samples collected from gullies Treatment 3 and Treatment 4 during the monitoring period. Further investigation of the PSD analysis data for these samples showed that the samples collected from gullies Treatment 1, Treatment 3, and Treatment 4 had lower PSDs once they had been sonicated (i.e., exposed to sonication during analysis) compared to when they were not sonicated during analysis (Figure 64). Analysis using non-sonication is considered to provide sample PSD that is more representative of the sediment when transported by a flow event. The same comparison (i.e., sonication compared to non-sonication) of samples collected from the Control gully show little to no variation between sonicated and non-sonicated analysis methods. These trends suggest that sediment transported through remediated gullies are aggregating more so than in the control gully and that the aggregation of these particles appears to remain consistent from year to year. The aggregation could be a caused by one or more of the erosion controls applied to the remediated gullies (e.g., organic matter from mulch, gypsum). Further investigation into this trend is currently underway.

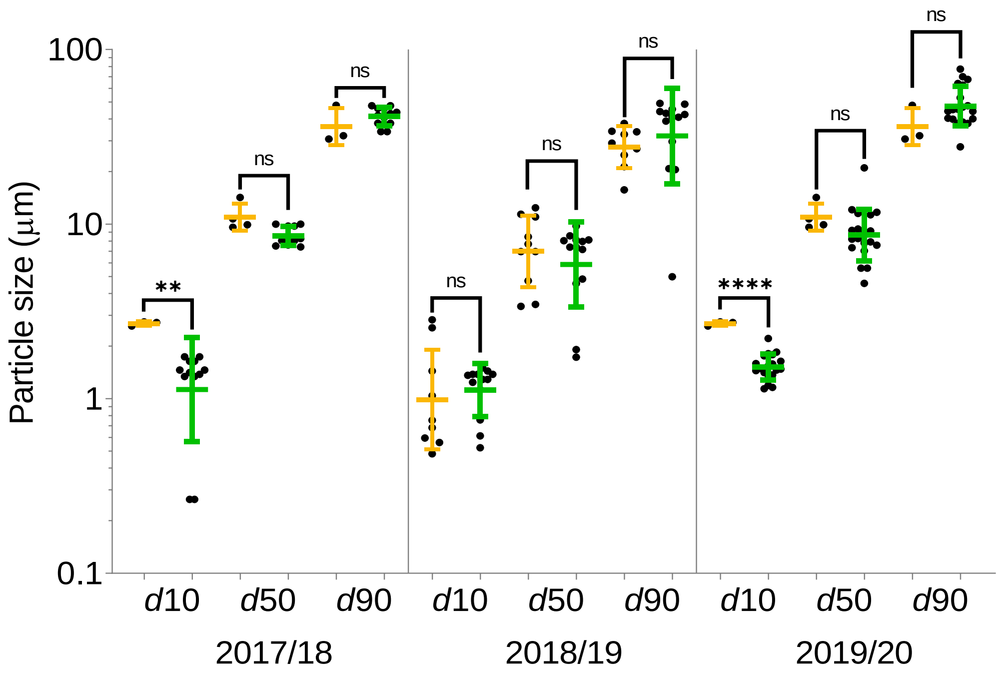


Figure 63. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from Treatment-1 (yellow) and Control (green) gullies across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where p < 0.01 (**) or p > 0.05 (ns).

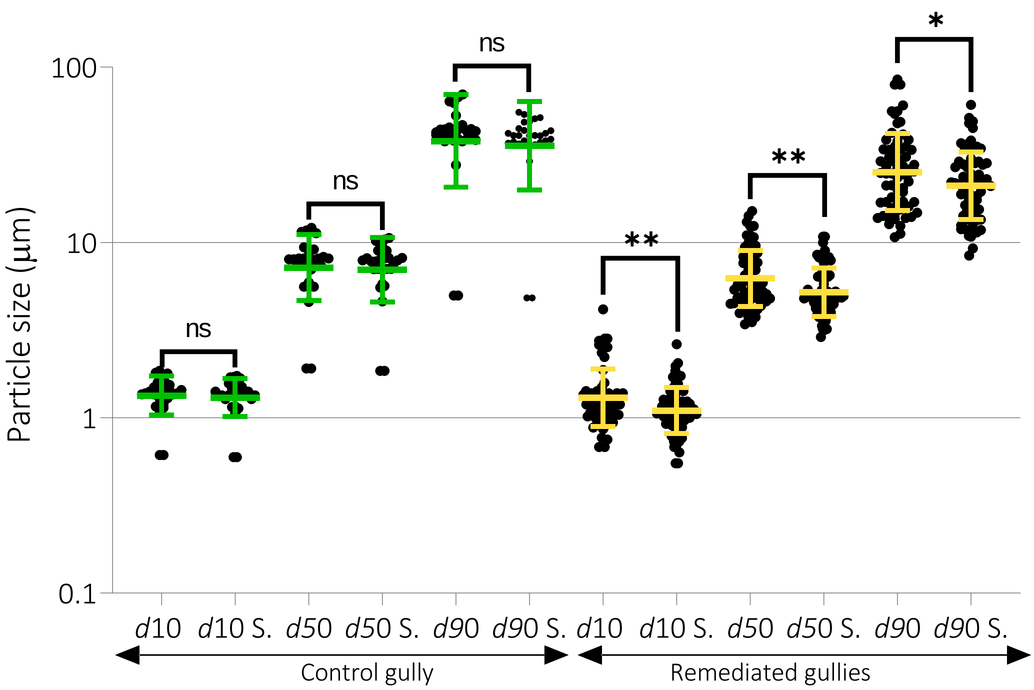


Figure 64. Comparison of PSD analyses conducted on samples collected from the Control (green) and remediated (T1, T3, and T4 (yellow)) gullies during the monitoring period (2017-2020). Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where p < 0.01 (**), p < 0.05 (*), or p > 0.05 (ns). Note the significant difference between the sonicated and non-sonicated particle size data at the treatment site which is not evident in the control site data.

Gully Treatment-2

Very few suspended sediment samples were collected from Treatment-2 (n=2 for wet seasons 2018/19 (34,765 SSC mg/L) and 2019/20 (5,990 SSC mg/L)). The two samples collected indicate that the remediation measures may have been effective in reducing SSC of the water flowing through the gully. However, more samples are needed in-order to properly assess the effectiveness of the remediation measures used.

Gully Treatment-3

Baseline sample SSC data, collected from the gully prior to remediation (2017/18), show similar SSCs trends between Treatment-3 and Control Gullies for the 2017/18 wet season. This suggests the suspended sediment transport dynamics were comparable for the two gullies. Comparison of 2017/18 baseline and 2017-2020 Control SSC sample data with post remediation samples collected from Treatment-3 indicate a reduction of SSC by one and two orders of magnitude for the 2018/19 and 2019/20 wet seasons respectively (Figure 65). Suspended sediment PSD measurements of baseline samples indicate coarser sediment flowed through the gully compared to the Control during wet season 2017/18. Whereas post remediation sample PSDs were notably reduced for the most frequent size fraction (i.e., the median particle size or *d*50). This suggests the remediation works have significantly altered the suspended sediment source flowing from the gully by greatly reducing the erosion of coarser sediments sourced from gully subsoil (Figure 66).

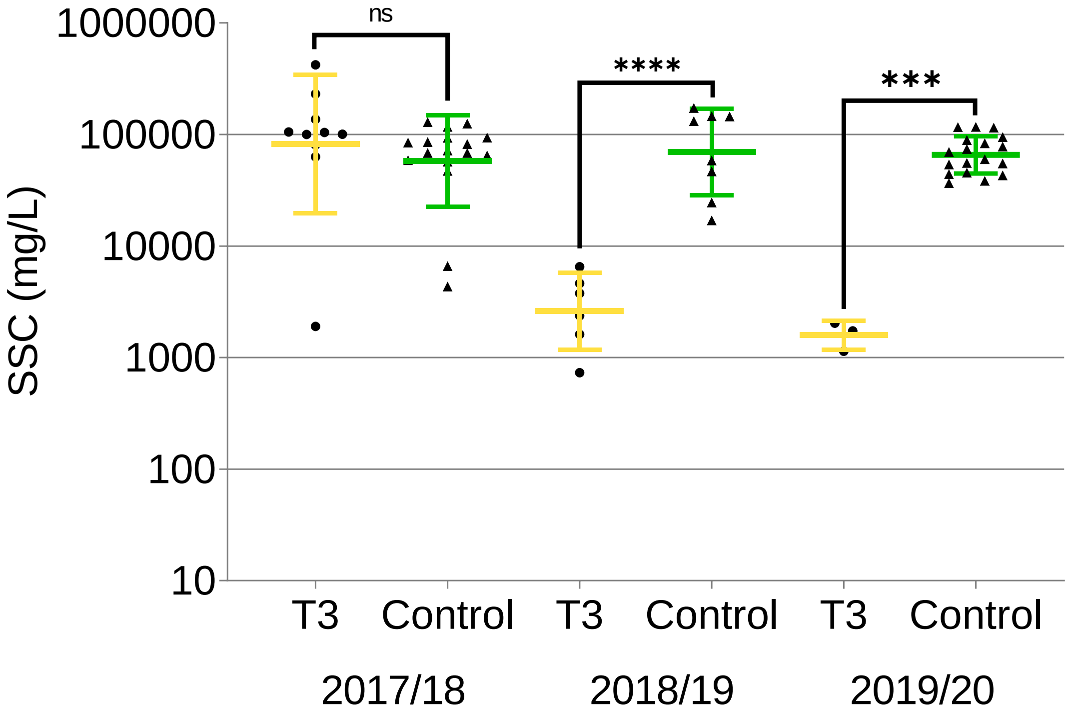


Figure 65. Geometric mean (long horizontal bars) and standard deviation factor (T bars) of sample SSCs (black markers) collected from Treatment-3 (yellow) and Control (Green) gullies for wet seasons 2017/18, 2018/19, and 2019/20. Brackets represent the results of unpaired t-tests, where p < 0.0001 (****), p < 0.001 (***), or p > 0.05 (ns).

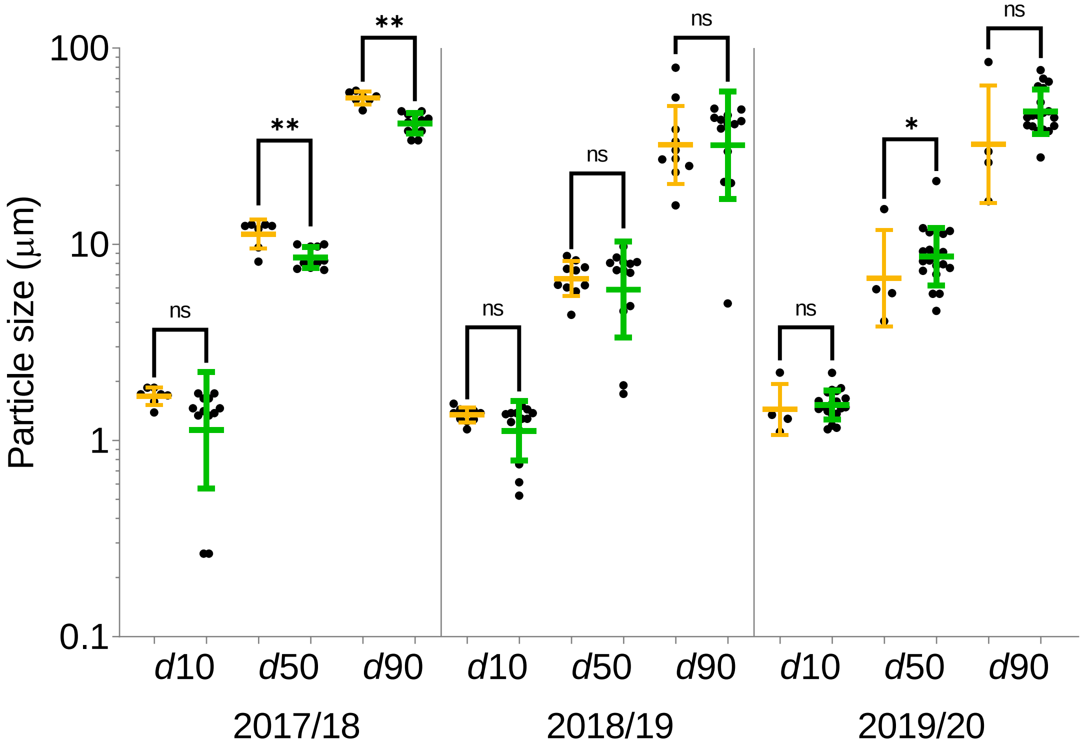


Figure 66. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from Treatment-3 (yellow) and Control (green) gullies across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where $p < 0.01$ (**), $p < 0.05$ (*), or $p > 0.05$ (ns).

Gully Treatment-4

Baseline sample SSC data, collected from the gully prior to remediation, show that Treatment-4 sample SSCs were generally higher than those collected from the Control gully during wet season 2017/18. This suggests the suspended sediment supply of the actively eroding gully may have been higher compared to the Control Gully. Comparison of 2017/18 baseline and 2017-2020 Control sample SSC data with post remediation samples collected from Treatment-4 indicate the remediation measures caused a dramatic reduction in SSC (approximately two orders of magnitude) for the samples collected during the 2018/19 and 2019/20 wet seasons (Figure 67). Suspended sediment PSD of the samples collected from Treatment-4 showed similar trends to Treament-3, where sediment was generally coarser prior to remediation and less coarse post remediation. This is likely a consequence of the remediation limiting the erosion of coarser gully subsoils, as observed in gullies Treatment-1 and Treament-3. There was a trend of increase in coarser particles (i.e., *d*90 values) over time, similar to Treatment-1 (Figure 68). This may indicate erosion of subsoil is increasing or that amendments used as part of the remediation process (e.g., addition of organic matter and/or gypsum) are flocculating smaller sediment particles into larger agglomerations as they are transported during a flow event.

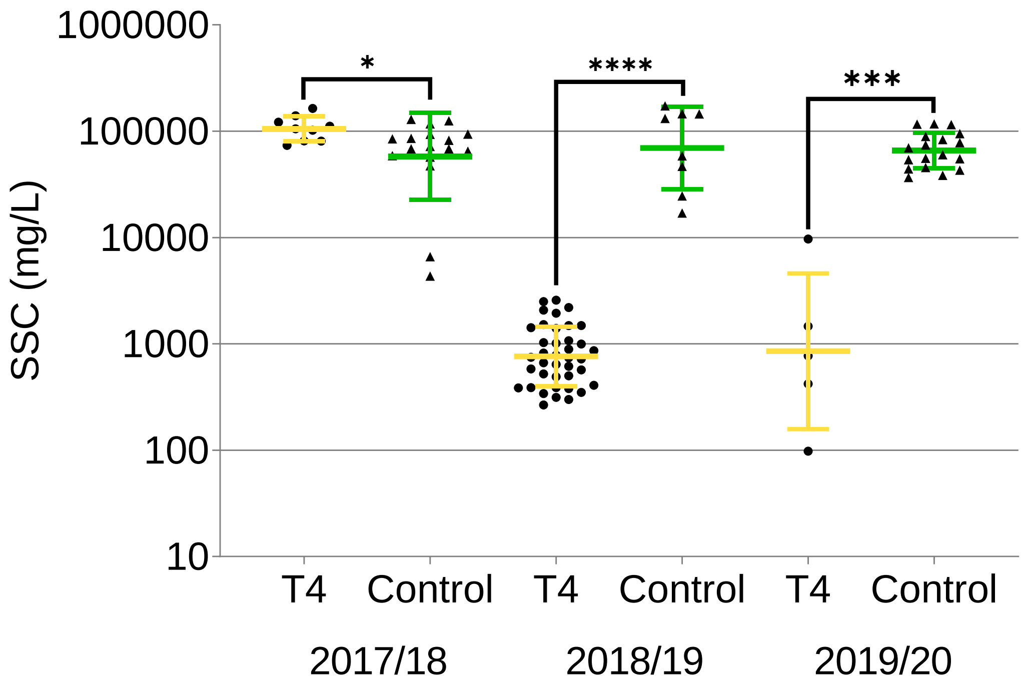


Figure 67. Geometric mean (long horizontal bars) and standard deviation factor (T bars) of sample SSCs (black markers) collected from Treatment-3 (yellow) and Control (Green) gullies for wet seasons 2017/18, 2018/19, and 2019/20. Brackets represent the results of unpaired t-tests, where p < 0.0001 (****), p < 0.001 (***), or p < 0.05 (*).

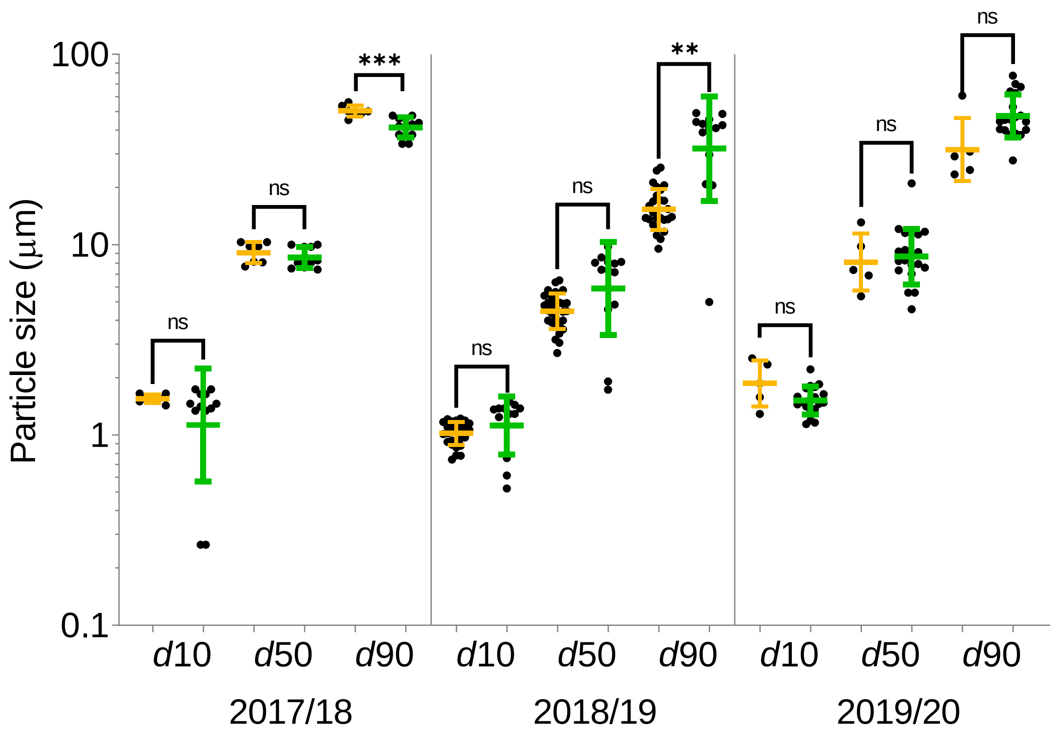


Figure 68. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from Treatment-4 (yellow) and Control (green) gullies across the study period. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where p < 0.001 (***), p < 0.01 (**), or p > 0.05 (ns).

Gully Treatment-6

Baseline suspended sediment monitoring was conducted for wet season 2018/19 and post remediation monitoring was conducted during wet season 2019/20 for gully Treatment-6. Comparison of the unremediated gully baseline (GM = 59377 *or÷1.3) and Control Gully (GM = 57925 *or÷2.6) SSC data indicate the two gullies had very similar suspended sediment transport dynamics during the 2018/19 wet season (Table 30). Sample SSC data collected during wet season 2019/20 indicate the SSCs were reduced by an order of magnitude post remediation. One sample collected during the 2019/20 wet season had a very high SSC (44579 mg/L) compared to the others collected. This was due to the RS sampler becoming buried with sediment likely biasing sample. Because of this, the sample is identified as an outlier (Figure 69). The sediment particle size of samples collected during baseline conditions (2018/19) compare well with the study period average for samples collected from the Control Gully. Post remediation samples show an apparent reduction in mid to larger size ranges (i.e., *d*50 and *d*90). Note the smaller size fraction (*d*90) of samples remained the same as the baseline and control values after remediation was completed (Figure 70).

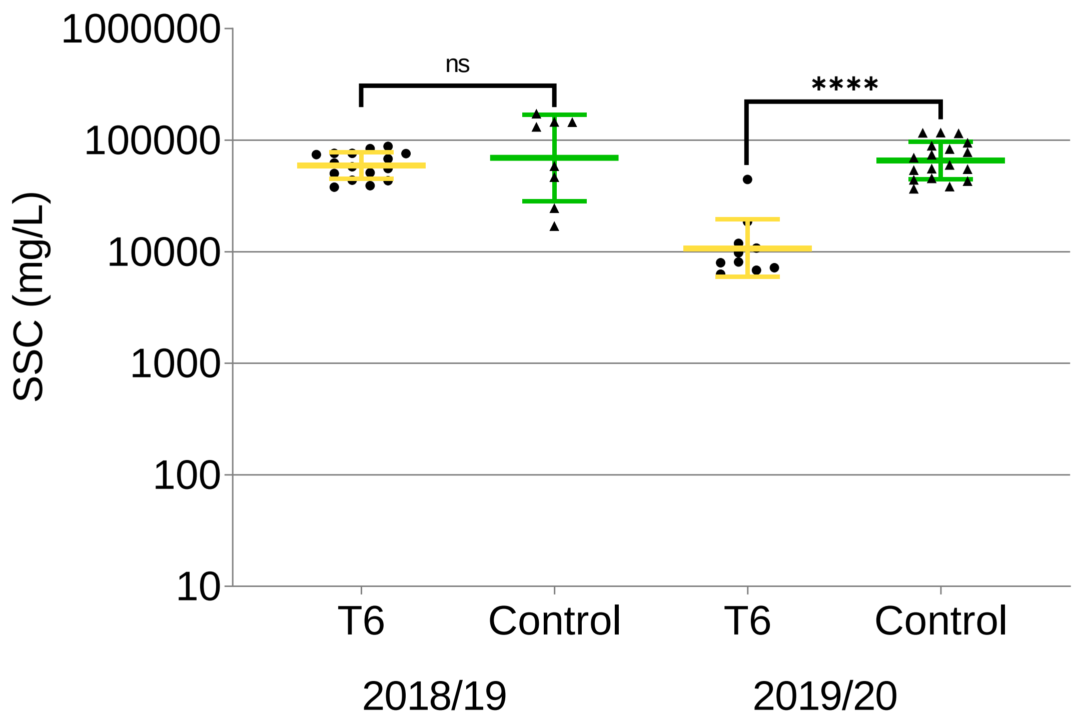


Figure 69. Geometric mean (long horizontal bars) and standard deviation factor (T bars) of sample SSCs (black markers) collected from Treatment-6 (yellow) and Control (Green) gullies for wet seasons 2018/19 and 2019/20. Brackets represent the results of unpaired t-tests, where p < 0.0001 (****) or p < 0.05 (*).

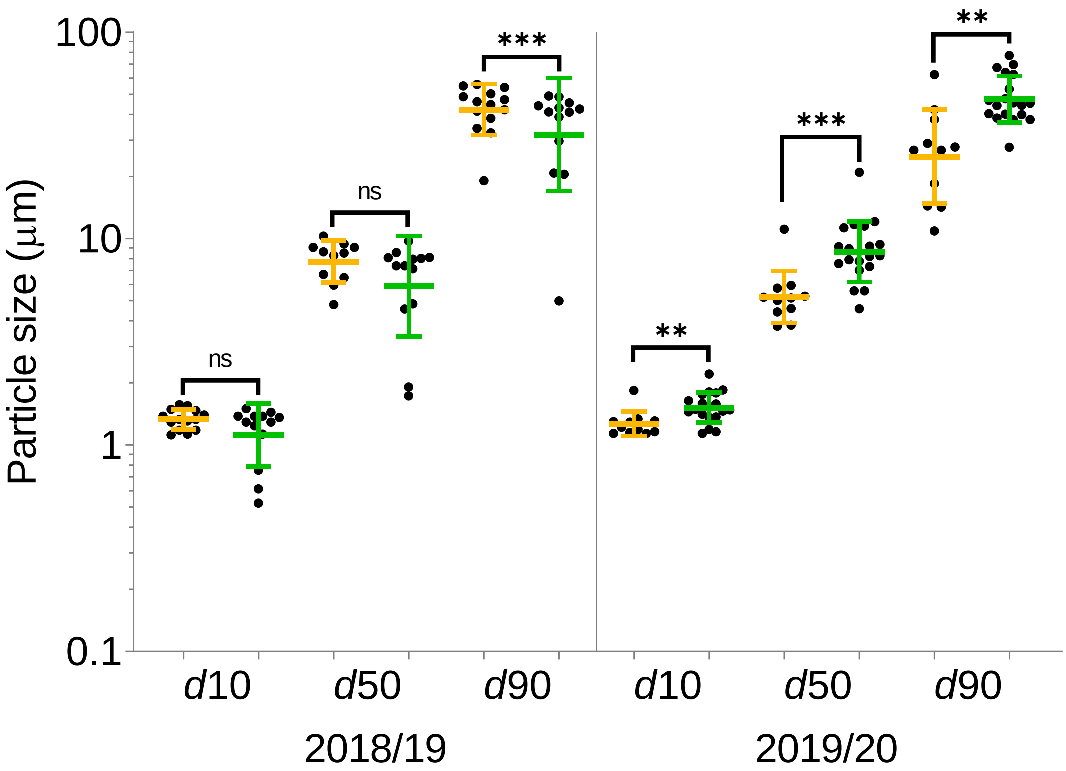


Figure 70. PSD characteristics (10th (d10), 50th (d50), and 90th (d90) of suspended sediment samples (black markers) collected from Treatment-6 (yellow) and Control (green) gullies across the 2018/19 and 2019/20 wet seasons. Horizontal bars and error bars represent geometric mean and standard deviation respectively. Brackets represent the results of unpaired t-tests, where p < 0.001 (***), p < 0.01 (**), or p > 0.05 (ns).

3.2.6 Estimation of gully suspended sediment yield

Appropriate rainfall data (1-minute resolution rainfall totals) was only available for the 2018/19 and 2019/20 wet seasons. Thus, SSYs were only calculated for those wet seasons. The gully SSYs discussed in this section are based on a limited number of samples collected from each gully. Thus, the estimates should be considered to likely represent a slight overestimation and underestimation of sediment yield from the control and remediated gullies respectively. All of the remediated gullies had significantly lower SSYs compared to baseline (sediment yields for T3, T4, and T6 2018/19 wet season) and control gully SSYs (2018-2020). There was very little difference between the total fine suspended sediment yield (i.e., clay and silt (<20 µm)) and the total sediment yield. This was expected as the baseline and control gully samples contained mostly fine sediment (*d*90 < 60 µm). Comparison of the SSY from each gully, normalised for gully catchment area, indicate that the remediation measures applied at gullies T1, T3, and T4 all had similar effectiveness in reducing suspended sediment export to less than 15 t/ha for both wet seasons. Comparatively, the erosion control measures applied to gully T6 appear to be less effective than those used at gullies T1, T3, and T4 (Figure 71).

The rainfall totals, and subsequent water discharge volumes, for the 2018/19 and 2019/20 wet seasons were significantly different from one another. The 2018/19 wet season rainfall total was much higher than average. Whereas the 2019/20 wet season rainfall total was much lower than average. Thus, comparing the total sediment yields from one year to the next can be misleading. For example, the Control gully suspended sediment yield for the 2018/19 wet season was greater than the 2019/20 wet season yield by a factor of 2.9. This difference in yield can be attributed to the dramatic difference in discharge from the gully over the two-year period. Comparison of gully total suspended sediment yield per cubic metre of water discharged nullifies the effect of gully discharge variance between the two wet seasons. When these sediment yields are compared it is apparent that all of the gullies have relatively consistent sediment loads, per cubic metre of discharge, during both wet seasons, except for gully T6. These data also indicate that the gully T1 had the lowest sediment yield (<0.0005 t/m^3), followed by T4 (<0.0009 t/m^3), T3 (<0.0026 t/m^3), T6 (<0.01 t/m^3) *cf* control (<0.07 t/m^3) (Figure 72).

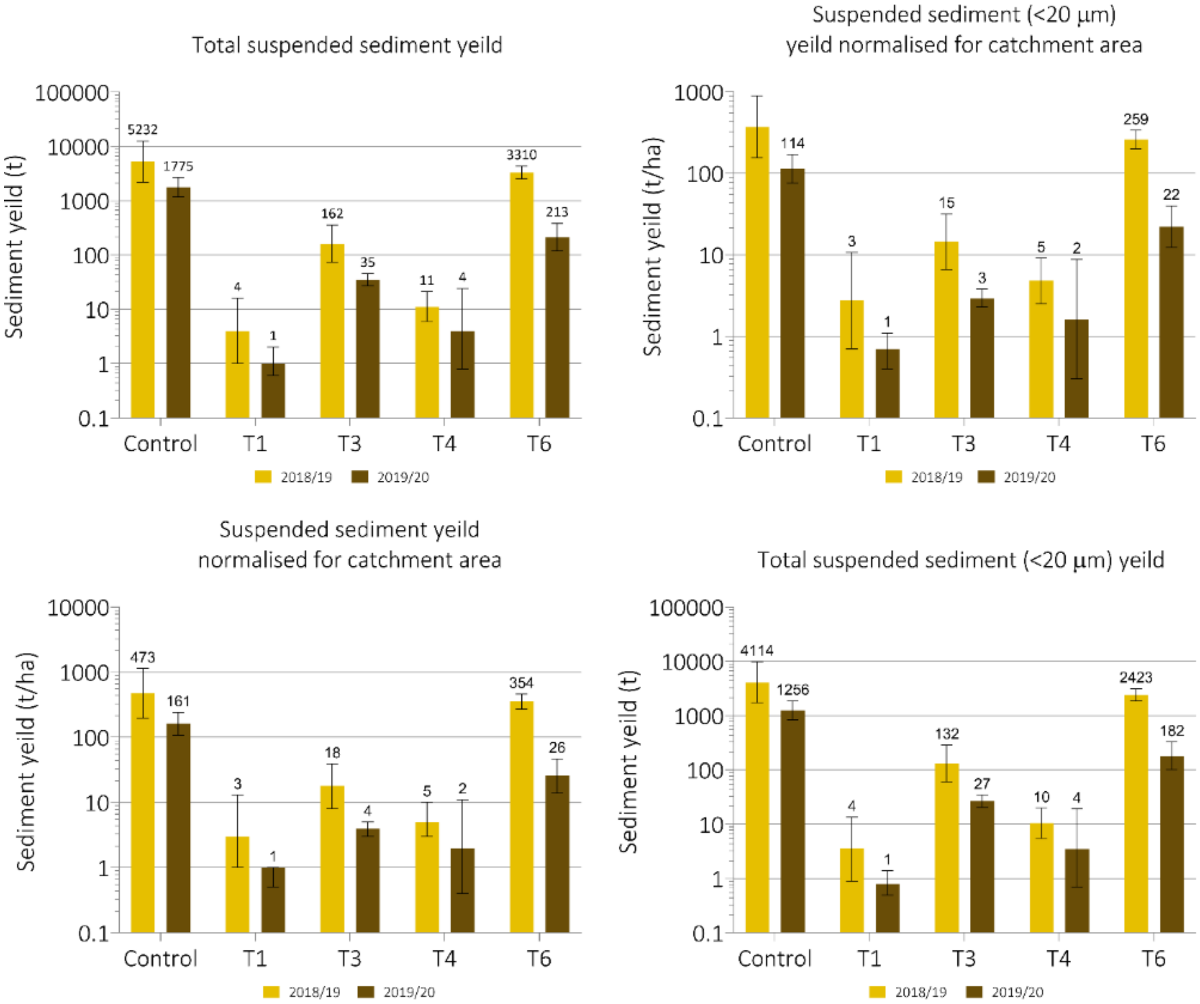


Figure 71. Total Suspended sediment yield (LHS) and < 20µm suspended sediment yield for the four treatment gullies with sufficient data and the control gully for the water years 2018/19 and 2019/20. Top graphs are total annual yield, and bottom graphs are normalised to catchment area.

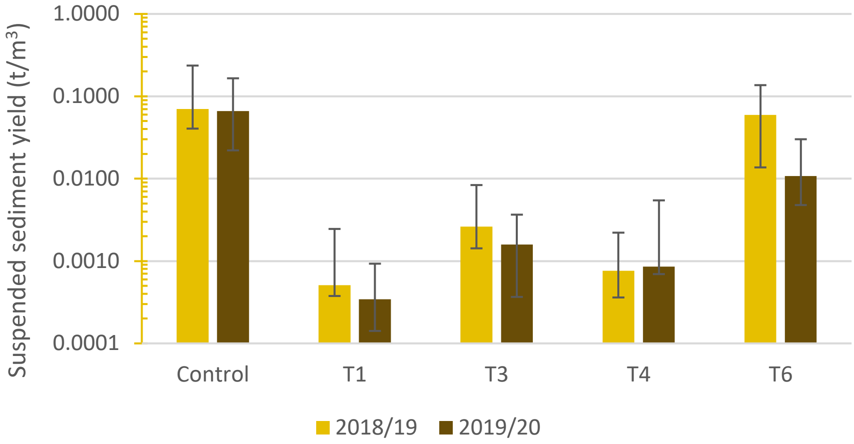


Figure 72. Suspended sediment yield from the control and treatment gullies for the water years 2018/19 and 2019/20 normalised to water yield.

3.2.7 Summary of lidar DoD Changes

Lidar change detection data for each of the treatment areas between 2017 and May 2020 are shown in Figure 73 - Figure 77. Note lidar DoD data at this timescale is close to the limit of detection particularly due to the fact that the surface treatments using mulch are not penetrated by the lidar. Lidar change detection of these treatments is only useful for detecting the appearance of rills and/or new gully incisions. Subtle changes are simply noise associated with reaching the limits of detection of the data, and the fact that the surface mulch treatments do not represent the ground surface, and so subtle changes detected between years likely represent the settling of the mulch, rather than surface erosion. The DoD data does, however, shows very clearly the cut and fill that was undertaken during the gully remediation process, as well as enabling the determination of pre-treatment baseline gully erosion rates. The data has been processed in such a way that in gullies with surface mulch, only areas where clear rills or small gullies had formed was the erosion quantified.

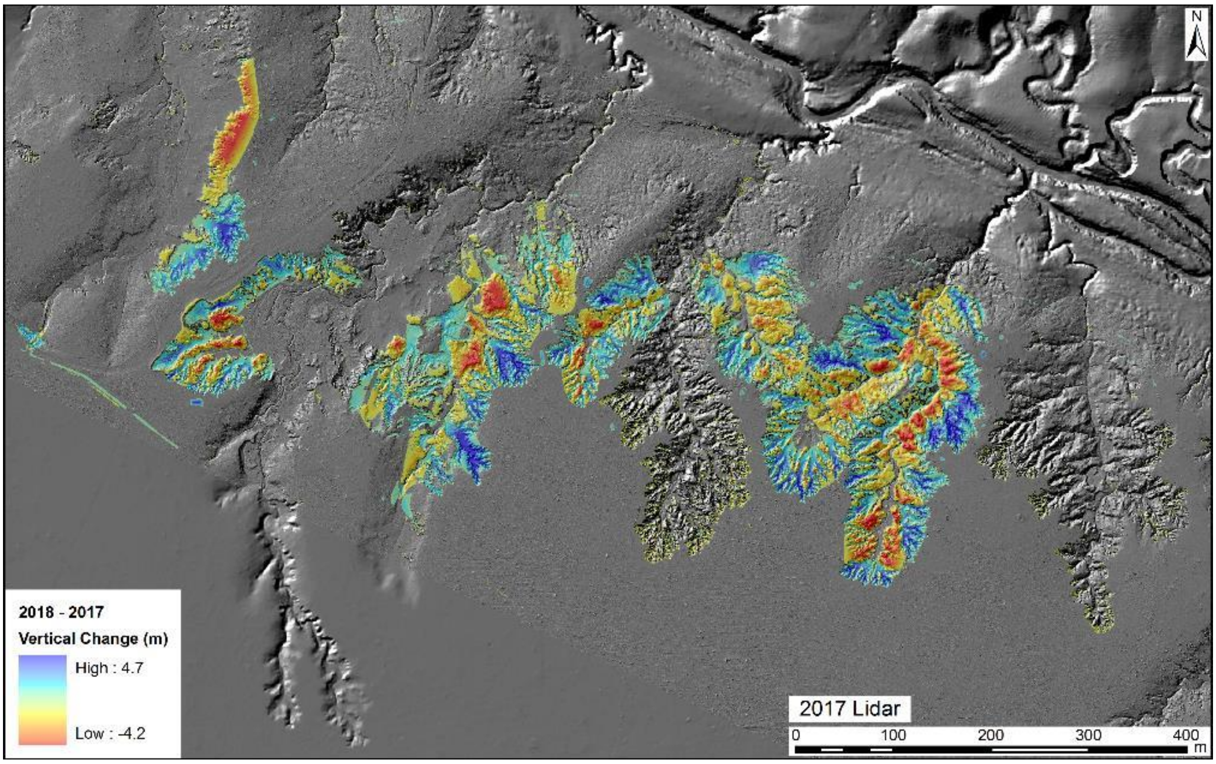


Figure 73. Baseline HR lidar survey from Sept 2017with the DoD changes from Sept 2017 to 2018 superimposed.

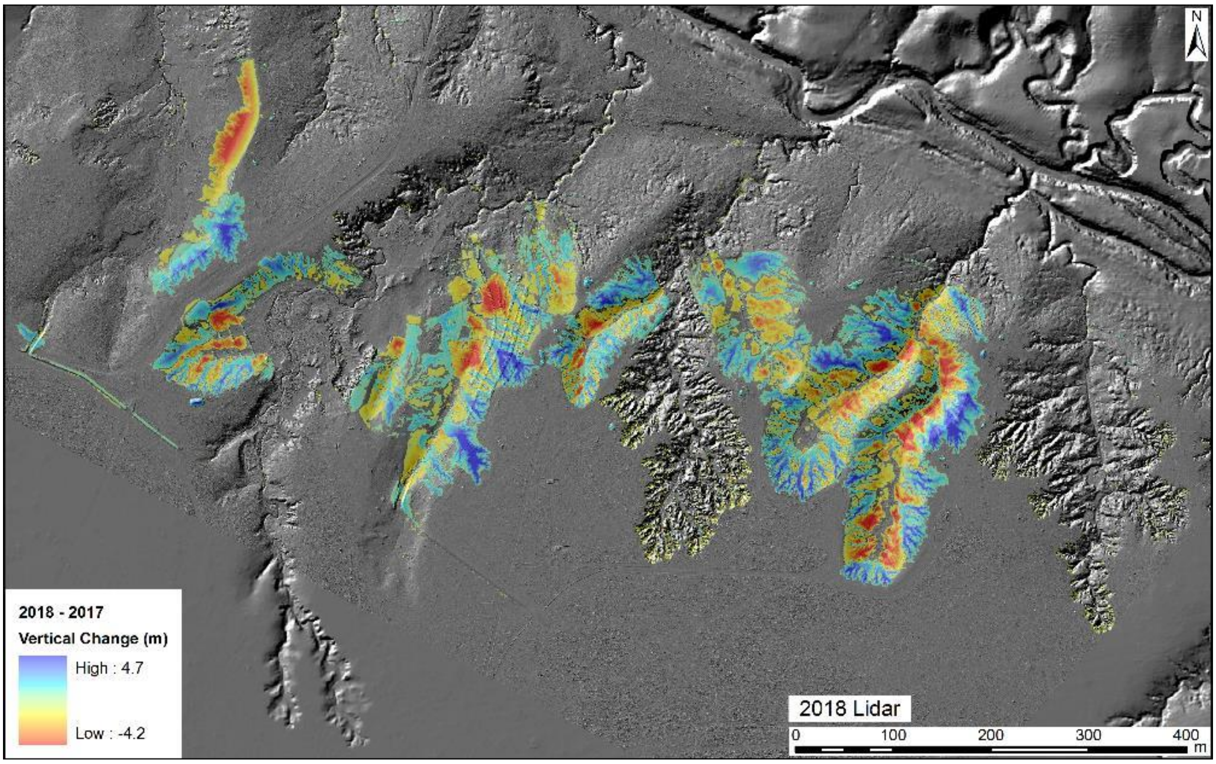


Figure 74. 2018 HR aerial lidar with the DoD between Sept 2017 and 2018 superimposed to highlight the areas of cut (reds/yellows) and fill (blues). Also shown are the erosion that occurred over the wet season in the untreated gullies.

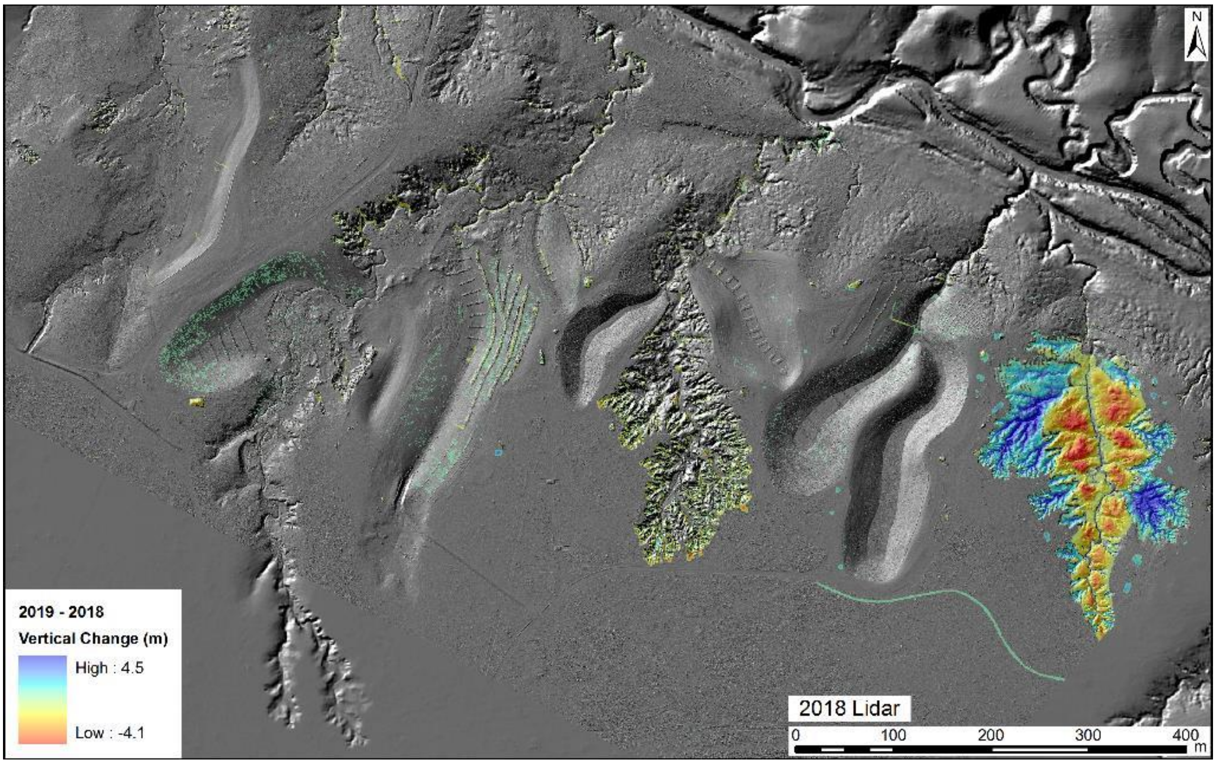


Figure 75. 2018 HR aerial lidar with the DoD between Sept 2018 &2019 superimposed to highlight the areas of cut (reds/yellows) and fill (blues). Also shown are the erosion that occurred over the wet season in the untreated gullies.

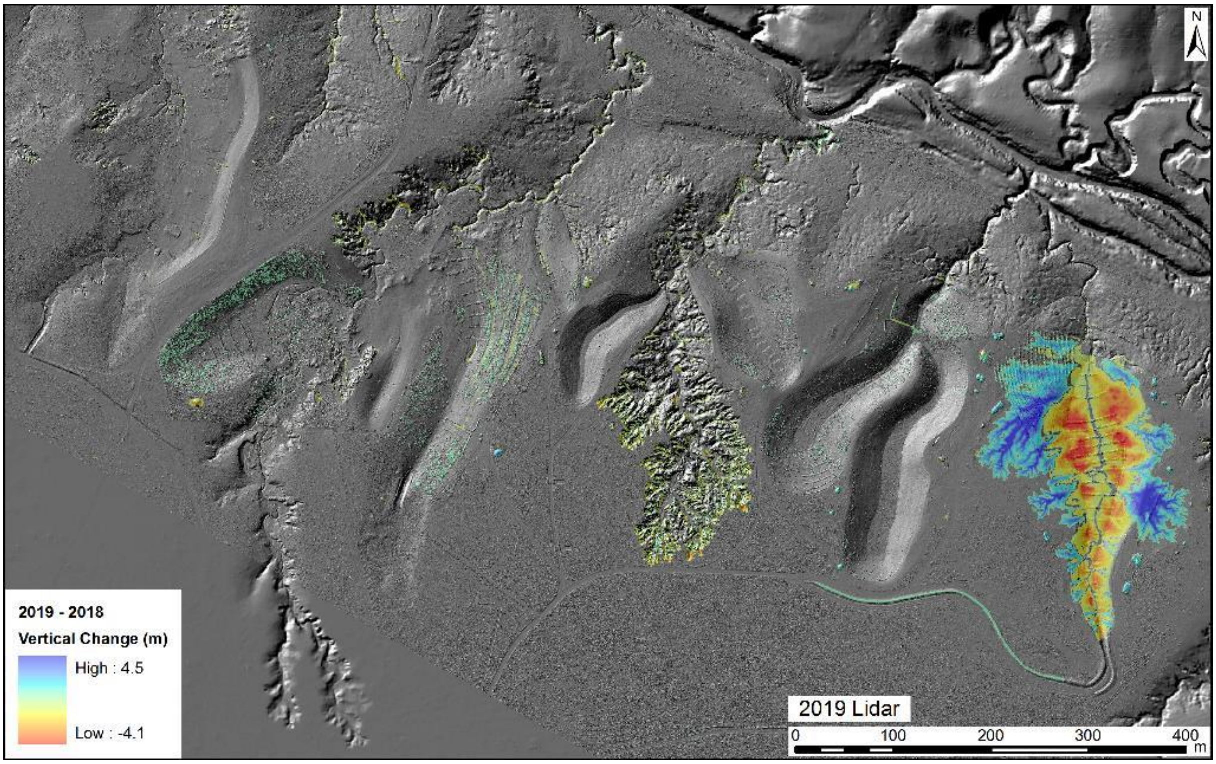


Figure 76. 2019 HR aerial lidar with the DoD between Sept 2018 and Sept 2019 superimposed to highlight the areas of cut (reds/yellows) and fill (blues). Also shown are the erosion that occurred over the wet season in the control gully.

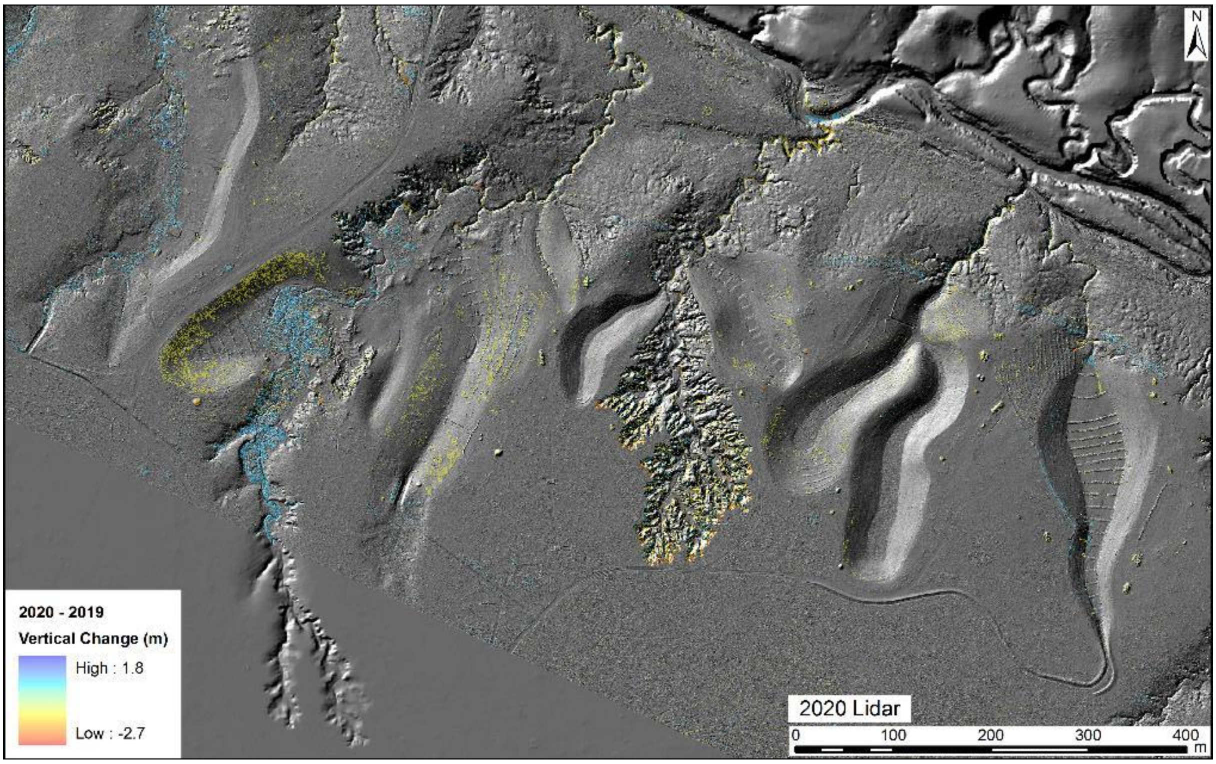


Figure 77. 2020 HR aerial lidar with the DoD between Sept 2019 & May 2020 superimposed to highlight the areas of erosion that occurred over the wet season in the control gully.

3.2.8 Remediation Effectiveness Ratios - Strathalbyn

The remediation effectiveness for each of the treated gullies is calculated using equations 1 and 2 based on the before and after treatment and the control vs treatment (impact) lidar DoD data and water quality monitoring data. These results are also presented in Table 33 and Table 34 for the 2018/19 and 2019/20 wet seasons. For each year the CI comparisons use an adjusted control yield to account for the variation in baseline yield at the outset, as outlined in Table 32, ensuring the that control/impact comparisons are as unbiased as possible. The lidar DoD for each year is also adjusted for annual (water year) rainfall across each DoD comparison. The average RER using al methods across all treatments for the whole site is 98% and 97% across the 2018/19 and 2019/20 wet seasons respectively. The variation between the two years is likely explained by the measurement error within all monitoring techniques.

Table 32. Summary table showing the lidar derived baseline erosion rates for each treatment gully in terms of total annual load (t), specific yield (t/ha), and specific yield per mm of incident rainfall recorded on site. The final column shows the ratio of the specific yield normalised to rainfall relative to the control (to normalise the variation in baseline yields between each site).

May 2018 - Sept 2017 (baseline erosion rates)						annual RF (mm)	402		
Treatment	Area_ha	Deposition m	Erosion m	Net	Volume m^3	t	t/ha	t/ha/mm	baseline ratio cf control
Control (T1 - 8)	2.75	6168	-76096	-69928	-699	1168	424	1.05	100%
RT 4 I (bf baseline)	0.54	137	-4672	-4534	-45	76	140	0.35	33%
RT 4 II (bf baseline	0.48	17	-120	-103	-1	2	4	0.01	1%
RT 4 III (bf baseline)	0.25	17	-455	-438	-4	7	29	0.07	7%
Site A1	1.66	576	-3369	-2792	-28	47	28	0.07	7%
Treatment 1	Earth works affected lidar (used mean of cntrl,T2, 3, 6,7, 8a, 8b)					142	194	0.48	46%
Treatment 2	1.29	515	-5260	-4746	-47	79	62	0.15	15%
Treatment 3	0.75	1389	-19798	-18408	-184	307	408	1.01	96%
Treatment 3-4 Ext	Earth works affected lidar (used mean of cntrl,T2, 3, 6,7, 8a, 8b)					209	194	0.48	46%
Treatment 4	Earth works affected lidar (used mean of cntrl,T2, 3, 6,7, 8a, 8b)					376	194	0.48	46%
Treatment 6 (bf baseline)	3.90	2304	-27171	-24867	-249	415	107	0.27	25%
Treatment 7	1.51	1656	-12325	-10669	-107	178	118	0.29	28%
Treatment 8a	2.41	2829	-26108	-23279	-233	389	161	0.40	38%
Treatment 8b	0.53	228	-2774	-2545	-25	43	81	0.20	19%
	16	**15837**	**-178147**	**-162310**	**-1623**	**3437**	**214**	**0.53**	

Table 33. Summary statistics showing the DoD erosion data for the various treatments from Sept 2018 to June 2019. 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 Remediation 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 baseline (t/ha/mm)	RER_{CI} (lidar)	RER_{BA} (lidar)	diff.	Effectiveness ratio SSY/m^3
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**					

Table 34. Summary statistics showing the DoD erosion data for the various treatments from Sept 2019 to 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 Remediation 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.

May 2020 - Sept 2019			annual RF (mm)= 514						
Treatment	area (ha)	t	t/ha	t/ha/mm	adjusted load cf baseline (t/ha/mm)	RER_{CI} (lidar)	RER_{BA} (lidar)	diff. (cntrl vs Bf)	Effectiveness ratio SSY/m^3
Control	2.77	815.64	294.84	0.57	0.57				
RT 4 I	0.54	3.33	6.17	0.01		94%	97%	*2%*	
RT 4 II	0.48	0.80	1.67	0.00		98%	64%	*35%*	
RT 4 III (control)	0.25	26.49	104.41	0.20		cntrl			
Site A1	1.08	34.88	32.29	0.06	0.95	-65%	10%	*75%*	
Treatment 1	0.73	0.00	0.00	0.00	0.00	100%	100%	*0%*	99%
Treatment 2	1.12	17.79	15.87	0.03	0.21	63%	80%	*17%*	
Treatment 3	1.45	2.40	1.65	0.00	0.00	99%	100%	*0%*	98%
Treatment 3-4 Ext	1.08	5.40	5.01	0.01	0.02	96%	98%	*2%*	
Treatment 4	1.93	0.00	0.00	0.00	0.00	100%	100%	*0%*	99%
Treatment 6	2.58	93.00	36.08	0.07	0.28	51%	74%	*22%*	84%
Treatment 7	1.51	0.87	0.58	0.00	0.00	99%	100%	*0%*	
Treatment 8a	2.41	12.89	5.35	0.01	0.03	95%	97%	*2%*	
Treatment 8b	0.54	11.30	21.09	0.04	0.21	63%	80%	*17%*	
totals	**18.46**	**1024.79**							
	all treatment average		**7.0**	**0.014**		**98%**			
	all control average		**278.8**	**0.542**					

3.2.9 Bioavailable nutrient monitoring

The data presented here only cover two wet seasons 2018/19 and 2019/20 and represent short-term effects of remediation techniques on water quality and should be understood as such. These results are provided as a summary of the ongoing investigation conducted by the Queensland Department of Environment and Science (Garzon Garcia et al., 2020). Access restrictions meant fewer samples than planned were collected from the control and remediated gullies at Strathalbyn. Further monitoring is required for the evaluation of the longer-term effects of gully remediation on water quality. However, initial results provide insight to the nutrient processes that occur following remediation.

Nutrients (nitrogen and phosphorus) and organic carbon were measured at high concentrations compared to other ephemerally water ways in the region (e.g., concentrations were often >1 mg/L) (Davis et al., 2017). The bulk of nutrients and carbon were transported in particulate form rather than being dissolved (Figure 78). Comparison of bioavailable nutrient sample concentration data collected from the remediated and control gullies indicate the remediation activities have significantly lowered particulate nutrient concentrations. In contrast, dissolved nutrient sample data collected from the remediated gullies were either not significantly different or notably higher compared sample data collected from the Control gully. The reduction in particulate nutrients was an expected result of the soil erosion controls significantly reducing the amount of suspended sediment flowing through the remediated gullies. The stable and increased dissolved nutrient concentrations appears to be a by-product of the erosion control measures applied as part of the gully remediation process (i.e., mixing and compaction of soil and addition of soil enhancements such as, mulch, compost, and gypsum). This possibility is further supported by preliminary PASS sample data (n=2) collected from the gully catchments which had very low particulate and dissolved nutrient concentrations compared to the samples collected from the gullies.

Evaluation of the relationship between nutrients and suspended sediment concentration indicate particulate nutrients have a moderate to strong relationship with suspended sediment in the Control gully (Figure 79). Whereas this relationship is not evident in the sample data collected from the remediated gullies. Dissolved nutrients appear to have no relationship with suspended sediment in the control, except for phosphorus which as a weak correlation with SSC. Dissolved nutrient sample data from remediated gullies also show no obvious trends except for the dramatic difference in sample concentration range and correlation slope between SSC and dissolved organic carbon. This influx of organic carbon, likely sourced from the added mulch and compost in the gully remediation structures, may be a factor influencing the biogeochemistry interactions within the gully system during flow events. Further investigation regarding this issue is currently underway.

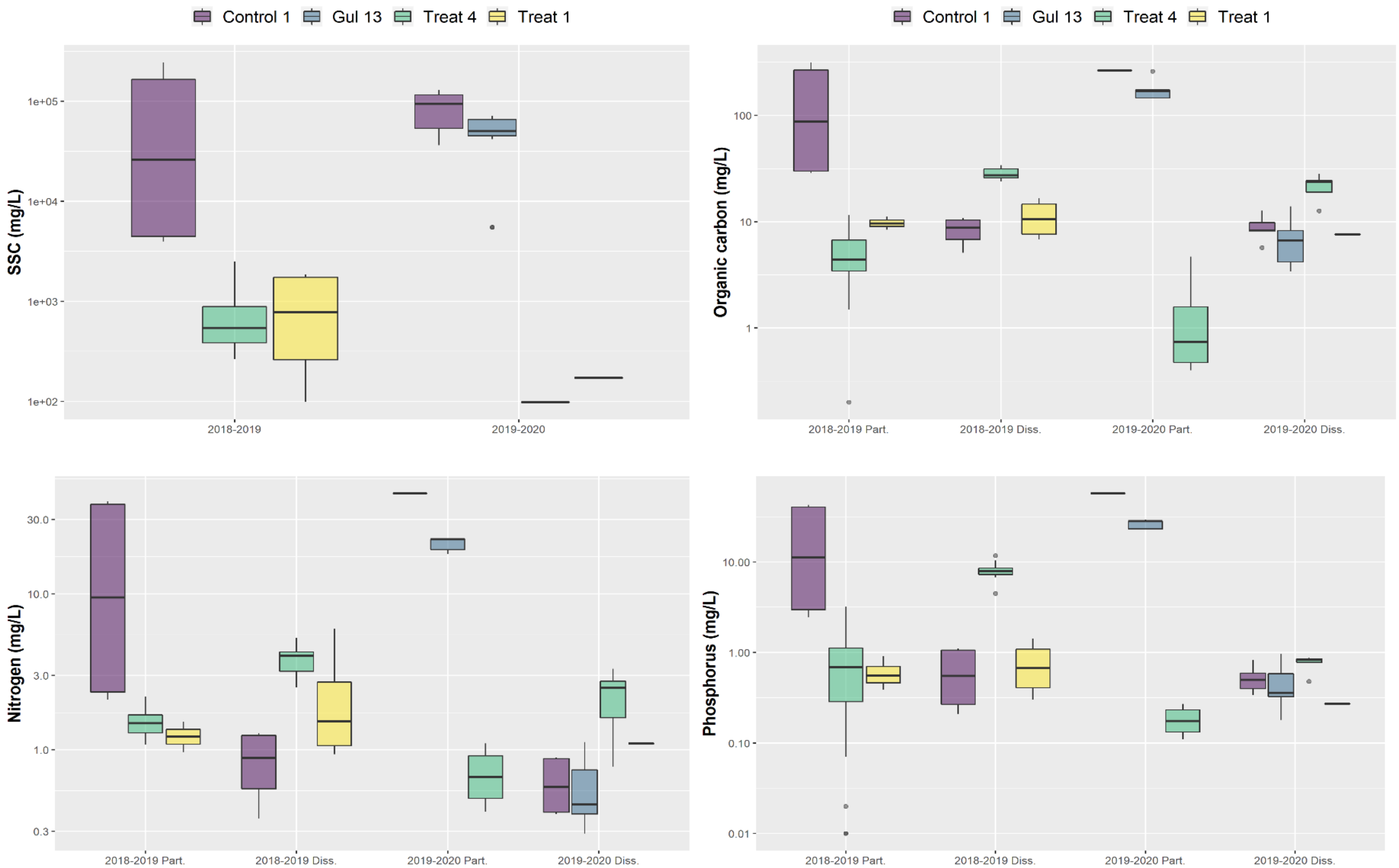


Figure 78. SSC and nutrient concentrations of samples collected during flow events in the 2018/19 and 2019/20 wet seasons. Box plots represent the minimum, maximum, 25th and 75th percentiles, median (horizontal line in box), and mean (cross). Note, these figures are adapted from Garzon-Garcia et al., (2020). Thus, concentration data for Gully-13 should be disregarded as it is not related to this Project.

Figure 79. Relationships between SSC, organic carbon, and nutrient concentrations in the control (red) and remediated gullies T1 (grey) and T4 (yellow) from samples collected during multiple flow events for wet seasons 2018/19 and 2019/20

3.3 Comparison of TSS and SSC measurements

TSS and SSC analyses were performed on collected samples from both Crocodile Station and Strathalbyn station sites to compare and evaluate if TSS could be used instead of SSC. The presence of sand in a sample can negatively impact the accuracy of TSS measurements (Gray et al., 2000). Our data for the gully sediment studied here showed that, when sand was present (23% by mass), the TSS method tended to underestimate the mass of sediment in the sample by 14 ± 8%, whereas the SSC method underestimated the mass by only 0.2 ± 2%. In contrast, when sand was removed from the sample (i.e. sieved to < 63 µm), the TSS method underestimated the SSC by only 1 ± 5%, which compared well to the SSC method, which only underestimated the sample mass by 2.7 ± 2%. There was little variation in error with increasing sample concentration for both sediment types (Table 35). Based on these results it could be argued that TSS might be a viable analytical method for gullies with little to no suspended sand during flow events. However, the rapid changes to PSD associated with active gully erosion, and the low likelihood of an alluvial sediment without any sand, means that SSC is the more reliable approach for measuring the concentration of suspended sediment in gully systems (Shellberg et al., 2013a). Also, comparison of TSS and SSC analyses of suspended sediment samples collected, from Strathalbyn during the 2017/18 wet season, indicated the TSS method generated variable results compared to the SSC method (i.e. SSC and TSS measurements differed on average by 20% ± 40%) (Appendix 0). This example further demonstrates how the TSS method can be unreliable with samples consisting of mostly silt and clay and high SSCs.

Table 35. Comparison of measured SSC and TSS compared to mass of sediment added, with different particle size distributions.

<63			***<2000***		
Sediment mass added (mg)	***SSC (mg L^{-1})***	***TSS (mg L^{-1})***	***Sediment mass added (g)***	***SSC (mg L^{-1})***	***TSS (mg L^{-1})***
107 (± 8)	76 (± 21)*	76 (± 21)*	120 (± 8)	105 (± 2)*	105 (± 2)*
5,133 (± 6)	539 (± 14)	469 (± 13)	501 (± 5)	570 (± 11)	472 (± 44)
1,007 (± 4)	1,077 (± 37)	993 (± 7)	1,010 (± 10)	1,132 (± 6)	782 (± 150)
5,022 (± 3)	5,150 (± 11)	5090 (± 102)	5,012 (± 9)	5,260 (± 17)	4,194 (± 175)
10,040 (± 28)	10,268 (± 33)	10,238.333 (± 135)	10,035 (± 27)	10,195 (± 281)	8,720 (± 530)
15,047 (± 19)	15,268 (± 102)	15,562 (± 449)	15,035 (± 31)	15,305 (± 36)	12,810 (± 539)
20,027 (± 23)	20,054 (± 28.)	20,648 (± 291)	20,021 (± 22)	20,187 (± 2)	17,930 (± 1074)

* = TSS and SSC are considered the same whole sample analysis.

4.0 COST-EFFECTIVENESS OF GULLY REMIDIATION

4.1 Crocodile Station

4.1.1 Gully-specific costs of remediation

Total upfront costs incurred in remediating four gullies (Treatments 2.234, 0.1, 0.2 and 1.1) on Crocodile Station is just under $182,000, split between on-ground construction costs (87%) and project management cost (13%). A large proportion of the on-ground construction costs is for the rock and machinery at $114,458. The design cost and construction supervision are $20,000 each. Table 36 summarises the gully-specific costs of remediation.

Table 36. Gully-specific remediation costs for Crocodile Station. All costs in 2019 Australian dollars.

Costs	Gully treatment site			
	2.234	**0.1**	**0.2**	**1.1**
On-ground construction				
Rock & machinery	54,298	24,064	12,032	24,064
Gypsum & geotextile	2,000	800	400	800
Design	10,000	4,000	2,000	4,000
Construction supervision etc.	10,000	4,000	2,000	4,000
Project Management	11,600	4,640	2,320	4,640
Total	87,898	37,504	18,752	37,504

4.1.2 Treatment effectiveness

The baseline fine sediment yield at EOG, treatment area, treatment effectiveness ratios and the corresponding fine sediment load reduction at EOG are reported in Table 34. Treatment effectiveness in the first year post treatment suffers from early arrival of rainfall before remediation works could be completed, hence, the negative treatment effectiveness ratios for Treatments 0.2 and 1.1. However, during the second year post treatment, treatment effectiveness ratios return to positive values as remediated sites stabilised. Fine sediment load reduction is therefore calculated using treatment effectiveness ratios from 2018/19. As such, cost-effectiveness calculations are only based on the second year treatment effectiveness representative of the likely ongoing remediation effectiveness.

Table 37. Baseline fine sediment yield, treatment effectiveness calculated from monitoring data in years 2017/18 and 2018/19, and fine sediment load reduction at end of gully.

Gully ID	Treatment area (ha)	Fine sediment yield (t/yr)	Treatment effectiveness 2017/18 (%)	Treatment effectiveness 2018/19 (%)	Fine sediment load reduction§ (t/yr)
Treatment 2.234	0.4	184	101	99	182
Treatment 0.1	0.1	69	7	81	56
Treatment 0.2	0.12	47	-80	94	44
Treatment 1.1	0.3	182	-236	68	124

§ Fine sediment load reduction is calculated using treatment effectiveness ratio for the year 2018/19

4.1.3 Cost-effectiveness results

Based on the gully-specific upfront costs of remediation in Table 34 and gully-specific fine sediment reductions in Table 34, the cost-effectiveness of treatment sites 2.234, 0.1, 0.2 and 1.1 over a 25-year lifetime is reported in Table 38. The 30-year lifetime is reported in Appendix 0. Cost-effectiveness ranges between $26/tonne reduction EOG and $58/tonne reduction EOG, and between $58/tonne reduction EOS and $128/tonne reduction EOS at 7% discount rate per annum over a 25 year lifetime (Table 38). Treatment 1.1 is the most cost-effective whilst Treatment 0.1 is the least cost-effective (Figure 80). Longer lifetime improves cost-effectiveness of these remediated gullies, all else equal.

Table 38. 25-year cost-effectiveness ($ per tonne of fine sediment abated) calculated using Equation 3, and cost-effectiveness ($ per tonne of fine sediment abated per year) calculated using Equation 4 with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum.

End of gully				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 2.234	25	34	42	484
Treatment 0.1	34	48	58	670
Treatment 0.2	22	30	36	425
Treatment 1.1	16	21	26	303
End of system				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 2.234	55	76	92	1075
Treatment 0.1	76	106	128	1490
Treatment 0.2	48	67	81	944
Treatment 1.1	34	48	58	673

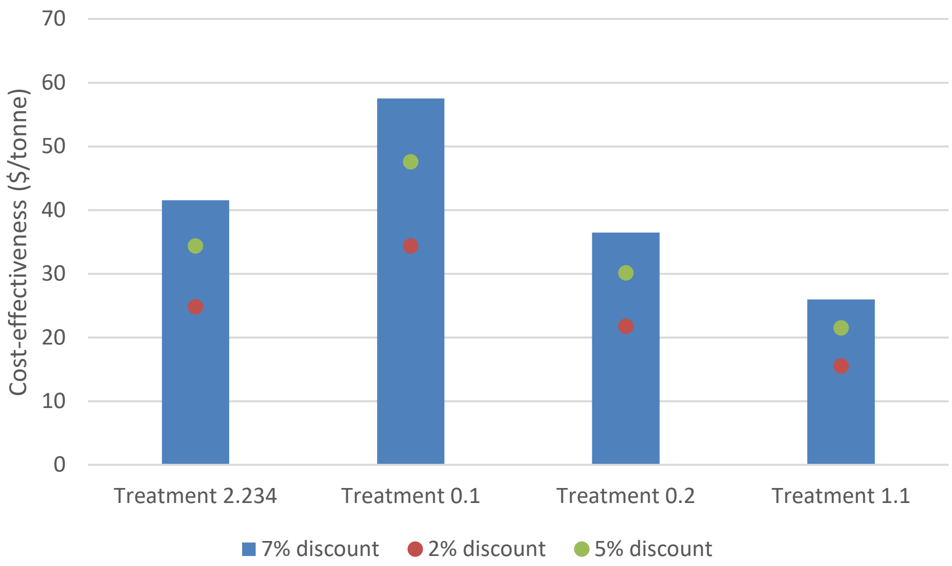


Figure 80. Cost-effectiveness over a 25-year lifetime with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum

4.2 Strathalbyn Station

4.2.1 Gully-specific costs of remediation

Upfront costs

The upfront costs to design and remediate all 10 gullies on Strathalbyn Station under the Innovative Gully Remediation Project is $2.51 million. Of this, $2.4 million was incurred for the on-ground works with the remainder of the costs going towards project planning and design ($50,000), and Lidar ($60,000). These costs are appropriately allocated to each gully to obtain the gully-specific remediation costs shown in Table 39.

As shown in Table 39, total upfront cost generally increases with the increase in treatment area (Figure 81). Treatment 5 involved construction of rock chute, diversion bund and drain to divert flows during rainfalls to the level of future Treatment 8 gully bed (Telfer, 2019). Total upfront cost for Treatment 6 is relatively inexpensive considering it being the largest area being treated as shown by the relatively low total upfront cost per hectare treated at $129,000/ha which sits below the median at $142,263. This is attributable to remediation technique being significantly different to the other treatments in that relatively low volume of rock material was used but instead involved significantly more earthworks to initially remove tunnelling followed by batter regrading to an optimal slope, compaction and spreading of topsoils obtained from within the treatment footprint (Telfer, 2019). Figure 82 shows components of gully-specific total on-ground costs and total on-ground cost per hectare of treatment area. The most substantial components of on-ground cost are earthworks and rock. The rock cost varies substantially between treatments reflecting different treatment approaches.

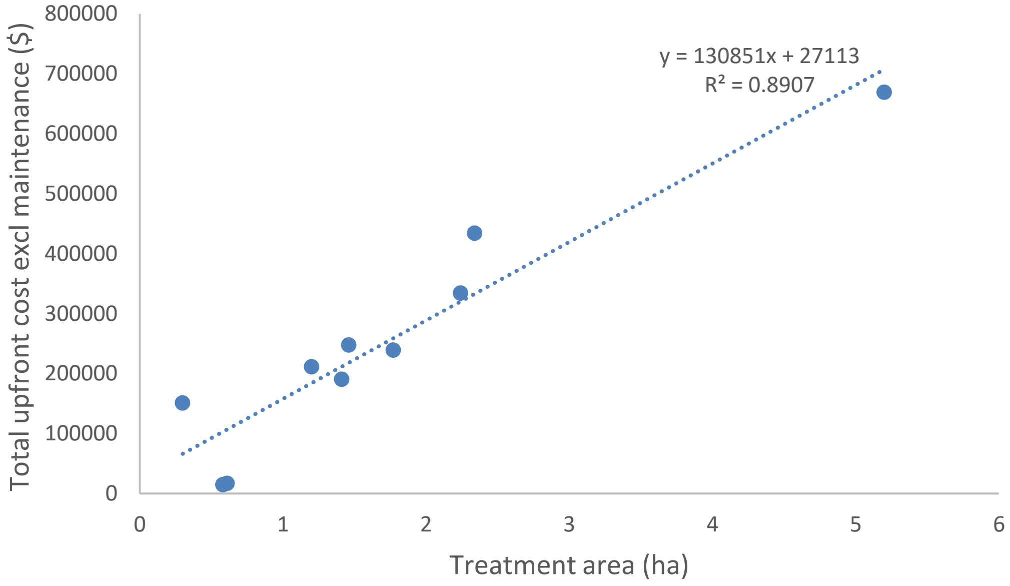


Figure 81. Total upfront cost as a function of treatment area. Total upfront costs include costs of all on-ground works, lidar, and project planning and design.

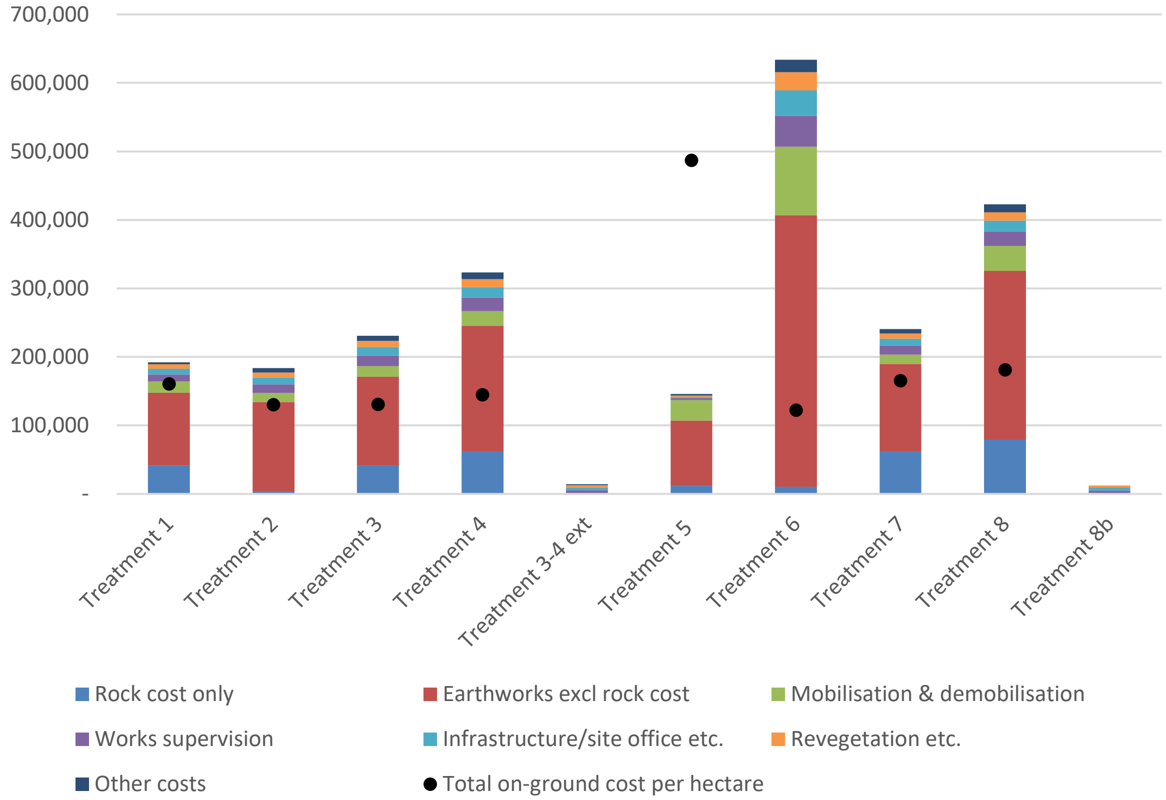


Figure 82. Components of the total on-ground cost of remediation work and total on-ground cost expressed on a per hectare basis for each treatment.

Table 39. Gully-specific remediation costs for Strathalbyn Station. All costs in 2019 Australian dollars.

Gully ID	Treatment area (ha)	Total on-ground cost ($)	Project planning & design cost ($)	Lidar cost ($)	Total upfront cost ($)	Total upfront cost per ha ($/ha)
Treatment 1	1.2	192,197	3,507	16,000	211,704	176,420
Treatment 2	1.41	183,666	4,120	2,709	190,495	135,103
Treatment 3	1.77	230,893	5,172	3,401	239,466	135,292
Treatment 4	2.24	323,433	6,546	4,304	334,283	149,233
Treatment 3-4 ext	0.61	n/a	1,783	1,172	n/a	n/a
Treatment 5	0.3	146,055	877	4,000	150,931	503,104
Treatment 6	5.2	633,964	15,196	20,000	669,160	128,685
Treatment 7	1.46	240,680	4,267	2,805	247,752	169,693
Treatment 8	2.34	422,913	6,838	4,496	434,246	185,575
Treatment 8b	0.58	n/a	1,695	1,114	n/a	n/a
Total	**17.11**	**2,400,000**	**50,000**	**60,000**	**2,510,000**	**-**

Note: Total on-ground cost consists of costs of earthworks (including rock); equipment and machinery; mobilisation and demobilisation; works supervision; site survey; infrastructure (site office etc.); water; and revegetation. Lidar cost is $20,000 per year for years 2017, 2018 and 2019. Lidar cost and project planning and design cost are allocated across treatment sites according to their share of total treatment area i.e. costs are scaled by treatment area.

Maintenance cost

Maintenance cost incurred in 2018, 2019 and 2020 were $4,942, $10,095 and $18,595, respectively. The sum of this maintenance cost as a proportion of total on-ground cost of $2.4 million is very modest at approximately 1.4%. We therefore apply this proportion of 1.4% to gully-specific total on-ground cost to obtain indicative estimates of gully-specific maintenance cost, as shown in Table 40.

All treatments (except treatment 6) have been completed prior to 2018/19 wet season. Despite the 2018/19 wet season being the 6th wettest year in 120 years, these remediated gullies remained intact, requiring just minor repairs at a very modest cost. This gully remediation project demonstrates that when gullies are remediated to a high standard of treatment, the risk of failure is low. The very low subsequent maintenance cost, as shown by the maintenance cost data here, may compensate for the relatively high upfront cost associated with this standard of treatment.

Table 40. Gully-specific on-ground and maintenance costs for Strathalbyn Station. Maintenance cost is calculated as 1.4% of total on-ground cost

Gully ID	Treatment area (ha)	Total on-ground cost ($)	Maintenance cost $
Treatment 1	1.2	192,197	2,693
Treatment 2	1.41	183,666	2,574
Treatment 3	1.77	230,893	3,236
Treatment 4	2.24	323,433	4,532
Treatment 3-4 ext	0.61	n/a	197
Treatment 5	0.3	146,055	2,047
Treatment 6	5.2	633,964	8,884
Treatment 7	1.46	240,680	3,373
Treatment 8	2.34	422,913	5,926
Treatment 8b	0.58	n/a	170
Total	17.11	2,400,000	33,632

4.2.2 Treatment effectiveness

The baseline fine sediment yield, treatment effectiveness ratios derived from monitoring data and the corresponding fine sediment load reduction at EOG and EOS are reported in Table 41 for treatments 1, 3, 4 and 6. For completeness, we also report fine sediment load reduction for Treatments 2, 3-4 ext., 7, 8a and 8b using the same baseline fine sediment yield but applying treatment effectiveness ratios derived from repeat high resolution airborne lidar change detection data between one or two years prior to treatment and post treatment in years 2018/19 and 2019/20 (i.e. based on the BACI method). The baseline fine sediment yield, treatment effectiveness ratios and fine sediment load reduction at EOG and EOS for Treatments 2, 3-4 ext., 7, 8a and 8b are shown in Table 42.

Table 41. Baseline fine sediment yield, treatment effectiveness derived from monitoring data and fine sediment load reduction at end of gully (EOG) and at end of system (EOS), for Treatments 1, 3, 4 and 6.

End of gully			
Gully ID	Fine sediment yield (t/year)	Treatment effectiveness (%)	Fine sediment load reduction (t/year)
Treatment 1	301 ± 45	99.5	300 ± 45
Treatment 3	521 ± 170	97.6	509 ± 166
Treatment 4	660 ± 213	98.7	651 ± 210
Treatment 6	862 ± 255	83.8	722 ± 214
End of system			
Gully ID	Fine sediment yield (t/year)	Treatment effectiveness (%)	Fine sediment load reduction (t/year)
Treatment 1	283 ± 42	99.5	282 ± 42
Treatment 3	490 ± 160	97.6	478 ± 156
Treatment 4	620 ± 200	98.7	612 ± 197
Treatment 6	810 ± 240	83.8	679 ± 201

Table 42. Baseline fine sediment yield, treatment effectiveness and fine sediment load reduction at end of gully (EOG) and at end of system (EOS) for Treatments 2, 3-4 ext., 7, 8a and 8b. Treatment effectiveness ratios represent the average of the four estimates from BACI data over two years post treatment, with the minimum and maximum values shown in brackets.

End of gully			
Gully ID	Fine sediment yield (t/year)	Treatment effectiveness (%)	Fine sediment load reduction# (t/year)
Treatment 2	255 ± 102	85 (74, 93)	217 (189, 237)
Treatment 3-4 ext	104 ± 35	99 (96, 100)	103 (100, 104)
Treatment 7	457 ± 149	99 (98, 100)	453 (448, 457)
Treatment 8a	1,362 ± 202	88 (70, 98)	1,198 (953, 1,334)
Treatment 8b	605 ± 90	78 (66, 87)	472 (400, 527)
End of system			
Gully ID	Fine sediment yield (t/year)	Treatment effectiveness (%)	Fine sediment load reduction# (t/year)
Treatment 2	240 ± 96	85 (74, 93)	204 (178, 223)
Treatment 3-4 ext	98 ± 33	99 (96, 100)	97 (94, 98)
Treatment 7	430 ± 140	99 (98, 100)	426 (421, 430)
Treatment 8a	1,280 ± 190	88 (70, 98)	1,126 (896, 1254)
Treatment 8b	569 ± 85	78 (66, 87)	444 (376, 495)

Fine sediment load reduction is calculated using the mid-point value of fine sediment yield baseline. Figures in brackets represent the minimum and maximum load reductions by applying the corresponding minimum and maximum treatment effectiveness.

4.2.3 Cost-effectiveness results

Based on the gully-specific upfront costs of remediation in Table 39 and gully-specific fine sediment reductions in Table 41, the EOG cost-effectiveness of treatments 1, 3, 4 and 6 ranges between $43/tonne reduction and $85/tonne reduction at 7% discount rate per annum over a 25 year lifetime (Table 43). The lower and upper bound values of the cost-effectiveness arise from applying treatment effectiveness to the baseline fine sediment yields error margins (Table 41), thus the range on the cost-effectiveness for each treatment reflects the magnitude of the margin of errors for the baseline sediment yields. . Cost-effectiveness calculations for a 30-year lifetime using the same discount rates are presented in Appendix 0. For completeness, the EOS cost-effectiveness (CE) of treatments 2, 7 and 8a calculated using the mean treatment effectiveness ratios from Table 42 are shown in Figure 83. Cost-effectiveness for treatments 3-4 ext and 8b could not be calculated because earthworks and rock costs were not allocated to these treatments in the data provided for analysis.

Looking across all treatments in Figure 83, treatment 8a is the most cost-effective at $31/tonne, followed by treatments 3 and 4, whilst treatment 6 is the least cost-effective at $80/tonne, using a 7% real discount rate per annum over 25 years. Cost-effectiveness figures are dependent on the choice of discount rates used. While a 7% discount rate is commonly considered for cost-effectiveness calculations, the 2% and 5% discount rates illustrate the sensitivities of the cost-effectiveness results to variations in the discount rate. Under a 2% discount rate per annum, over a 25 year lifetime the remediation cost-effectiveness is ~40% lower than that at a 7% discount rate, ranging from $18-48/tonne (Figure 83).

Figure 84 shows the mean, best and worst cost-effectiveness in $/tonne (i.e. in Currency 1) for the same set of treatment sites and discount rate (7%) but also including a 30-year lifespan. Remediated gullies that have longer lifetimes will deliver better cost-effectiveness, all else equal. However, as the assumed upfront costs are the same and maintenance costs are likely to occur in initial post-treatment years, the improvement in cost-effectiveness is only modest when considering a 30-year lifespan (Figure 84). When assumed project lifespan is 30 years and no additional ongoing maintenance costs, at 7% discount rate the cost-effectiveness metrics at EOG are $57/tonne, $38/tonne, $41/tonne and $75/tonne for Treatments 1, 3, 4 and 6, respectively.

Cost-effectiveness may be considered on a per hectare basis, normalising the CE to treatment area to reflect any potential economies of scale in treatment. Under such calculations, all CE values (in $/t/ha) are lower than the total CE of the gully treatment (Figure 85). In some circumstances, there is a near inversion of results, as treatment 6 is adjusted from being the least cost-effective to the most cost effective at $16/t/ha. While other treatments are presented as more cost effective, proportionally and comparatively they are the same.

Variations in the CE values are small for Treatment 7. Changing the CE unit from $/tonne (Currency 1) to $/tonne per year (Currency 2) increases the calculated value by more than a factor of 10 as shown in Figure 86. Cost-effectiveness expressed in Currency 2 (Table 43 and Figure 86) does not require specific assumptions about project lifetime and discount rate, however, the use of this metric is not appropriate when comparing gully remediations that have different expected lifetimes and different upfront cost and future cost portfolios.

Table 43. 25-year cost-effectiveness ($ per tonne of fine sediment abated) calculated using Equation 3, and cost-effectiveness ($ per tonne of fine sediment abated per year) calculated using Equation 4 with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum. Figures in brackets represent the lower and upper bound cost-effectiveness values from application of baseline sediment yield error margins (Table 41)

End of gully				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 1	36 (32,43)	50 (44,59)	60 (53,71)	706 (615,830)
Treatment 3	24 (18,36)	33 (25.18,49.59)	40 (30,60)	471 (355,699)
Treatment 4	26 (20,39)	36 (28,54)	44 (33,65)	513 (388,758)
Treatment 6	46 (37,67)	66 (51,93)	80 (61,113)	927 (715,1317)
End of system				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 1	39 (34,45)	53 (46,63)	65 (56,76)	75752 (655,883)
Treatment 3	26 (19,38)	36 (27,53)	43 (32,64)	501 (377,744)
Treatment 4	28 (21,41)	39 (29,57)	47 (35,69)	546 (413,806)
Treatment 6	51 (39,72)	69.95 (54,99)	85 (65,120)	986 (761,1400)

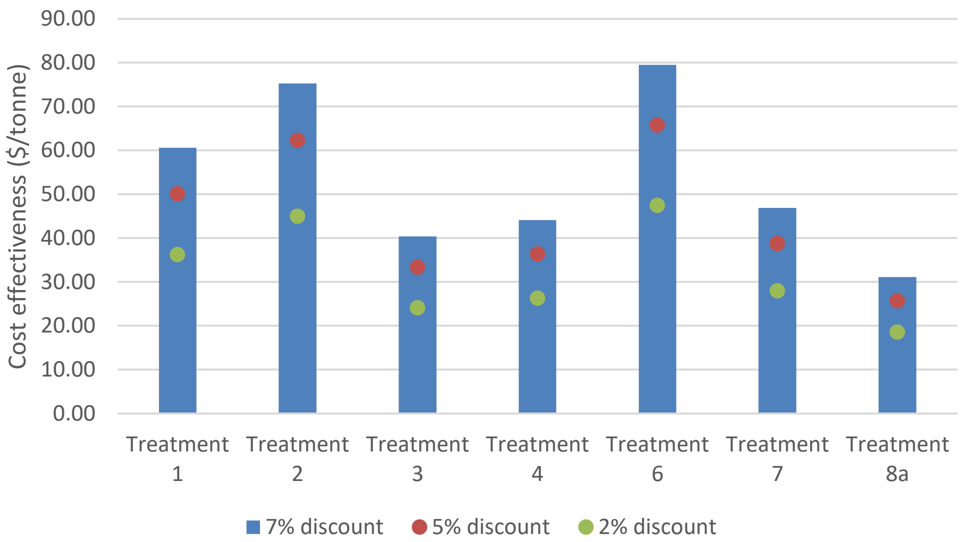


Figure 83. The EOG cost-effectiveness calculated at different discount rates over 25 years for all treatments, calculated via Equation 3 (CE Currency 1), and evaluated at the mean treatment effectiveness.

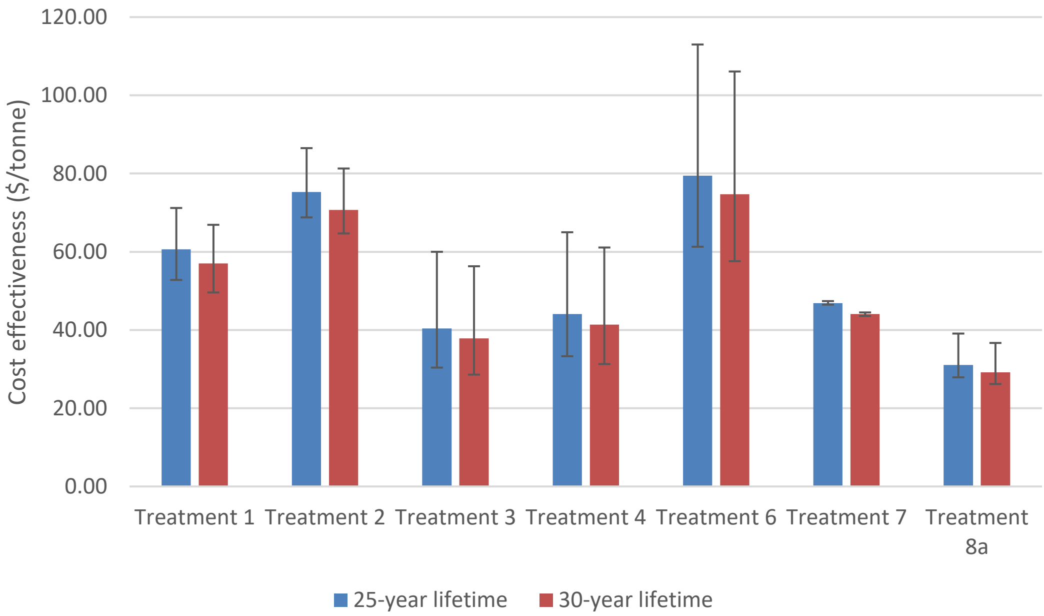


Figure 84. Comparison of EOG cost effectiveness at 7% discount rate over 25 years and 30 years. The lower and upper ends of error bars indicate the best and worst cost-effectiveness adjusting for baseline sediment yield (T1, T3, T4 and T6) and treatment effectiveness (T2, T7 and T8a).

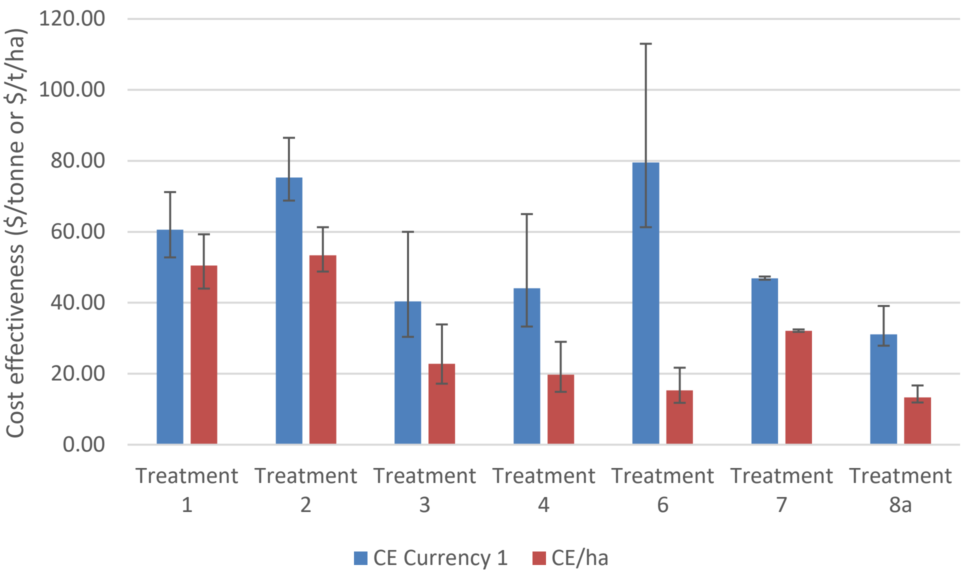


Figure 85. A comparison of cost-effectiveness when calculated at the gully scale and then normalised by gully area. Error bars calculated from baseline sediment yields for Treatments 1,3,4 & 6 and treatment effectiveness ratios for Treatments 2, 7 & 8a

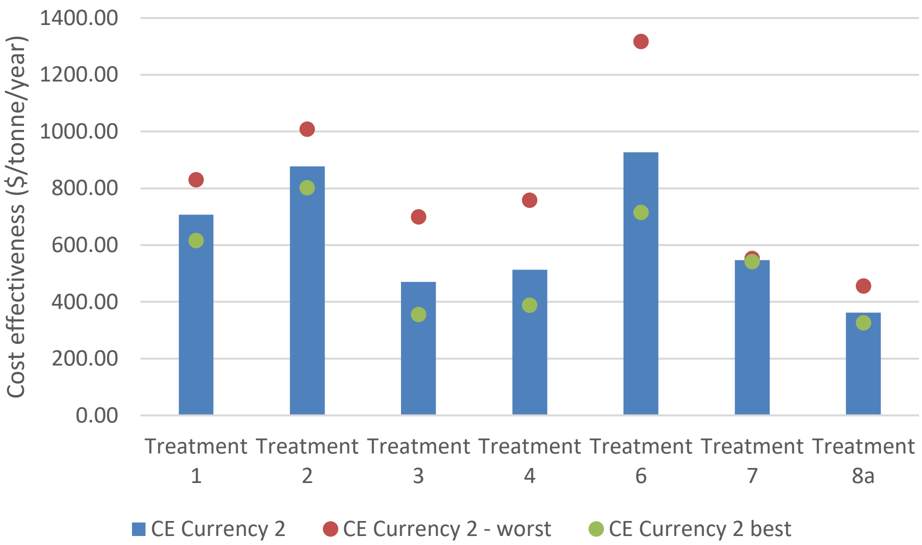


Figure 86. The cost-effectiveness at EOG calculated via Equation 4 (Currency 2) and evaluated at the mean treatment effectiveness ratios. Best and worst CE are calculated from baseline sediment yields for Treatments 1,3,4 & 6 and treatment effectiveness ratios for Treatments 2, 7 & 8a

5.0 DISCUSSION

When this project began four years ago it is fair to say that there was considerable nervousness amongst policy makers and land managers regarding the risks associated with large scale alluvial gully remediation, and whether it was economically feasible. Four years on, having monitored the effectiveness of some very ambitious large-scale gully remediation works (> 18 ha total treatment area), particularly those undertaken through the IGRP, we are now in a position to evaluate the efficacy and cost-effectiveness of large-scale alluvial gully remediation as a front-line strategy for improving GBRL water quality, and it's a good news story for GBR water quality. Overall, the results indicate that alluvial gullies can be remediated very effectively, to the point that they can be completely eliminated as sediment sources, provided that they are treated to the high standards outlined here. Given the dominance of alluvial gullies, in particular, as a key sediment source to the GBR, it is very clear that catchment water quality targets cannot be met without the remediation of alluvial gullies along the lines outlined in this report. It is also becoming apparent through associated gully mapping work (NESP Project 5.10) and a report recently produced for the NQDT LDC Project (Brooks et al., 2020), that catchment water quality targets can potentially be met through the remediation of several hundred alluvial gully systems of commensurate scale to those outlined in this project.

In the following discussion we return to the key research questions posed at the outset of this project.

5.1 Primary Questions

> *What is the erosion control effectiveness factor for alluvial gully remediation in different settings, using different remediation techniques, and how long does it take to achieve it (combining Q1 & 2)?*

As outlined in the introduction, current estimates of the alluvial gully remediation effectiveness (i.e. for fine suspended sediment reduction) within the Gully Toolbox second edition (Wilkinson et al., 2019) are relatively low at between 0.5 and 0.6. We can now conclude from the evidence presented in this study that these estimates are too low. Of the 16 individual gully treatments evaluated in this study, all sites except Crocodile 0.2 & Strathalbyn A1, achieved RERs of > 80% within 1 – 2 years. Indeed, all of the largest, most intensively treated gullies, achieved RERs of >95% within 1 year. Given the extreme effectiveness of the major treatments at the Strathalbyn sites (e.g. T1, 3, 4, 7, 8a) and gully 2.234 at Crocodile, which achieved a RER of >100% within one year (i.e. 100% stabilisation plus net deposition), it is difficult to provide commentary on the pros and cons of the variations in treatments between these sites as far as sediment reduction is concerned. Decisions regarding whether certain treatment approaches are adopted will likely depend on other remediation objectives (e.g. associated nutrient reductions as discussed below) and cost effectiveness (discussed below).

For the few sites that have lower RERs, some are explicable, while others will require some further investigation to explain the results. Site 0.2 at Crocodile, along with site 0.1 and 1.1, had a major issue in year one due to the fact that they were constructed late in the dry season (early November) and were caught out by early wet season (late dry season) rains. Indeed, they experienced a 60mm rainfall event during construction. The results from the first wet season at these three sites indicate that they delivered significantly more sediment than the baseline or control. The treatments were also initially implemented as “minimalist treatments” to test the limits of what one can get away with in terms of treatment intensity. The key lessons from this experience were twofold. First, do not risk undertaking gully remediation works late in the dry season, given that all it takes is a single storm to set you back several years in terms of fine sediment abatement. Secondly, the key lesson is ‘do it right the first time’. There is nothing to be gained by under designing the initial remediation works as they will require ongoing costly repair works. The three sites at Crocodile where this strategy was undertaken required significant repair work after the first wet season. The data from year two at these sites suggests that these sites are ‘back on track’ to achieve ongoing RERs > 80%. The reason these sites (Croc 0.1, 0.2, 1.1) will likely never achieve RERs > 90% is because they are rock chutes only, not full gully reshaping/stabilisation projects, and there is still side wall erosion occurring downstream of the chute. The extent to which this occurs, and whether it becomes an issue that could compromise the stability of the structure, will need to be monitored into the future.

The lower RERs at Strathalbyn site A1, 8b and to a lesser extent 8A and treatment 2 (in year 1 post treatment) can be explained in two ways. First there were several sites in gully 8 where drainage concentration occurred into the gully, in some cases facilitated by cattle tracks that were produced when stock inadvertently accessed the site over the wet season. These concentration zones initiated rills, and in some cases small gullies, the largest of which have subsequently been repaired. However, these were responsible for the sediment yields recorded at these sites. This did, however, occur during the 6th largest wet season in 120 years. Site A1 and treatment 2 both involved treatments that did not include rock capping, relying on soil amelioration and organic mulch alone. Such treatments are always going to be inherently risky, particularly during an above average wet season such as occurred in 2018/19.

How resilient are the treatments in large events?

As outlined above, the majority of the treatments implemented at Strathalbyn in 2018 were immediately followed by the sixth largest wet season on record at the site. The first wet season post treatment is always going to be the largest test for any remediation treatment, given the earth works have had little time to settle in and ground cover is at an absolute minimum. Hence the 2018/19 wet season at Strathalbyn could be regarded as being almost a worst-case scenario as far as a test for the resilience of the gully remediation strategy. That being the case, the majority of these treatments stood up remarkably well. Minor repair works that were required following the 2018/19 wet season amounted to a cost equivalent to around 1.4% of the upfront capital costs for remediation. During the 2018/18 wet season the Strathalbyn sites also experienced a backwater event from Bonnie Doon Creek, albeit only to a fairly minor degree at the lower end of each gully. This backwater, while causing a major problem for all of the water quality sampling data (i.e. contaminating most samples- see below). appears to have had little impact on the treatment. It is possible that larger backwater events will be experienced in the future, due to floods in Bonnie Doon Creek and from the Burdekin River. However, the experience from the Crocodile site suggest that this will provide little cause for concern.

At the Crocodile site, a number of backwater events were experienced over the study period, with the largest inundating the remediated gully to a depth of 4m above the gully floor and overtopping the entire remediated gully to a depth of 1 – 2m. This event had no negative impact on the remediated gully at all, indeed if anything it is likely that the backwater event led to some deposition within the gully, both due to sediment settling from the backwater, and from the overland flow delivered from the gully catchment into a stillwater environment during the backwater event.

Is there a commensurate reduction in bioavailable nutrients associated with observed reductions in fine sediment yield associated with gully remediation?

The relationship between sediment and nutrient reductions associated with alluvial gully remediation is currently conflicted, and more data is required to establish a clear relationship. However, available data suggests that gullies treated with rock capping alone result in a reduction in nutrient yields (both particulate and dissolved) that is commensurate with the reduction in sediment yields. This trend is currently only evident from the Crocodile treatments, as all of the Strathalbyn gullies had some sort of additional organic matter added to the treatments. Gullies treated with rock and organic ameliorants (e.g. mulch, bagasse etc.), or organic ameliorants alone, demonstrate a reduction in particulate nutrient yield, but a **net increase in dissolved nutrient** yields. Current data from Strathalbyn suggests this effect is still evident 2 years post treatment. Whilst it is expected that this effect would dissipate with time, ongoing monitoring is required to determine how long the elevated dissolved nutrient loads persist after treatment. Indications are that these increases are directly related to the organic material added to the sites, but more research is required to determine the exact mechanism leading to this increase above background, and how long it is likely to persist.

How cost-effective is large scale gully remediation?

Cost-effectiveness is a useful metric when comparing fine sediment reduction across projects. When these projects have varying lifespans, cost-effectiveness metric expressed in $/tonne (Currency 1, calculated using Equation 3) provides a consistent measure of project performance. Cost-effectiveness could inform prioritisation of investment across a mix of projects designed to deliver reductions in similar type of pollutant(s) over different time periods (Star et al. 2018). Despite its usefulness, to date, studies on site-specific cost effectiveness and factors that drive cost-effectiveness are limited (Rust and Star 2018). Site-specific cost-effectiveness spanning two GBR catchments reported in this study provides useful insight into how the choice of remediation techniques affect the level of upfront cost incurred and their effectiveness in reducing the fine sediment load discharged.

Comparison of cost-effectiveness calculated at 7% discount rate over 25 years across the two study areas indicate that EOG cost-effectiveness in the Normanby ($26/tonne up to $58/tonne) is generally better than that in the Burdekin ($31/tonne up to $80/tonne). However, the large difference in the delivery ratios translate to lower EOS cost-effectiveness of remediated gullies in the Normanby. EOS cost-effectiveness could be used as a metric to inform investments in gully remediation across different GBR catchments, provided that a given fine sediment load can be assumed to have the same adverse impact on different sections of the GBR.

The lower EOG costs at Crocodile are likely explained by the fact that rock capping material was sourced form an on-site quarry, from which the turnaround time for a 40t load was 15 minutes. Mobilisation costs were also extremely low, given that all machinery and operators were locally based at Lakeland, less than a half hour drive from the site. Given that the cost of rock and plant are the largest expenditure items in any gully remediation strategy, it is unlikely that many sites will be able to achieve a more efficient treatment costs than those experienced in this situation.

The cost-effectiveness metrics reported in this study only include the upfront costs. Upfront costs here consist of lidar, project planning and design, on-ground works and project management. Maintenance costs are not included in the cost-effectiveness calculations because at this stage the scale and frequency of maintenance required over the next 25 to 30 years is not known. Information on upfront costs are generally more readily available from other studies (e.g. Wilkinson et al. 2015b; Bartley et al. 2018), thus to some extent, our reported upfront costs can be compared with those reported elsewhere. For example, cost-effectiveness calculations reported in Bartley et al., (2018) consider only upfront costs of designing and remediation works (including remediation works supervision) for gullies located on five properties in the Burdekin catchments. Our reported EOS CE results for remediated gullies on Strathalbyn Station in the Burdekin ranges between $386/t/yr to just under $1000/t/yr and are sitting at the lower end of the CE range reported in Bartley et al. (2018).

Comparison of our cost-effectiveness results with other studies should be done with caution due to differences in the components of costs included in the calculations, assumptions regarding the discount rate and project lifespan, and assumptions in the level of treatment effectiveness. Nevertheless, comparisons of cost-effectiveness are still worthwhile when undertaken carefully to ensure the metrics being compared are indeed equivalent. As the cost-effectiveness calculations reported in this study utilised treatment effectiveness based on observed monitoring data over two or three years, this study has contributed to better understanding on the observed link between remediation techniques and their costs, and treatment effectiveness.

Using preliminary data on Strathalbyn maintenance cost incurred in 2018, 2019 and 2020, the sum of maintenance cost as a proportion of total on-ground cost is very modest at 1.4%. Most treated gullies on Strathalbyn Station with the exception of Treatment 6, only required minor repairs at a very modest costs following the 2018/19 wet season, even though this was the 6th wettest year in 120 years. This suggests that when gullies are remediated to a high standard, the risk of failure following storm events is low, and therefore the scale and frequency of maintenance required is also expected to be low for many years into the future. Thus, to some extent, the very low subsequent maintenance cost may compensate for the relatively high upfront cost associated with high standard of gully remediation.

Any analysis of the cost-effectiveness is ultimately a function of the rehabilitation effectiveness ratio (RER) compared with the baseline sediment yield, and whilst there is considerable uncertainty in the calculation of the RER, there is much greater uncertainty in the determination of the baseline yields. Hence caution should be used in over analysing the CE data, given the uncertainty in baseline yield determination. This is most apparent when comparing CE in terms of $/t/ha, because this has the potential to amplify uncertainties in baseline yields for the smaller sites, which are inherently harder to derive baseline yields due to the fact that have greater proportional measurement error (per unit area). While it would seem to make sense to normalise yields according to treatment area, the difference between gully yield and the area normalised yields in some cases seems somewhat misleading. Hence it may be best to consider the CE (which is already normalised per tonne of sediment abatement) at the gully scale rather than attempting to further normalise the data to area as well.

Finally, it should be noted that the range of remediation techniques used in this project is intended for demonstration and learning. The techniques used do not necessarily represent the most cost-effective option available for these sites. It is expected that cost-effectiveness would improve as the findings from these initial experimental/demonstration sites are fully operationalised, particularly with regards to:

- which technique(s) are best suited to which sites
- the most cost-effective approach for implementing those techniques by exploiting economies of scale where appropriate.

5.2 Secondary Questions

What are the best ways to monitor gully erosion remediation efforts at scale?

This project required the use of various water quality monitoring methods in order to effectively evaluate suspended sediment and associated bioavailable nutrient dynamics in actively eroding and remediated gully systems, and to thereby calculate the RERs for all treatments. As a part of this work, an intensive method evaluation study was conducted using Gullies Control and 2.234 at Crocodile station (Doriean et al 2020a). The objective of the method evaluation study was to appraise and compare the capabilities of various suspended sediment monitoring methods, used in gullies, under controlled laboratory conditions and in the field and assess their ability to collect or measure representative data. Table 44 summarises the key findings of the method evaluation study. Monitoring data collected from Strathalbyn Station, using RSS and autosamplers were consistent with the findings of the crocodile method evaluation study (Doriean et al., 2020a). Note manual sampling was not included in Table 44 because it is not commonly used to monitor gully suspended sediment dynamics, despite being the most accurate and representative method available. Often manual sampling is infeasible or unsafe to conduct in gully systems, due to its technical, logistical and financial requirements and the difficulties associated with predicting gully flow events. Thus, in the absence of manual sampling it is optimal to use a minimum of two sampling methods that will provide complimentary data. For example, the use of an autosampler and PASS sampler would provide a combined sample dataset that is both representative of changes to SSC over the hydrograph of different flow events (autosampler) and less biased by the effect of under-sampling coarser sediments (PASS sampler, Doriean et al., 2020a). The successful remediation of the gullies monitored during this project suggest that gully remediation is a viable environmental management option for reducing soil erosion and improving catchment water quality. It is likely that the number of gully remediation works will increase in future. Thus, there is a need to further develop suspended sediment sampling/measurement methods to make gully water quality monitoring more affordable, reliable, and representative.

Loads vs Concentrations

When assessing the efficacy of the full monitoring strategy at a gully, there is also an argument as to whether it is necessary to require the determination of sediment loads from the sediment concentration data in order to determine the sediment abatement (savings) from the remediated gullies. Given that sediment abatement is calculated by multiplying the baseline yields by the derived RER, the far greater source of relative uncertainty in these calculations comes from the determination of the baseline loads. The results from both locations indicates that when alluvial gullies are appropriately treated, and the sediment yields are being reduced more than an order of magnitude, the effectiveness ratio are essentially the same whether they are based on monitored concentrations alone or on derived loads (Table 45). Given the considerable additional costs associated with converting concentrations to loads (requiring the deployment of doppler velocity meters, likely within a flume), it would seem to be a case of diminishing returns undertaking the additional effort required to come up with sediment loads when the RER is virtually the same whether concentrations are converted to loads using measured or modelled discharge, or whether the changes in concentration in treated gullies is compared to changes in concentration in control gullies (which would account for any effect year on year changing discharges could have on concentration).

Resources saved from measuring discharge could then be directed towards the collection of more baseline data, to reduce the uncertainty where it is going to achieve the greatest relative improvement (see below).

This must be qualified, however, with the following caveats:

- The baseline sediment yield must be above a defined threshold (further monitoring is required to firmly establish the threshold - but suggest it should be at least > 5000 mg/l)
- The treatment undertaken using a full reshaping and capping approach likely to achieve an order of magnitude sediment reduction as a minimum, similar to those undertaken at the Crocodile 2.234 and Strathalbyn T1, 3, 4, 7, 8.

Alternatively, it is not appropriate to only use a concentration approach:

- in gullies which have a relatively low baseline yield (< 3000 mg/l).
- in gullies undertaking a low intensity treatment that will only lead to a relatively low RER.

Table 44. Characteristics of suspended sediment monitoring approaches evaluated in this study. Modified from Doriean et al., 2020a.

Sampler Type	***Approximate Cost (AUD)***	***Installation and operation***	***Principal of operation***	***Sampling capacity***	***Advantages***	***Limitations***
Automatic Sampler	$5,000-$30,000	Complex installation and regular maintenance.	Actively collects discrete samples by pumping	1-24 discrete samples (typically 1-3 flow events)	Multiple samples collected over a limited number of flow events. Can be triggered by multiple parameters (stream height, flow, or time).	Provides quality data for short flow events only. Non-continuous, as well as potential incomplete sampling of an entire flow event, can cause bias. Requires power and regular maintenance. Non-isokinetic and high potential under-sampling of sand if pump elevated above sample intake.
Turbidity Logger	$2,500-$10,000	Simple installation and low maintenance.	Records turbidity to memory at defined intervals (e.g., every 5 minutes).	>10,000 measurements over weeks or months (unlimited events)	High-resolution data over multiple flow events (limited by battery life).	Data requires site-specific calibration to be converted to SSC. No particle size information. No additional analysis possible as no sample is collected. Cannot be relied on without SSC calibration.
Rising Stage Sampler	$90-$600*	Complex installation and frequent maintenance.	Passively collects discrete samples during a single event as the water stage rises	3-12 discrete samples (single flow event)	Multiple samples collected over a limited number of flow events, on the rising hydrograph only. No power required.	No data for falling stage. Non-continuous sampling and lack of sustained or falling stage samples can cause bias toward initial flow concentrations. Requires frequent collection and replacement. Non-isokinetic.
PASS Sampler	$500-$1500	Simple installation and low maintenance.	Continuously collects sample at defined pump rate during flow event (triggered by float switch)	1-3 time-integrated samples (unlimited flow events)	Time-integrated samples collected over one or multiple flow events (limited by battery-life). Samples can be used for multiple analyses due to large sample volume.	Characterisation of hydrograph or individual events not possible. Non-isokinetic.

* = Price for six samplers, SSC = SSC, AUD = Australian dollars as of June 2019. References: (Edwards et al., 1999; Fowler et al., 2009; Gray et al., 2009; Horowitz et al., 2015; HQS, 2018; JMG, 2018; Perks, 2014)

Table 45. Comparison between RERs derived from lidar data, sediment concentrations (SSC) and loads normalised to water yield with the standard deviation between the concentration and loads effectiveness ratios.

	Crocodile		Strathalbyn						
	2.234		T1		T3		T4		T6
	2017/18	2018/19	2018/19	2019/20	2018/19	2019/20	2018/19	2019/20	2019/20
RER $_{ldr\ CI}$	101%	99%	99%	100%	99%	99%	99%	100%	12%
RER $_{ldr\ BA}$	101%	98%	99%	100%	99%	100%	98%	100%	54%
RER $_{conc\ CI}$	99%	110%	99%	99%	97%	98%	99%	98%	85%
RER $_{conc\ BA}$	-	-	-	-	97%	98%	99%	99%	82%
RER $_{wql\ BA}$	-	-	-	-	-	-	-	-	82%
RER $_{wql\ CI}$	99%	112%	99%	99%	96%	98%	99%	99%	84%
stdev $_{-conc\&wql}$	***0.21%***	***1.41%***	***0.00%***	***0.00%***	***0.56%***	***0.36%***	***0.31%***	***0.39%***	***1.51%***

Before / After vs Control / Impact

In studies like this, the gold standard experimental design is one in which the results are compared both before and after (BA) at the same site (requiring one and ideally more years of water quality monitoring, or topographic monitoring before the treatment is applied), coupled with measurements collected from a control site at the same time as from the treatment site (i.e. the impact) (CI). From the results summarised in Table 45 we show that for most sites we were able to present both BA and CI data for key sites using at least one method, and some cases up to three methods (i.e. topographic, concentration and loads). It is also evident that for most sites, the BA and CI RERs are very similar. Given that it is often difficult to find a comparable control site, these results suggest that robust results regarding treatment effectiveness can be determined from the BA water quality data alone, although the ideal scenario is to rely on both a topographic and water quality monitoring approach, given the inherent difficulties often experienced in the collection of water quality data (e.g. loss due to backwatering). In some cases there were variations between the two BA methods, and this likely represents the fact that we are approaching the limits of detection using the lidar topographic data. The limit of detection is hampered by the influence of grass cover established on the gullies post-treatment, and the application of mulch as part of the remediation works which settles in the years after treatment.

What are the minimum requirements for baseline site analysis at a new gully remediation site? (i.e. as the basis for site design and sediment abatement determination).

Given the issue outlined above, both in terms of establishing the sediment yield abatement and determining the Cost Effectiveness, by far the greatest uncertainty (in absolute terms) is that associated with the baseline sediment yield determination, particularly in scenarios like those outlined here where SSC is reduced by > two orders of magnitude following remediation. Based on the methods outlined in Daley 2020, the best estimate of baseline measurement uncertainty is 14%. Hence in a gully with a baseline yield of 50,000 mg/l, this means that the uncertainty is ± 7000 mg/l. If the mean post-rehabilitation yield is 1000 mg/l, then even with 100% uncertainty in the monitored sediment yield (or concentration), the error associated with calculating the net sediment abatement or the CE, is dwarfed by the error associated with the baseline. Given this, there is a strong case to be made for significantly improving the baseline yield through the following:

- Systematic collection of repeat airborne lidar data across GBR gully hotspot areas to quantify gully baseline yields from repeat lidar; this would involve the acquisition of airborne lidar every 2 – 5 years, so that a time series could be built up that will enable to the extension and verification of yields determined from airphoto analysis.
- Using photogrammetric approaches to improve the delineation of gully boundaries from historical aerial photography.
- Developing a systematic program of pre-treatment SSC measurement for at least two years prior to any gully treatment. This way it will be possible to determine the baseline sediment concentrations, and thereby establish the RERs from Before/After concentration data.

Ensuring that soil material characterisation is undertaken rather than standard surface soil mapping and classification (see below), as a way of characterising and sampling the soil materials for baseline yield assessment. Where possible soil sampling should be carried out in such a way that it proportionally represents the volumetric contributions from different soil material units through the whole sedimentary profile for the purposes of baseline sediment yield calculations. Relying on Australian Soil Classification (ASC) surface soil classification in alluvial settings will likely produce anomalous results if the characteristics of these soils are assumed to represent the entirety of the soil material being eroded by the gully.

Is the conventional surface soil classification appropriate for characterising the gully soil landscape?

The conventional soil survey of the alluvial floodplain gave valuable information and data for the 'soil profile' of up to approximately 1.5 m. It provided information on the topsoil (or surface layer if not actually an A horizon topsoil) characteristics as a primary growth medium both *in situ* and for use in rehabilitation works. The survey also provides information to classify the soil types – whether they be the prior SPC classification or the generic Australian Soil Classification.

The soil-geomorphological 'soil materials assessment' (SM)- allowed for investigation deeper that the 1.5 m augering and coring by observation and sampling to the depths of the gullies themselves (over 4 m in places). This soil materials assessment uses soil survey data but adds more information and data for the purposes required of it, as can be seen from the summary soil material analysis data (see Supplementary Information).The data rows in bold type are those that have been acquired from below the augering/coring depth and are associated with distinct layers (as the sample depth selection was based on layers rather than an agricultural regular depth interval).

- Conventional soil survey is purpose-driven for land use and land management requirements, rather than geomorphic feature management such as gullies and alluvial materials. SM allows for recognition of sedimentary layers and their correlation between gully systems where they occur in clusters.

- Soil materials assessment does not rely on generic soil classification (as it is conceptually inappropriate) but defines individual layers that have distinctive characteristics.
- Soil profile classes (SPCs) are identified by the horizons/layers *as a whole* to a soil classification system within soil landscapes; they identify *classes of soil profiles*. The SM approach gives an *individual layer* classification of SMUs within SMSs.
- Soil survey identifies types from surface characteristics (best for residual soils: pedologists will say this is where the process breaks down: when dealing with alluvial soils).
- Surface soil associations of horizons do not necessarily translate to the deeper alluvial sedimentary layers, although they may be pedogenically altered through the section (e.g. creation of carbonate and iron nodules).
- The surface soil classification is of very limited use when planning for rehabilitation and designing rehabilitation works. Details about lower layers and individual layers are more important.
- Referring to Chromosols, Sodosols etc. (ASC) is of limited use as it only refers to the A and B horizons of soil material and the relationship between the two. It conveys nothing of what are called the D horizons, which are not included in soil classification either generically (ASC) or locally (SPCs). All the soil classifications are geared towards agricultural land uses and management - not rehabilitation of geomorphic and geologic materials.
- Some layers and material characteristics important for rehabilitation design and planning can be missed by coring to only 1.5 m. (see summary data tables in Supplementary Information).
- Gullies are eroding from sub-surface – not the surface, so sub-surface material characteristics are the more important. Surface soil classification doesn’t convey the highly erodible nature of subsurface. So, surface soil classification and data are not necessarily useful to identify which are the most erodible materials (often at depth) or why (e.g. sodicity, salinity levels, PSD, dispersibility).

6.0 RECOMMENDATIONS AND CONCLUSION

6.1 Overview

The results presented here represent the first comprehensive quantification of alluvial gully remediation effectiveness in the GBR, and there is clearly a need for further data to be collected on similar remediation efforts within the GBR catchment to ensure that we are appropriately quantifying the remediation effectiveness and the cost-effectiveness. However, the effort and expense involved in collecting the data to the level outlined here is unlikely to be repeated, other than in a research context. However, there are lessons from this research that should enable us to streamline the process in the future, potentially making the process much more cost effective for ongoing remediation efforts so that they can be fed back into the GBR catchment modelling, providing greater confidence in cumulative GBR water quality improvements.

6.1.1 Baseline Data Collection

Remediation effectiveness (RER) and cost effectiveness (CE) calculations are highly dependent on the baseline sediment yields determined for each gully. Whilst it is important to focus on rigorous post-treatment water quality monitoring methods, to date little consideration has been given to the most important part of the RER and CE equations; the baseline sediment and nutrient yield. To ensure baseline sediment yields are as accurate as possible we recommend that baseline yields be determined by a centralised independent entity (to be determined) underpinned by an ongoing program to collect repeat airborne lidar every 2 – 5 years and water quality data. Baseline sediment yield data would then be determined by a combination of the following datasets:

- Historical airphoto analysis (2D) – as outlined in Daley et al. (2020).
- Where possible additional photogrammetry using the historical airphoto dataset
- Volumetric analysis based on the prior surface elevation reconstruction, also outlined in Daley et al., 2020, and Stout et al., (2019) - requires at least a baseline lidar dataset
- Standard airborne lidar DoD analysis (once the repeat lidar data coverage is built up)

The number of gullies requiring this detailed baseline can be limited to a set of several hundred high priority gully systems that have been identified through a separate prioritisation process (such as that undertaken for the LDC Project – Brooks et al., 2020). In this way a set of priority gullies will have their baseline sediment yields assessed prior to allocation for treatment. Using this approach, gully remediation resources would only be allocated to a pre-determined set of gullies, for which the baseline data analysis has been undertaken.

In addition, the historical sediment yield analyses at the selected gullies, “before” water quality monitoring would be undertaken to collect sediment concentration data using a combination of low-cost methods (e.g. RSS and PASS sampling), for at least two years prior to any remediation being undertaken. This would provide the necessary data for undertaking a Before/After SSC comparison to determine the RER for the selectively remediated gullies. The before SSC monitoring would also establish whether the gully meets the criteria for deriving the RER from sediment concentration data alone.

Soil and sediment sampling would be undertaken at the prioritised sites using the SM sampling approach, to establish the particle size characteristics for the sites, the soil chemistry and baseline nutrient status (which would be built into the sediment baseline yield determination). These data would serve the purpose of providing the soil material data required for remediation design purposes as well.

6.1.2 General Gully Monitoring Recommendations

The successful execution of monitoring water quality conditions in gullies situated in remote and harsh conditions, such as those described in this study, requires extensive planning, appropriate budget, and incorporation of equipment redundancy. The years of monitoring water quality at Crocodile and Strathalbyn Stations have provided much needed experience regarding what is required to successfully monitor water quality in actively eroding and remediated gully systems. The following framework is intended as a guide for future gully monitoring projects. Adherence to the different components of the framework will ensure the best possible monitoring outcome is achieved by avoiding external influences (i.e., flooding and insect/animal damage to equipment) and method-based bias (i.e. use of appropriate monitoring equipment).

Gully Catchment Monitoring

All gullies are connected to a catchment upstream that discharges water into the eroding structure. Thus, any water quality monitoring plan related to gully remediation needs to account for water quality conditions in the catchment upstream of the gully and at the gully outlet. This will allow for the assessment of remediation success without the uncertainty associated with catchment processes occurring upstream. Furthermore, to enable cross comparison between water quality monitoring data and topographic monitoring data, which is only focused on the actively incised and treated component of the gully complex, it is necessary to be able to disaggregate the gully catchment water quality from the active/remediated gully portion.

Meteorological monitoring

A rain gauge with datalogging capabilities should be placed in a location that will measure rainfall totals that are representative of rainfall volumes in the gully and catchment. The rain gauge should be equipped with a datalogger and be capable of recording high resolution data (i.e. date and time stamp each 0.2 mm increment of rainfall). Ideally, two rainfall gauges should be used on the one site, in-case of equipment failure or damage. Rainfall data is an essential component for the following monitoring objectives: provide context for the characteristics of the wet season monitored compared to historical records, relate gully flow intensities to rainfall, identify backflow events, provide data as redundancy for discharge modelling if needed.

Hydrological Monitoring

Water discharge measurements are required to estimate the yield of suspended sediment or nutrients discharged from the gully and catchment. Doppler velocity sensors were used at Crocodile and Strathalbyn stations. Velocity sensors work well in streams and rivers, however the sensor were unable to provide the necessary data to accurately estimate water discharge when deployed in remediated and actively eroding gullies. A major complication with the use of doppler technology for measuring water discharge is the influence of turbulence from channel structures (e.g. debris or rocky channel surfaces) and the risk of equipment becoming covered or stranded as a result of vertical channel bed movement from scouring or aggradation respectively. Recent studies have identified that flume structures (e.g. ramped weir or Parshall flume) are the most reliable and accurate discharge measurement methods for ephemeral streams, such as gullies (Turnipseed and Sauer 2010). These structures reduce the influence of channel bed scour or aggradation and rely on water level in the flume structure to infer water discharge, via a predetermined velocity/water level rating curve formula (Turnipseed and Sauer 2010). As outlined in the discussion above, it may not always be necessary to collect discharge data, particularly where the expected decline in sediment discharge is greater than an order of magnitude.

Water quality monitoring

At a minimum, two water quality monitoring methods should be used in tandem to collect samples from the catchment or gully outlet. The use of two methods is necessary as it ensures potential sampling bias can be measured and to provide redundancy for unexpected failures or damage. Initially, samples should be collected for SSC and PSD analysis. Note, SSC analysis is not interchangeable with total suspended solids (TSS). The analysis method for TSS was designed for measuring effluent from wastewater treatment plants rather than natural surface waters (Gray, 2000). TSS analysis results are known to significantly underestimate (10-30%) total SSC measurements in natural waters as noted by other authors (Gray 2000; Howley et al., 2018) and as demonstrated experimentally in this study. For the estimation of suspended sediment yields, it is ideal to collect discrete samples that represent different stages of a flow event hydrograph (i.e., rising stage, peak, and falling stage) of several flow events over a wet season should be collected. If this is not feasible, then event time-integrated samples (e.g., PASS samples) should be collected for as many individual flow events as possible. Sample equipment intakes should be placed in a location where the most representative sample will be collected (i.e., facing downstream in the centre of the channel at a height that is approximately 60% of ambient flow height). If a flume structure is used, sampling intakes may be placed on the side wall of the flume, instead of the centre, because the structure will create a high level of sediment mixing compared to a natural or constructed open channel (Turnipseed and Sauer 2010). Refer to the gully suspended sediment monitoring method evaluation study by Doriean et al., 2020a for more information.

Backwatering

All of the monitoring sites at Crocodile and Strathalbyn stations were inundated with floodwaters from backwater events generated by nearby rivers and creeks. The findings of this study suggest that backwater events may be a common feature of alluvial gully systems, with inundation water levels ranging from 0.25 to 4 m depending on gully elevation relative to nearby waterways. Backwatering should be taken into consideration when monitoring alluvial gullies. Failure to do so can result in the loss of data and damage or loss of equipment. For example, the backwater events that occurred at both monitoring sites during the 2018/19 wet season caused extensive damage to monitoring equipment and contaminated over 100 samples with floodwater. Had the sample times not been cross checked with the stage data the true sediment concentration emanating from the gullies could have been significantly misrepresented. Samples collected during a backwater event are more representative of the concentrations within the stream or river flow rather than the gully – and as such cannot be used.

6.1.3 Cost effectiveness Determination

To date there has been considerable confusion surrounding the appropriate approach for calculating the cost-effectiveness of gully remediation, and indeed all water quality improvements within the GBR. We recommend that a guideline is established that will outline the agreed methods for calculating the cost-effectiveness of all water quality improvements (including cross-comparison between disparate approaches), along the lines of those published by the World Health Organisation for public health investments (WHO, 2003).

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APPENDIX 1: DETAILED DESIGN STRATEGY FOR GULLY REGRADING AND STABILISATION

3D Post-Treatment Geometry

Aerial LiDAR data acquired in October 2015 (Figure A1.1) was used as the base dataset for the design of the earthworks required to reshape the gully into a potentially stable template upon which the additional stabilisation strategies could then be applied (i.e. gypsum application, gully head grade controls; capping of the whole gully with imported rock & shale material and grade control check dams within the gully complex). The design is based on the notion that the gully is regraded back to undisturbed parent material, where all material excavated as part of the reshaping exercise is removed from the gully, rather than relying on cut and fill. This is a conservative approach that may be able to be relaxed in future gully stabilisation works, providing adequate moisture is added or is present in the soils so that the disturbed material can be appropriately compacted. To minimise the likelihood of further incision, the gully floor is graded to a wide planar surface at least 9 m wide to minimise flow depths and reduce area specific bed shear stress under high flow conditions. Based on this analysis around 3000 m^3 of material is required to be removed from the gully (Figure A1.1), although it is recognised that this is an over estimate due to the fact that additional erosion has occurred between the time that the LiDAR data was captured in October 2015 (Figure A1.1a) and the time of construction in October/November 2016 (Figure A1.2).

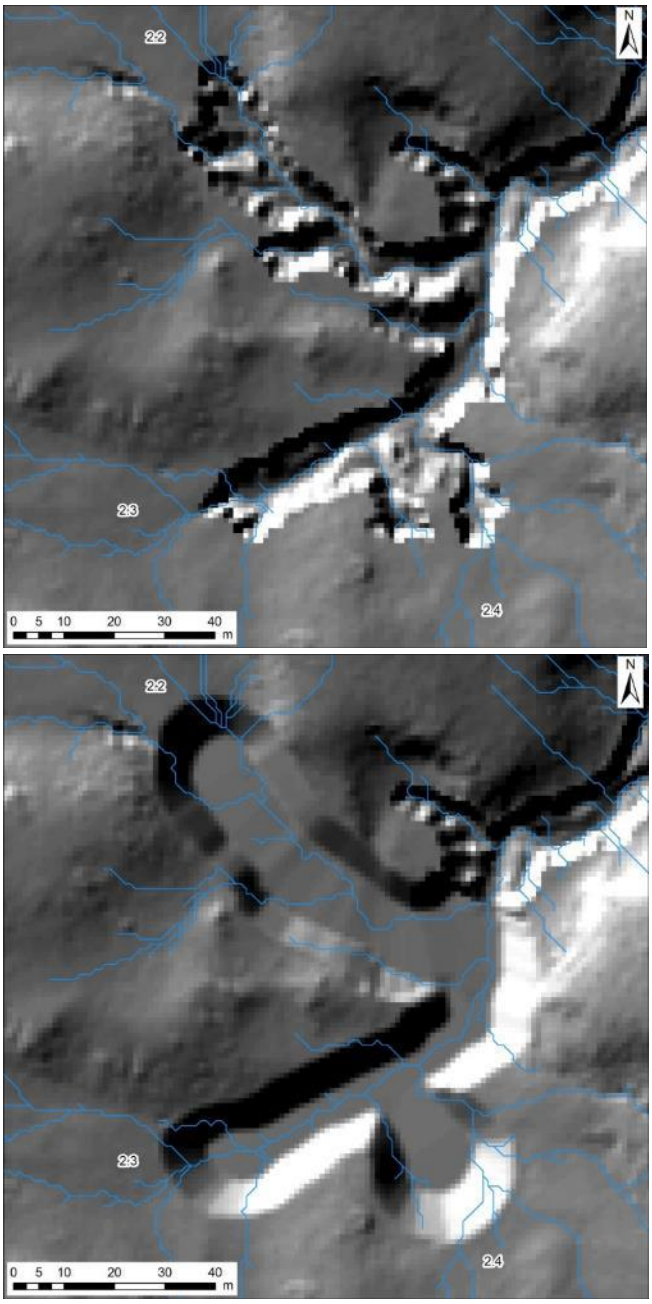


Figure A1.1. Lidar image of gully regrade treatment area from October 2015

Figure A1.2. Aerial imagery of treatment site from September 2016

Gully Treatment Materials Requirements

The three-dimensional post treatment gully geometry as shown in Figure A1.3 provided the basis for calculating material requirements as outlined in Table A1.1. As can be seen in Figure A1.3 a large geotextile apron is to be emplaced at the two main gully heads that receive most of the overland flow into the gully. A geotextile apron was not deemed necessary in gully 2.4 given the much smaller contributing catchment area and the broader more diffuse entrance to this part of the gully. Also shown in Figure A1.3 is the area of coarse rock required for the gully drop structures and the locations of the proposed rock grade control structures within the gully. Volumetric calculations for the gully head structures are based on the rock being 0.5m deep on average. The grade control structures are based on a rock structure 0.5m high x 1.5m at the base and 1m at the top (1m^3 per m structure width). Grade control size, location and spacing was determined from the stable channel gradient for each of the gully based on the existing channel long profiles of the different gully arms (Figures A1.5 – A1.6).

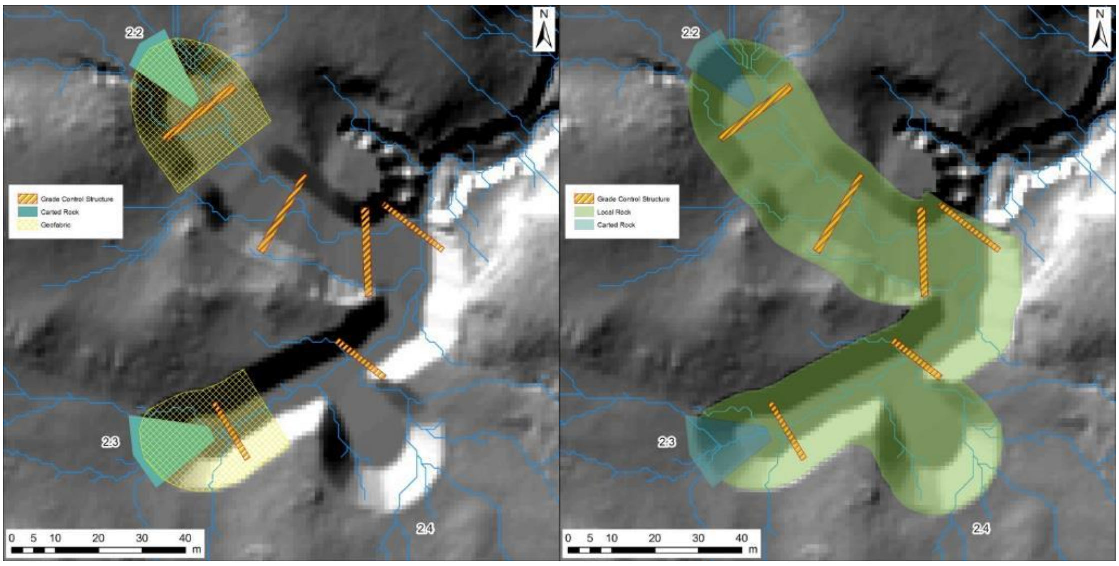


Figure A1.3. Hillshade DEM (1m resolution) showing the post-treatment gully form along with the proposed locations of the internal grade control structures and the area of geotextile apron at the two main gully heads, the area of the rock chutes and the area required to be capped.

Table A1.1. Area and volume calculations for gully treatment materials

Gully Component	Area/Vol required
Area of Geofabric Apron =	1352m^2
Carted Rock for gully head Area =	332 m^2
Carted Rock for gully head volume (@ 0.5m think) =	166 m^3
Local cap rock/dirt Area =	4391m^2
Local cap rock/dirt Vol (@ min 300mm thick) =	1320 m^3
Grade Control Structures rock volume (6 structures – 105 linear m)	80 m^3

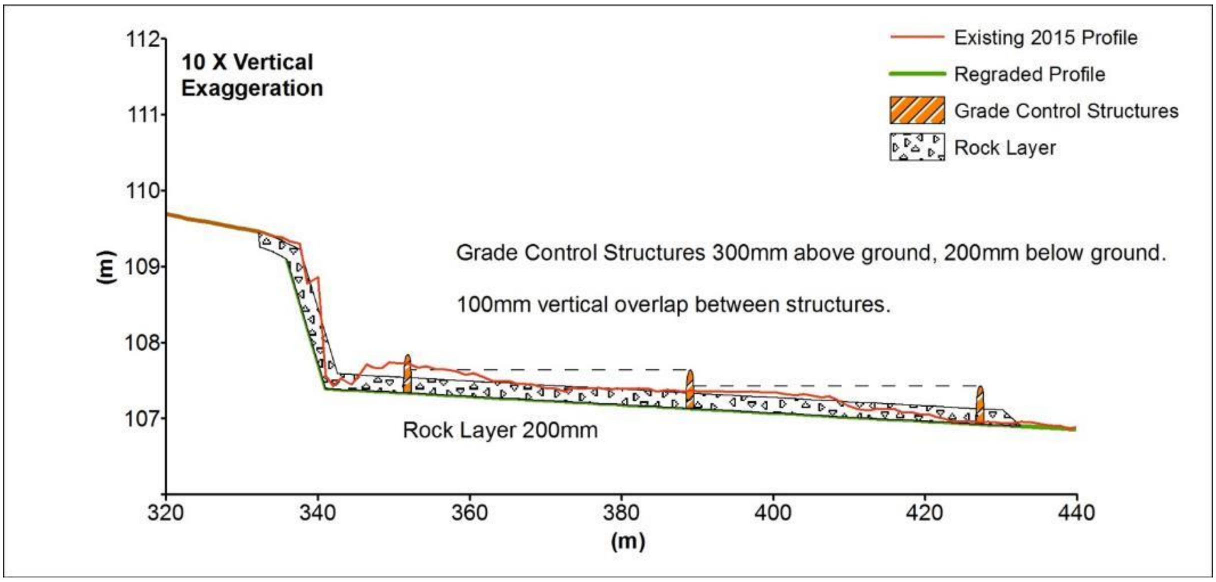


Figure A1.4. Gully long profile in section showing the pre-existing gully profile (2015) in red and the post treatment profile in green.

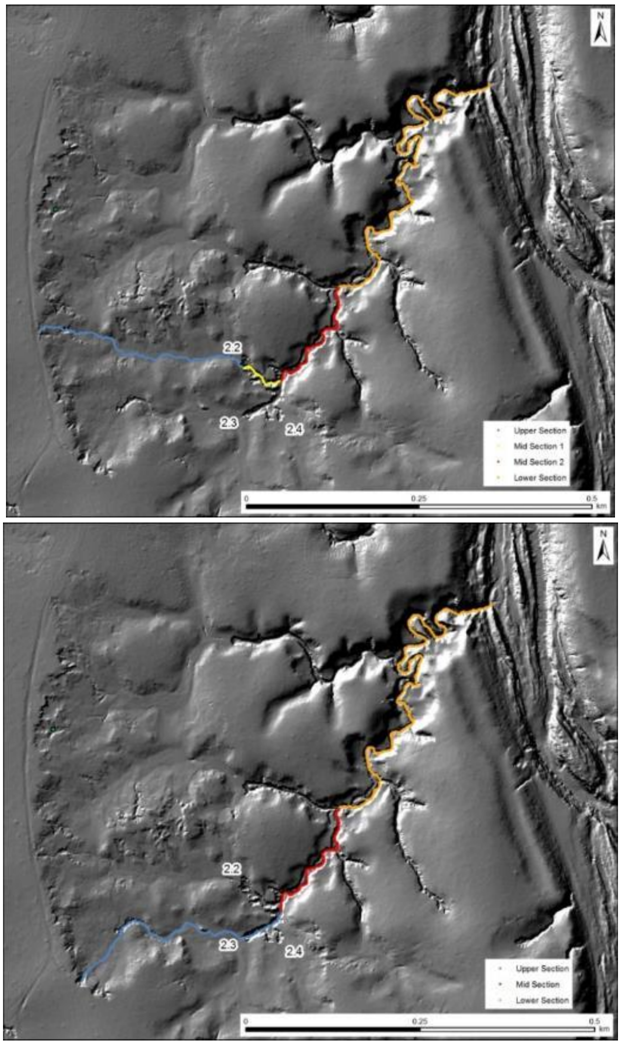
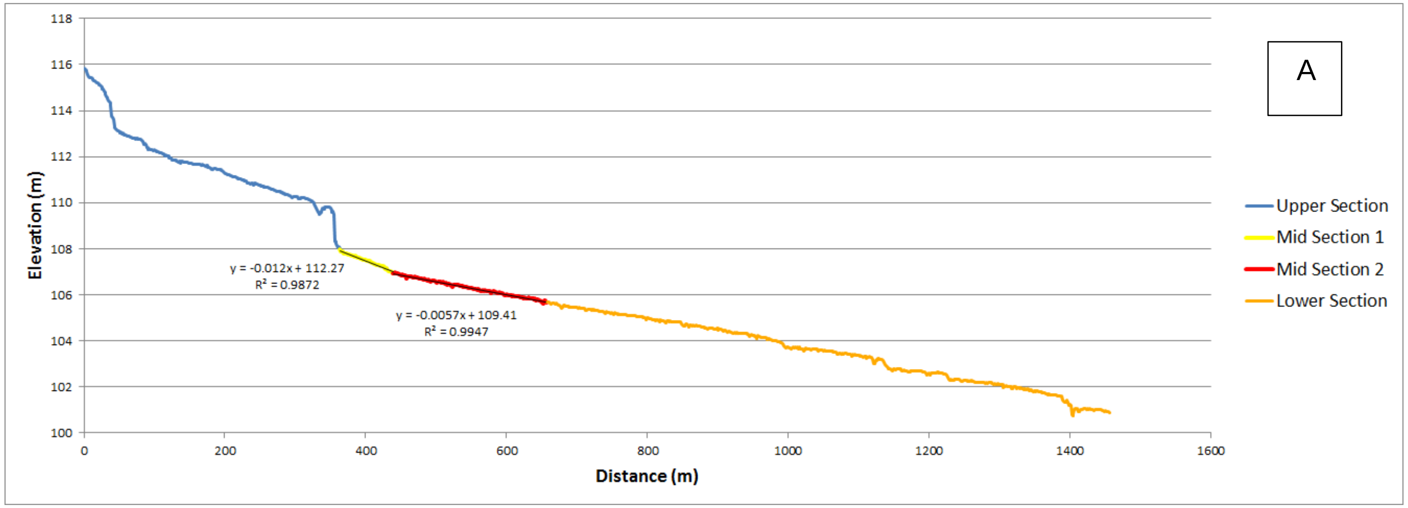


Figure A1.5. Planform view of the breakdown of the different sections of the gully profiles 2.2 (LHS) and 2.3 (RHS) shown in Figure A1.6



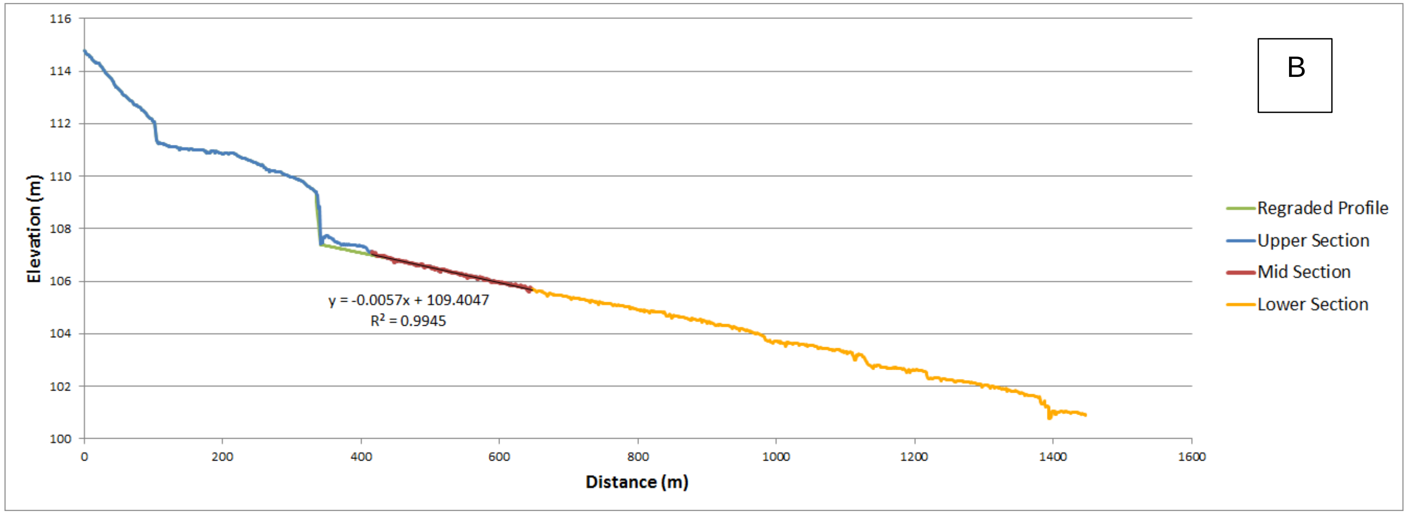


Figure A1.6. Gully long profiles from the two main arms of gully 2.2 (A) and gully 2.3 (B)

Table A1.2. Gully catchment Statistics required for calculating potential discharge extremes within the gullies

Gully	Area (ha)	ID	Catchment Length (m)	Percentage Slope Statistics MIN	MAX	RANGE	MEAN	STD
0.1	7.43	1	687	0	82.4	82.4	4.89	4.63
0.2	1.93	2	270	0	40.7	40.7	4.93	3.22
1.1	10.40	3	424	0	102.2	102.2	4.59	3.88
1.2	0.78	4	146	0	35.3	35.3	6.91	6.01
1.3	0.39	5	138	0.00027	39.5	39.5	6.85	5.44
2.1	4.18	6	401	0	58.6	58.6	5.91	4.70
2.2	3.30	7	377	0	58.1	58.1	5.82	4.49
2.3	7.19	8	369	0	52.1	52.1	5.01	4.22
2.4	1.60	9	217	0	43.6	43.6	5.62	4.48
2.5	1.41	10	---	0	44.2	44.2	6.13	5.57
2.6	3.54	11	348	0	39.2	39.2	5.23	3.60

Rock Chutes:

Gullies 0.1 and 1.1 will have head scarp rock ramps constructed according to the following:

- Batter/reshape headcuts back from the current channel to a stable grade of at least 1:6 on ramp face and 1:4 on sidewalls
- All fill material will be used to regrade gully to design slope
- Treat all disturbed areas with gypsum working in to a depth of at least 100mm (application rates determined by soil analyses – see below) – with some additional factor of safety due to the limited sampling
- Line the batters and floor of the headcut ramp with geotextile to minimize risk of scour
- Construct rock chutes with appropriate sized rock where high flow volume enters gully headcut
- Place appropriate sized rock and capping material on gully floor and walls
- Topdress with smaller rock or gravel to fill any air voids in rock chutes and batters
- Place appropriate sized rock for grade control structures in gully channel
- Apply gypsum and sow all disturbed areas with native grass seed mix and/or jap millet where appropriate (jap millet initially – followed by native seed later in wet season)

Key Design Features to Note:

- 2m Apron recessed into existing land surface above gully ramp
- Rock to be flush with existing surface when capping finished
- Rock ramp surface to be as flat as possible (no flow concentration in channel centre)
- Energy dissipater structure at bottom of ramp to have d50 1.5 x design size for other bed control structures
- Gully floor to be completely flat – with minimum flat bed width of 10m if possible

- Bed control structures (check dams) recessed into capped gully floor and into gully sidewalls,
- Check dam crests elevated ~ 400mm of gully floor. Structures spaced so that downstream crest elevation intersects with upstream structure (i.e. complete backwatering).
- Excess rock to be placed downstream of lowest bed control structure to act as launch material for armouring bed downstream of check dams

Regrading and Capping

Gullies 0.2 will be regraded and capped – as per gully 2.4

- Batter/reshape headcuts back from the current channel to a stable grade of at least 1:6 on gully head and sidewalls
- All fill material will be used to regrade gully to design slope
- Treat all disturbed areas with gypsum working in to a depth of at least 100mm (application rates determined by soil analyses – see below) – with some additional factor of safety due to the limited sampling
- Place appropriate sized rock and capping material on gully floor and walls
- Topdress with smaller rock or gravel to fill any air voids in rock chutes and batters
- Place appropriate sized rock for grade control structures in gully channel (~0.4
- Apply gypsum and sow all disturbed areas with native grass seed mix and/or jap millet where appropriate (jap millet initially – followed by native seed later in wet season)

Table A1.3. Summary table showing key design criteria for Crocodile Station Rehab gullies

	gully 2.1 (cntrl)	gully 2.2	gully 2.3	gully 2.4	***phs1 total***	gully 0.1	gully 0.2	gully 1.1	***phs2 total***
catchment area (ha)	4.18	3.31	8.60	1.60	***13.51***	7.43	1.93	10.40	***19.75***
Q50 yr (m^3/sec)	2.03	1.53	4.16	0.83	***1.53***	3.19	0.87	4.37	***8.43***
Q20 yr (m^3/sec)	1.55	1.17	3.17	0.63	***4.97***	2.45	0.67	3.35	***6.47***
Q10 yr (m^3/sec)	1.35	1.02	2.76	0.55	***4.33***	2.14	0.58	2.93	***5.65***
inlet ch width (m)	16.7	15	20	15		11	15	11	
inlet slope	0.0132	0.0103	0.0155	0.0245		0.0152	0.0205	0.0091	
inlet flow depth (Q50) (m)	0.18	0.206	0.279	0.11		0.347	0.12	0.495	
treated gully slope		0.083	0.083	0.083		0.167	0.167	0.167	
Ramp/batter face rock d50 (m) (Q50)		0.16	0.24	0.10		0.20*	0.08	0.25*	
Grade control structure d50 (m)						0.32*	0.15*	0.37*	

* Denotes basalt rather than sandstone – Sg = 2.7 (all other calcs based on sandstone Sg = 2.1)

Comparison of suspended sediment analysis methods

Sample ID	Gully ID	Sample collection date	SSC (mg/L)	TSS (mg/L)	TSS/SSC (%)
S_CEN_R50_180314	Central	14-Mar-18	45870	52560	13%
S_CEN_R100_180314	Central	14-Mar-18	126400	143400	12%
S_NT1_R50_180313	T1	13-Mar-18	848	709	-20%
S_NT3_R50_180313	T3	13-Mar-18	62987	71140	11%
S_NT3_R100_180313	T3	13-Mar-18	80685	101040	20%
S_NT4_R50_180313	T4	13-Mar-18	73551	91080	19%
S_NT4_R100_180313	T4	13-Mar-18	80482	94560	15%
S_NCA_R50_180313	Central	13-Mar-18	71784	83680	14%
S_NCA_R150_180313	Central	13-Mar-18	58568	67200	13%
S_NCB_R50_180313	Central	13-Mar-18	64567	74280	13%
S_NCB_R100_180313	Central	13-Mar-18	4320	1200	-260%
S_CEN_R50_180329	Central	29-Mar-18	79475	89400	11%
S_CEN_R100_180329	Central	29-Mar-18	115798	127240	9%
S_NCA_R50_180329	Central	29-Mar-18	93077	107580	13%
S_NCA_R100_180329	Central	29-Mar-18	128975	149020	13%
S_NCA_R150_180329	Central	29-Mar-18	68070	83720	19%
S_NCB_R50_180329	Central	29-Mar-18	93720	115740	19%
S_NT1_R50_180329	T1	29-Mar-18	956	1355	29%
S_NT1_R100_180329	T1	29-Mar-18	859	1250	31%
S_NT3_R50_180329	T3	29-Mar-18	105412	132620	21%
S_NT3_R100_180329	T3	29-Mar-18	231114	306640	25%
S_NT3_R150_180329	T3	29-Mar-18	137037	143080	4%
S_NT4_R50_180329	T4	29-Mar-18	102357	138000	26%
S_NT4_R100_180329	T4	29-Mar-18	105381	144800	27%
S_NT4_R150_180329	T4	29-Mar-18	164148	158720	-3%
SNT3R50	Central	02-Mar-18	420148	422520	-1%
SNT3R100	Central	02-Mar-18	104374	30180	71%
SNT3R150	Central	02-Mar-18	100392	117340	-17%
SNT4R50	Central	02-Mar-18	111412	118820	-7%
SNT4R100	Central	02-Mar-18	121616	126620	-4%
SNT4R150	Central	02-Mar-18	139985	144280	-3%
SNCBR50	Control	02-Mar-18	85224	93740	-10%
SNCBR100	Control	02-Mar-18	116901	123940	-6%
SNCBR150	Control	02-Mar-18	124512	131500	-6%
SNCAR50	Control	02-Mar-18	47132	51800	-10%
SNCAR100	Control	02-Mar-18	84353	84480	0%
SNCAR150	Control	02-Mar-18	68104	63900	6%
SCENR50	Central	02-Mar-18	80164	84380	-5%
SCENR100	Central	02-Mar-18	115195	117240	-2%
SCENR150	Central	02-Mar-18	225681	220000	3%
SNT1R50	T1	02-Mar-18	770	306	60%
SNT1R100	T1	02-Mar-18	1948	1422	27%
SNT1R150	T1	02-Mar-18	1781	1546	13%

Cost Effectiveness Tables

Crocodile Station

Table A1.4. 30-year cost-effectiveness ($ per tonne of fine sediment abated) calculated using Equation 3, and cost-effectiveness ($ per tonne of fine sediment abated per year) calculated using Equation 4 with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum.

End of gully				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 2.234	21.61	31.48	39.00	484
Treatment 0.1	29.93	43.61	54.02	670
Treatment 0.2	18.96	27.63	34.22	425
Treatment 1.1	13.52	19.69	24.40	303
End of system				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 2.234	48.02	69.96	86.66	1075
Treatment 0.1	66.51	96.90	120.04	1490
Treatment 0.2	42.14	61.39	76.05	944
Treatment 1.1	30.04	43.76	54.22	673

Strathalbyn Station

Table A1.5. 25-year cost-effectiveness on a per-hectare basis with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum. Figures in brackets represent the lower and upper bound cost-effectiveness values from application of baseline sediment yield error margins

Gully ID	CE Currency 1 $/tonne/ha r = 2%	CE Currency 1 $/tonne/ha r = 5%	CE Currency 1 $/tonne/ha r = 7%	CE Currency 2 $/tonne per year/ha
End of gully				
Treatment 1	30.17 (26.27,35.42)	41.79 (36.39,49.07)	50.54 (44.01,59.34)	588.93 (512.83,691.57)
Treatment 3	13.62 (10.27,20.22)	18.87 (14.22,28.02)	22.82 (17.20,33.88)	265.92 (200.46,394.85)
Treatment 4	11.74 (8.88,17.33)	16.26 (12.30,24.01)	19.67 (14.87,29.04)	229.24 (173.33,338.40)
Treatment 6	9.13 (7.04,12.97)	12.64 (9.75,17.97)	15.29 (11.80,21.73)	178.21 (137.47,253.24)
End of system				
Treatment 1	32.09 (27.94,37.68)	44.45 (38.71,52.20)	53.76 (46.81,63.13)	626.52 (545.56, 735.71)
Treatment 3	14.49 (10.92,21.52)	20.07 (15.13,29.80)	24.28 (18.30,36.05)	282.90 (213.26, 420.06)
Treatment 4	12.49 (9.44,18.44)	17.30 (13.08,25.54)	20.93 (15.82,30.89)	243.87 (184.39, 360.00)
Treatment 6	9.71 (7.49,13.80)	13.45 (10.38,19.12)	16.27 (12.55,23.12)	189.58 (146.25, 269.41)

Table A1.6. 30-year cost-effectiveness ($ per tonne of fine sediment abated) calculated using Equation 3, and cost-effectiveness ($ per tonne of fine sediment abated per year) calculated using Equation 4 with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum. Figures in brackets represent the lower and upper bound cost-effectiveness values from application of baseline sediment yield error margins

End of gully				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 1	31.56 (27.48,37.05)	45.97 (40.03, 53.99)	56.95 (49.59,66.88)	706.72 (615.39,829.88)
Treatment 3	21.02 (15.84,31.21)	30.62 (23.08, 45.46)	37.93 (28.59,56.32)	470.68 (354.82,698.89)
Treatment 4	22.93 (17.34,33.85)	33.40 (25.26, 49.31)	41.38 (31.29,61.09)	513.46 (388.25,758.01)
Treatment 6	41.38 (31.92,58.80)	60.28 (46.50, 85.66)	74.68 (57.61,106.12)	926.68 (714.87,1316.86)
End of system				
Gully ID	CE Currency 1 $/tonne			CE Currency 2 $/tonne per year
	r = 2%	r = 5%	r = 7%	
Treatment 1	33.57 (29.23,39.42)	48.91 (42.59, 57.43)	60.59 (52.76,71.15)	751.83 (654.67,882.85)
Treatment 3	22.36 (16.85,33.20)	32.57 (24.55, 48.37)	40.35 (30.42,59.92)	500.72 (377.47,743.50)
Treatment 4	24.39 (18.44,36.01)	35.54 (26.87, 52.46)	44.02 (33.28,64.98)	546.27 (413.03,806.39)
Treatment 6	44.02 (33.96,62.55)	64.13 (49.47, 91.13)	79.44 (61.29,112.89)	985.83 (760.50,1400.91)

Table A1.7. 30-year cost-effectiveness on a per-hectare basis with annualised present value (upfront) cost calculated at real discount rates of 2%, 5% and 7% per annum. Figures in brackets represent the lower and upper bound cost-effectiveness values from application of baseline sediment yield error margins

End of gully				
Gully ID	CE Currency 1 $/tonne/ha r = 2%	CE Currency 1 $/tonne/ha r = 5%	CE Currency 1 $/tonne/ha r = 7%	CE Currency 2 $/tonne per year/ha
Treatment 1	26.30 (22.90,30.88)	38.31 (33.36,44.99)	47.46 (41.33,55.73)	588.93 (512.83, 691.57)
Treatment 3	11.87 (8.95,17.63)	17.30 (13.04,25.69)	21.43 (16.15,31.82)	265.92 (200.46, 394.85)
Treatment 4	10.24 (7.74,15.11)	14.91 (11.28,22.01)	18.47 (13.97,27.27)	229.24 (173.33, 338.40)
Treatment 6	7.96 (6.14,11.31)	11.59 (8.94,16.47)	14.36 (11.08,20.41)	178.21 (137.47, 253.24)
End of system				
Gully ID	CE Currency 1 $/tonne/ha r = 2%	CE Currency 1 $/tonne/ha r = 5%	CE Currency 1 $/tonne/ha r = 7%	CE Currency 2 $/tonne per year/ha
Treatment 1	27.97 (24.36,32.85)	40.76 (35.49,47.86)	50.49 (43.96,59.29)	626.52 (545.56, 735.71)
Treatment 3	12.63 (9.52,18.76)	18.40 (13.87,27.33)	22.80 (17.19,33.85)	282.90 (213.26, 420.06)
Treatment 4	10.89 (8.23,16.07)	15.86 (11.99,23.42)	19.65 (14.86,29.01)	243.87 (184.39, 360.00)
Treatment 6	8.46 (6.53,12.03)	12.33 (9.51,17.53)	15.28 (11.79,21.71)	189.58 (146.25, 269.41)

APPENDIX 2: FIELD PROTOCOLS FOR UNDERTAKING SOIL MATERIALS ASSESSMENT IN LARGE GULLY ENVIRONMENTS

Field preparation

Equipment

- GPS units
- RTK GPS pack
- UAV (Drone) with 4K camera
- DSLR camera
- Field clipboard box with
  - Field data sheets
  - Base maps
  - Pens
- Spade / Mattock
- Soil pick
- Sample bags
- Water
- Plastic dish

Resources

- Lidar DEM base map(s) with auto-mapped gully boundaries and Strahler flow lines of the area. Large enough for adding mapping detail and annotation.
- High-resolution satellite imagery of the area
- Field Data Sheets
- Sketch Sheets

Field Assessment

Reconnaissance

Environs

Scouting around the gullied area is necessary to observe and record the topography, erosion activity, and land surface conditions that lead to the gullies or may indicate the direction and extent of further erosion. Vegetation cover and changes in the vicinity is also of importance.
Any observations of surface soils and sediments in the neighbourhood are valuable to put the gully erosion in its soil-landscape context. Any obvious surface soil changes need to be noted and sketch-mapped where possible.

RPAV / Drone photography

Use RPAV drone photography whenever possible. An initial video flight of the gully area under investigation is useful for later reference.
Otherwise broadscale photography by free-flight at 50 m altitude taken after walking the gullies (having selected soil material sample sites each marked with a white cloth, flag, or similar marker). Fly an aerial photographic survey of the gully area by pre-programmed plan or by free-flight – this aids:

i) mapping the vegetation densities and types,
ii) mapping the soil material boundaries and changes linked to the sample sites,
iii) keying in the sampling sites to the DEM and GIS locations.

Overview site description

- At head of gully or best accessible overview point or overlooking gully system. Record on Overview Site Description Sheet observations from viewpoint as much as possible concerning landform, vegetation, land surface condition and location data.
- take vertical photographs with a drone of whole gully system being mapped from 50-100 m altitude.

Detail mapping

Number of Soil Material Observation Points

At least two OPs will be required to characterise the soil materials in any gully or gully system if it is less than a hectare in size. It is recommended that at least two OPs usually be used to sample the Soil Materials (layers) for any gully site investigation for rehabilitation management.

For small, simple gullies, **two OPs** for observing, recording and sampling Soil Material layers for laboratory analysis will be sufficient. Further soil material observations will be required to describe the layer variation and to map the Soil Material pattern.

For larger and/or more complex gullies, and gully systems **at least three OPs** for observing, recording and sampling for laboratory analysis will be required, depending on the size of the Gully or Gully System being investigated.

A rule of thumb should be **no less than three (3) OPs per hectare** for recording Soil Materials, with **four (4) OPs per hectare** for more complex sites. On average **two (2) OPs per hectare** should be used for sampling for laboratory analysis.

Multiple Soil Material Systems and Stratified systems may need further OPs
Choose further sites if soil material complexity demands it.

Gully margins mapping

- From convenient access point (near head/apex) walk the obvious gully margin with RTK with real-time tracking above the gully wall, i.e. outside the gully.
- Track with GPS the field observed gully margin.
- Check soft edges for being legitimate eroded part of gully – contributing or having contributed sediment to the system. Is it bare ground, vegetated, stabilised? Record on lidar dem base map status of area within soft edge.
- Record bare ground / scalding around gully margins that have little or no topographic expression.
- Record, cracks and holes/pits and flow lines into the gully from outside the margin (draw on map).
- Check vegetation type and changes against remotely assessed vegetation mapping. Note on vegetation map location of differences to map and type of difference. Estimate densities by eye.
- Record evidence of erosion / deposition activity on field data sheets at selected points = Observation Point (**OP**)
    - Record ID number of each OP and locate with GPS as waypoint.
    - Photograph erosion activity and Gully edge, Wall, Floor with DSLR.
        - From within gully: at target; up-gully; down-gully
        - From above gully wall/edge: at target; across gully, up-gully; down-gully
- Record active heads (or selected sub-sample) of gully on field data sheet and by In-gully photography and aerial photography as above.

Determine Soil Material System

- (Refer to the Field Guide). Determine whether gully soil materials are Uniform overall, Stratified, or Horizons - comprising largely of a soil profile on bedrock

    - Determine the different System classes for identified changes in soil material type through the system
    - Stratified materials will need further investigation to establish the number and type of layers.
- Record point at which gully is deemed to ‘end’, i.e. the ‘terminus’, which may be transition to a stream channel, egress to a drainage line, transition to depositional fan, or other. Record point on map, and photograph as above.

In-gully mapping

- While walking the eroded margin of gully and observe type, number, depths and association of soil material layers.
- Locate potential soil material observation and sample sites while walking the gullies.

In-Gully

- *Initial walk of gullies*
    - Take waypoints, photographs, and notes at strategic points and sites of active erosion.
    - Take note of vegetation cover, densities and types around and inside the gullies.
    - Take note of distinct soil material layers, their location, depths, and association.
- *Record vegetation cover*
    - Outside the gully - record on data sheet
    - Within the gully - record on data sheet
    - Verify or revise previous remote/desktop assessment where necessary
    - Estimate densities by eye
    - Attempt to identify vegetation types or species
    - Take samples for identifying later if necessary

- Record evidence of erosion / deposition activity within the gully interior and gully architecture on Field Data Sheets at selected points = Observation Point (OP)
    - Record ID number of each OP and locate with GPS as waypoint,
    - Photograph erosion activity and gully margin, wall, and floor with high resolution photography, from within gully: at target; up-gully; down-gully.
- *Observe and record gully characteristics*
    - Complete the Gully System data sheet as far as possible
    - Take photographs, record any comments, like uncertainties and items out of the usual.
- *Determine soil material continuity*

- Does the nature of the soil material change through the extent of the gullies?
- If so, identify boundaries where the changes in fundamental soil materials change

- *Determine Soil Material Groups*
    - Refer to the Field Guide. Determine whether gully soil materials are Layered overall, Stratified, or Non-Layered (see Field Guide).
    - Determine the different Groups for identified changes in soil material type through the different gullies of the System, if appropriate.
    - Stratified materials will need further investigation to establish the number and type of layers (Soil Material Units).
- *Determine Soil Material Unit (Layer)*
    - Establish if the materials are Non-Layered, Layered, or Layered and Stratified in nature (see Field Guide)
    - Do this for each zone of different Soil Material Systems identified.

Observation and sample site selection

Soil material sampling even at this local scale can be random, purposive (judgemental), or systematic.

- *Random* does not mean haphazard but means selection of individual sites and types without bias, i.e. probability sampling.
- *Purposive* comprises sampling typical or visible differences and forms the basis for exploratory sampling and soil material assessment, but the results rely greatly on the personal judgment of the surveyor, hence the need for a suitably qualified person.
- *Systematic* is neither subjective nor objective but satisfies the need to cover the entire soil material population. Sampling points are located at regular intervals or by some systematic method (e.g. a grid). The results do not rely so much on the personal judgment of the surveyor.

Develop a simple sampling plan
A simple sampling plan should aim to sample all the distinct layers (Soil Materials) that have been identified in Step 3.1. Reconnaissance. It should also include a check on the spatial variation of these layers if the gully site being investigated is large and or complex.

The most appropriate observation and sampling plan depends on

- The type of gully (gully system);
- The size of gully (gully system);
- The perceived spatial complexity and number of the Soil Materials (layers);
- Time available for field assessment.

The number of samples to be taken for laboratory analysis will depend upon

- Spatial complexity and number of Soil Materials (layers);
- Scale of rehabilitation works being considered;
- Budget available.

There are a number of options for a sampling plan that should take the above into consideration as well as the results of the reconnaissance of the area being assessed – of both the gully system and the environs.

The reconnaissance step will give a better idea of the number and type of Soil Material layers there may be in and around the system, as well as how they vary spatially.

Types of sampling

- *Convenience sampling* – relatively easy to reach and selected for good exposure or comprehensive suite of relevant soil materials. The least preferred method but access restrictions and time constraints may mean that this is necessary.
- *Representative sampling* – (see Key Areas for combined use) selected for key soil material (layer) representation in the classification for the area developed from the survey.
- *Transect sampling* – possible down the long profile of the feature - and across the broadest part of the feature for broad gullies (Amphitheatres/Open/Scarp-fronts). Depends on the reconnaissance and interpretation of layer complexity.

A transect in this case means a roughly unidirectional or bi-directional line of at least three observation sites at irregular spacing (convenience or representative selection) of sites.

- *Key area sampling* – nested areas within the defined survey area selected from initial reconnaissance and ‘stratification’ of the area. Areas then mapped or sampled in more detail by purposive methods. Results in a better appreciation of local-scale variation and more effective mapping across the broader region.

Number of observations
Overall, the number of observations of the soil materials to be recorded will depend on the size of the Gully or Gully System) being investigated.

At least two sites will be required to characterise the soil materials in any gully or gully system if it is less than a hectare in size. It is recommended that at least two sites usually be used to sample the Soil Materials (layers) for any gully site investigation for rehabilitation management.

- *For small, simple gullies*, two sites for observing, recording and sampling Soil Material layers for laboratory analysis will be sufficient. Further soil material observations will be required to describe the layer variation and to map the Soil Material pattern.
- *For larger and/or more complex gullies, and gully systems* at least three sites for observing, recording and sampling for laboratory analysis will be required, depending on the size of the Gully or Gully System being investigated.

A rule of thumb for the number of observations should be:

- *no less than three (3) sites per hectare for recording Soil Materials,*
- *four (4) sites per hectare for more complex sites.*
- *on average two (2) sites per hectare should be used for sampling for laboratory analysis.*

Multiple Soil Material Systems and Stratified systems may need further sites
Choose further sites if soil material complexity demands it.

Where to record and sample and method to employ
Observation sites (Site Observation points – OPs) should be selected where:

- a full sequence of layers can be appreciated and accessed, especially in the active erosion zones;
- there is evidence of most active erosion of heads and walls;
- there is the greatest depth of exposure through the soil materials.

For simple Linear gullies and Linear systems consider:

  - Representative sampling (or Convenience sampling if necessary), or
  - possibly Transect sampling, where there are a number of soil materials with spatial variation.

Transects would be down the long profile of the gully(-ies). With many branches and/or a wide lateral axis to the system a single cross-profile transect could also be considered. At least two sites per transect must be located with samples taken for laboratory analysis.

A simple linear gully would need two sites for laboratory analysis sampling, with one being at the head.

- *For simple Dendritic gullies, simple Open gullies and complex Linear systems* consider:
  - Representative sampling (or Convenience sampling if necessary), on selected gullies in dendritic and complex linear, on walls of Open gullies/systems, or
  - Transect sampling, for linear gullies where there are a number of soil materials with spatial variation. For lateral variation across dendritic systems.

Linear systems: transects would be down the long profile of the gully(-ies) and would need at least two sites for laboratory analysis sampling, with one being at the head. *Complex or large linear gully systems* with many branches and/or a wide lateral axis to the system one or two cross-profile (lateral) transect(s) could also be considered.

Dendritic systems will need at least one lateral transect. At least two sites per transect must be located with samples taken for laboratory analysis.

Open gullies will require at least three observation sites with one at the head region, and one near the outlet.

- *For complex Dendritic gullies and complex Open gullies* consider:

- Transect sampling, for Open gullies where there are a number of soil materials with spatial variation. For lateral variation across Dendritic gully systems.
- Representative sampling (or Convenience sampling if necessary), on selected gullies within Dendritic system, and walls of Open gullies.

Complex Dendritic systems with many branches and/or a wide lateral axis to the system will need at least two lateral transects. At least two sites per transect must be located with samples taken for laboratory analysis.

Complex or large Open gully systems will require a long-profile transect down one side of the gully wall. At least one lateral transect is necessary; possibly two could be considered.

For Open Gullies consider:
- *Representative* sampling (or *Convenience* sampling if necessary), on selected sites on walls and active heads, or on residual pedestals within the gully.
- Transect sampling, where there are a number of soil materials with spatial variation.

For Scarp-front Gullies consider:
- Transect sampling, for linear gullies where there are a number of soil materials with spatial variation. For lateral variation across dendritic systems.
- Representative sampling (or Convenience sampling if necessary), on selected gullies.

For Open Gully Systems and Scarp-front Gully Systems consider:
- Key area sampling,
- Transect sampling, for linear gullies where there are a number of soil materials with spatial variation. For lateral variation across dendritic systems.
- Representative sampling (or Convenience sampling if necessary), on selected gullies.

Sampling

At each site it is preferable to take a sample and observe fresh soil materials. This can be done either by digging into the exposure for at least 0.2 m. If possible, it is best to take a soil auger core extraction for the surface soil material about 1 m away from the gully head/wall edge.

Record Soil Materials at sites

At each site record all details possible that appear on the Soil Materials data sheet.
Field data sheets in a standard format can serve as a checklist of characteristics that should be recorded. A checklist is especially valuable for field personnel not trained in soil science or geomorphology because it reminds to record, at minimum, data for the listed properties. Observations, however, should not stop with the listed properties. Good soil material descriptions typically require information beyond that needed to complete the form. So, space for notes and comments are available for further commentary, or a separate notebook can be used.

- Location data is essential
- Gully site conditions and characteristics
- Record soil material data for each identified layer
- Photograph the exposure
- Use a gardener's pH kit if available
- Use a flat dish and water (preferably distilled/deionised) for soil aggregate dispersion test.

How to sample

Sampling of soil material layers is required for laboratory analysis of the material, and any further analysis intended to be done back at the office. Take more samples of soil materials than are required for laboratory analysis. The actual samples for analysis can be chosen after full sampling of the gully(-ies) has been completed. Some samples may be required for local analysis at the office so these cannot be used for laboratory analysis purposes.

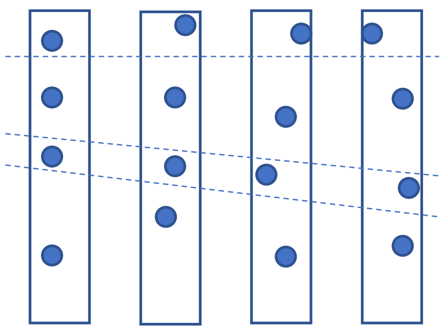
Bagged samples can also serve as reference material for confirmation or enquiry into soil material types at any site. They can also act as a back-up for any laboratory samples that may need to be replaced for analysis.

Composite sampling: 'bulking' samples together to 'average' the result of the attributes measured within the layer.

- Should be used topsoil materials around the site near the exposure, to counter localised variation.
- Could be used for sample site duplication from soil material exposures (e.g. opposite gully walls if close by, or soil material exposure 1-2 m away) to counter spatial and site-specific variations in attributes owing to exposure and surface processes that affect the soil material to varying depths into the profile (e.g. erosion; deposition; draping of material from above, biotic influences, piping/tunnelling; irregular saturation and drainage).

Where to sample

Use composite sampling within the layers if the material is easily extracted. Otherwise use stratified-random depth sampling in the profile to sample within the layers. Do not use systematic standard-depth sampling (e.g. every 20 cm).



Soil Material (Layer) boundary

Soil Materials / Layers can be soil horizons with distinct boundaries and sedimentary strata

Figure A2.1. Stratified-random depth sampling

Sample soil materials for analysis

Soil material samples are necessary for analysis of sodicity, salinity (electro-conductivity, chlorides), cation content, particle size, pH, phosphorus, total carbon, and other analytes if required

- Take a sample of each layer at each site where required with a trowel or pick.
- Samples for analysis can be chosen back in the office - rather take samples and discard them than not take samples then needing them later.
- Record if a sample of the layer has been taken and record the depths of the samples from the surface. Use a soil pit tape measure if available, otherwise a large retractable tape measure will do.
- Use zip-lock plastic bags and take between 250g and 500 g of soil material for each bag.
- Fill out a sample ID label and put it in the bag with the sample. Put the bagged sample in another bag.
- Label each bag with date, time, site ID, sample number, depth of sample.
- Record samples taken on the Data Sheet.
- Photograph the exposure and sample bags at the site.
- Make sure the site is recorded on a base map or imagery.

Sketch mapping

Make a sketch map of soil material boundaries

Record the location of any surface soil material boundaries and where layer boundaries occur at the surface.
Use an aerial photograph, image print, or DEM print of the gully as a base map to record sites and boundaries

Post-Field Analysis

i. Post-site visit: finalise the number of identified soil materials and characterise them using the information collected at the site and results of lab analysis.
ii. Determine the elevation of the top of each soil observation (waypoint) by intersecting with a reliable LIDAR derived DEM and convert soil material top and bottom depths to Australian Height Datum (AHD).
iii. With the aid of the drone photography, map each soil material across the site, using both plan and cross-section diagrams. If possible, develop a 3D model of soil materials that can be used in plans for site works to help with estimating costs, time frames and logistics for large scale gully remediation.

Crocodile Soil Material Summary Data

Table A2.1. a) mean averaged chemical analysis for the intensive sampling in the study gullies (EAL lab analysis). b) median averaged particle size analysis for the intensive sampling in the study gullies (EAL lab analysis).

a) Gully averages									
Chemical analysis	pH	EC	Ca:Mg	ESP	EMP	Ca	Mg	K	ECEC
Top-layer mean	6.4	0.2	0.9	43.3	33.6	21.1	33.6	1.9	8.9
Sub-layers mean	7.3	0.4	0.6	49.9	30.8	20.3	30.8	1.7	9.5
Sub-layers > 1.2 mean	7.7	0.6	0.6	47.1	24.5	19.0	26.0	1.4	14.4
Top-layer median	6.1	0.1	0.7	17.9	41.1	18.5	39.0	2.1	3.8
Sub-layers median	7.1	0.3	0.4	51.9	30.6	14.0	30.6	1.7	7.2
Sub-layers > 1.2 median	8.0	0.6	0.6	52.4	21.3	15.8	22.1	1.6	9.1

b) Gully averages	% Gravel	% Clay	% Silt	% Sand	
Particle size analysis	> 2 mm	< 2 µm	2 – 20 µm	0.02 – 2.0 mm	Total <0.02
MeanTopsoil	0.2	24.0	27.0	49.0	51.0
Mean Subsoil	1.1	27.1	21.8	51.0	49.0
Mean Subsoil > 1.2 m	2.6	31.2	20.2	48.6	51.4
Median Topsoil	0.1	23.4	21.8	49.1	45.2
Median Subsoil	0.4	22.0	21.1	56.6	43.1
Median Subsoil > 1.2 m	1.2	32.1	20.7	47.2	52.8

Table A2.2. a) Mean averaged particle size analysis for all the soil material sampling (DES+EAL lab analysis), b) median averaged particle size analysis for all the soil material sampling (DES+EAL lab analysis).

a) All averages									
Chemical analysis	pH	EC	Ca:Mg	ESP	EMP	Ca	Mg	K	ECEC
Top-layer mean	6.3	0.2	0.9	31.2	29.3	10.8	25.5	1.3	5.8
Sub-layers mean	6.8	0.3	0.5	39.4	33.9	10.3	18.5	1.1	7.3
Sub-layers > 1.2 mean	7.8	0.8	0.6	48.0	19.1	9.6	14.1	0.8	10.2
Top-layer median	6.0	0.1	0.7	12.3	36.9	9.4	28.6	1.2	3.2
Sub-layers median	6.4	0.2	0.4	31.6	39.5	7.1	17.0	1.0	5.7
Sub-layers > 1.2 median	8.3	0.8	0.5	53.3	14.8	8.0	12.2	0.9	7.6

b) All averages	% Clay	% Silt	% Sand	
Particle size analysis	< 2 µm	2 – 20 µm	0.02 – 2.0 mm	Total <0.02
Mean Topsoil	20.8	21.6	59.2	41.6
Mean Subsoil	28.7	19.8	52.5	48.5
Mean Subsoil > 1.2 m	31.1	21.1	48.3	52.1
Median Topsoil	6.9	18.6	49.1	49.9
Median Subsoil	14.7	18.9	40.2	47.8
Median Subsoil > 1.2 m	14.3	23.9	40.5	46.1

Strathalbyn Station: background to soil and geomorphological investigations

Existing soil information in the area (in order of publication year)

Hubble and Thompson (1953) produced a broad survey of the lower Burdekin valley from the Bowen River to the river mouth. Division of landscape into three groups, (a) The Plain Country; (b) The Upland Country; and (c) Miscellaneous areas. 32 soil associations grouped into four sets, (a) River levees; (b) River flood plain; (c) Plains of local alluvium; (d) Maturely dissected uplands; and seven land types of which one is *Gullied Land*. Report describes in detail (a) *River levee soil series*. The relevance to this project is the establishment of the landscape divisions.

Thompson and Reid (1982) – Compilation of soil profile classes and key from three 1:100,000 scale surveys covering the whole Burdekin River Irrigation Area (BRIA) from the Bowen River downstream and has been used in this survey.

Thompson et al. (1990) – 1:100,000 scale survey of the southern part of the BRIA with four 1:25,000 reference areas. One of these reference areas is on Strathalbyn and covers the southern gullies. A search of the departmental records archive found additional described soil profile records within the study area that were not in the SALI database. Where a location could be determined either from grid references or original project air photos, those soil descriptions were used to determine soil types.

Loi *et al* (1994) – Updated and refined SPCs first developed by Thompson and Reid (1982) with additional information from 1:25,000 scale surveys in selected areas of the BRIA. This guide provides a key to the landscapes and soils within the whole BRIA and was used in this survey.

McClurg (1997) – Medium intensity survey of Strathalbyn Station at a 1:50,000 scale (Figure A2.2) which over laps Thompson et al (1990) Strathalbyn reference area partly. It excludes the eroded (gullied) land and was undertaken for the purpose of sugarcane suitability. The survey conforms to the BRIA soil classification Loi *et al* (1994). Site locations within the SALI database and its derivatives was found to be in error by some hundreds of meters when compared with the original aerial photos used in the project. Site locations have been corrected and site descriptions and soil boundaries used in this project to determine soil types.

The soil mapping from this project is shown in Figure A2.3, augmenting that of the prior maps.

Table A2.3. Soil ID codes for the 1:100,000 Soil survey of the lower Burdekin River mapping in Figure A2.2

MAP CODE	DESCRIPTION	SPC	CONCEPT	AG LAND
2Dba	Brown solodics-solodized solonetz with 5-10cm A horizon, B horizon alkaline by 30cm	Sand or loam over sodic clay - Sodosols, Kurosols	Brown solodics-solodized solonetz with 5 to 10 cm fine sandy clay loam A horizon, profile alkaline by 30 cm.	Limited Crop Land
2Dbb	Brown solodics-solodized solonetz with 10-20cm A horizon, B horizon alkaline by 60cm	Sand or loam over sodic clay - Sodosols, Kurosols	Brown solodics - solodized solonetz with 10 to 20 cm fine sandy clay loam A horizon, profile alkaline by 60 cm.	Limited Crop Land
2Dyb	Grey solodics-solodized solonetz with 12-20cm A horizon, B horizon alkaline by 60cm	Sand or loam over sodic clay - Sodosols, Kurosols	Grey and dark solodics - solodized solonetz with 12 to 20 cm medium textured A horizon, profile strongly alkaline by 60 cm.	Crop Land - Broadacre and Horticulture
2Dyc	Gilgaied grey solodics-solodized solonetz	Sand or loam over sodic clay - Sodosols, Kurosols	Gilgaied grey solodics - solodized solonetz with 10 to 25 cm medium textured A horizon, profile strongly alkaline by 90 cm.	Crop Land - Broadacre and Horticulture
2Ugb	Dark grey medium to medium heavy cracking clay, alkaline by 120cm	Cracking clay soils - Vertosols	Dark grey medium to medium heavy clay with weakly mottled A horizon, profile alkaline by 120 cm.	Crop Land - Broadacre and Horticulture
2Ugc	Grey-brown and grey light cracking clays, alkaline by 90cm	Cracking clay soils - Vertosols	Grey brown and grey clays with weakly mottled light clay surface, profile alkaline by 90 cm.	Crop Land - Broadacre and Horticulture
3Uga	Black earths with carbonate throughout	Cracking clay soils - Vertosols	Black earths with carbonate throughout.	Limited Crop Land
5Drb	Red podzolics	Sand or loam over friable or earthy clay - Chromosols, Kurosols	Red podzolic soils, A2 present.	Crop Land - Broadacre and Horticulture
5Dye	Neutral and alkaline yellow duplex soil with colour A2 horizon	Sand or loam over friable or earthy clay - Chromosols, Kurosols	Neutral and alkaline yellow duplex soils with 15-30 cm sandy clay loam A horizon and colour A2 horizon.	Crop Land - Broadacre and Horticulture
6Dbf	Brown podzolics with 20-30cm A horizon and colour A2 horizon	Sand or loam over friable or earthy clay - Chromosols, Kurosols	Brown podozolic soils with 20 to 30 cm loam A horizon. Colour A2 horizon.	Crop Land - Broadacre and Horticulture
6Dbg	Brown podzolics with 70-100cm A horizon and colour A2 horizon	Sand or loam over friable or earthy clay - Chromosols, Kurosols	Brown podzolic soils with 70 to 100 cm loam A horizon. Colour A2 horizon.	Crop Land - Broadacre and Horticulture
6Drc	Red solodics-solodized solonetz	Sand or loam over sodic clay - Sodosols, Kurosols	Red solodics-solodized solonetz with 25-50 cm medium textured A horizon.	Crop Land - Broadacre and Horticulture
E	Areas of unstable gully erosion, including naturally gullied land	Not Applicable - Eroded land (other)	Miscellaneous type of mapping unit, used to identify areas not typically assessed in detail.	Pasture Land - native pastures, light grazing
H	Hills and areas of >8% slope	Not Applicable - Hills and areas of >8% slope	Miscellaneous type of mapping unit, used to identify areas not typically assessed in detail.	Pasture Land - native pastures

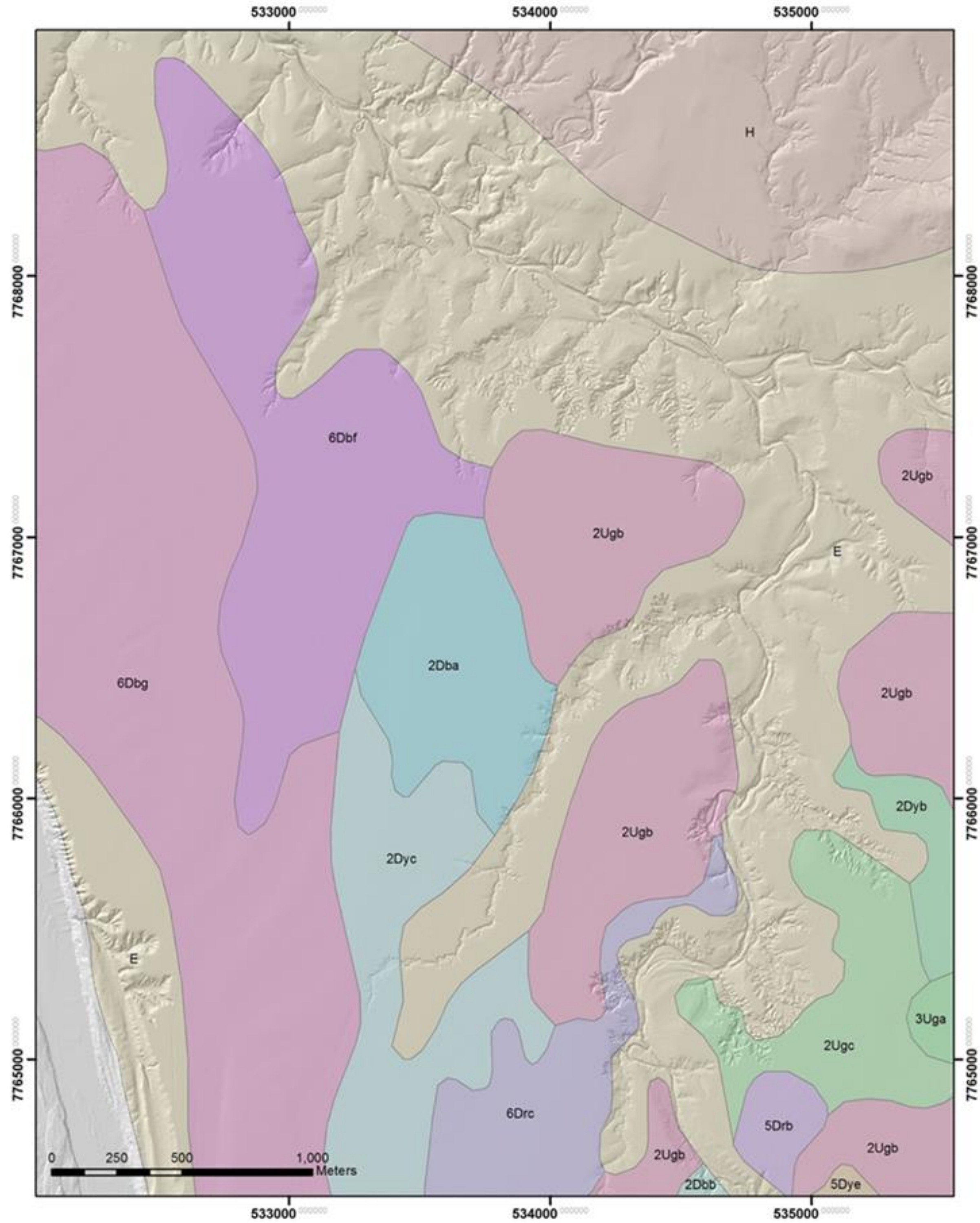


Figure A2.2. The definitive 1: 100,000 scale soil mapping (Thompson et al., 1990) omitting the eroded gully regions.

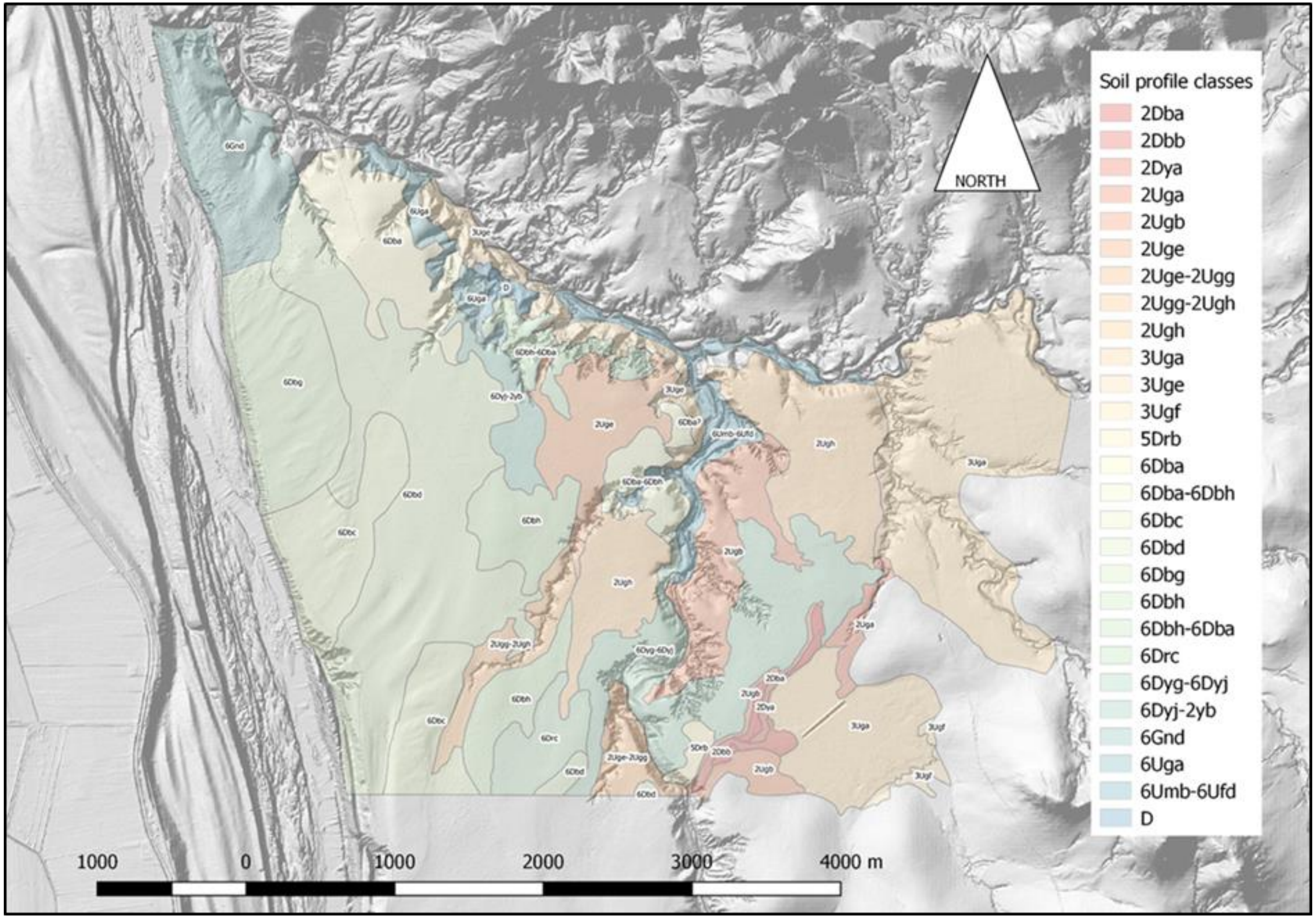


Figure A2.3. The final soil mapping revising the original soil mapping of Thompson and Reid (1982) and Loi et al. (1990).

The Geomorphic Landscape

The study area is located on largely high-level Burdekin River alluvial sediments (mapped as 'Qas' by the Qld Geological Survey. According to Hubble and Thompson (1953) these materials were deposited during the late Pleistocene to early Recent (Holocene) terminating during the early Recent arid period (> 3000 a BP), or at the uplift of land resulting in a 3-5 m rise. To the north (Burdekin R. downstream) the valley floor is constricted by the Bonnie Doon Hills potentially creating a block, resulting in sediment build-up immediately upstream forming the plain of Strathalbyn. The sediments are believed to cover existing rises (by prior planation?) of felsic and mafic rocks (country rock) formed 300 to 270 Ma (Hubble and Thompson, 1953). The thickness of the alluvial sediment is expected to be highly variable because of the original topography of the bedrock rises. Some bedrock of granite and granodiorite was found exposed in gully beds from the investigations connected with this survey, and outcrops of aplite dykes can be traced through the gully systems from exposures in Bonnie Doon Creek. These dykes leave fresh blocks of dark rock strewn across the gully floors and well-broken and fractured material at in situ exposures. Bore logs from the State Government Groundwater database indicate a sediment depth of approximately 25 - 30 m to bedrock on the plain. In a separate project investigation, we have found from deep coring that bedrock is found at 7 m in the area of the Southern gully cluster.

Bonnie Doon Creek rises in the granitic hills 8 km to the south-east of the study site and flows north through the back plain of the Burdekin. The creek is forced west after 15 km by the Bonnie Doon Hills at a point where a tributary of equivalent size and order joins from the east. This tributary rises in the Bogie Range which comprises weathered volcanic rocks: trachyte (feldspar-rich, felsic volcanic) near the top of the range and basalt (mafic volcanic) on the lower slopes. The sediments from this eastern tributary immediately east of the Bonnie Doon Creek junction are characteristically black cracking clays derived typically from basaltic origins. These appear to overlie the older Burdekin River sediments downstream along Bonnie Doon Creek. These sediments are probably palustrine or lacustrine in origin from the late Quaternary, at a low point at the junction of the two drainages.

A small tributary arising south-west of Bonnie Doon Creek on the Strathalbyn plain, appears to be the current expression of a prior backplain drainage, as a backplain swamp or cut-off of the Late Quaternary Burdekin River. Strathalbyn Lagoon is a 60 ha natural lagoon located at the base of granitic rises just east of Bonnie Doon Creek. This lagoon could also have been part of this channel cut-off drainage feature.

Geomorphic landscape regions

Using a system first developed by Hubble and Thompson (1953) and further developed by Thompson and Reid (1990) and Loi (1994) the study area can been split into 'Landscape Units' based on their origin and landform. Table A2.4 describes four topographic forms that occur in the study area which are shown in Figure A2.4.

Table A2.4. Landscape Units common to the study area (after Thompson & Reid 1982).

No.	Landscape Unit	Definition	Occurrence
2	Major river flood plains	Plains of low-lying alluvia with a subtle relative relief provided by old stream lines etc.	Central part of study area
3	Lacustrine plains of local alluvia	Basins of clay plains, drainage lines entering these basins are often indeterminate, ending in overland flow patterns associated with minor alluvial fans. Plains are essentially treeless, except for their margins or for woody weeds.	East of Bonnie Doon Creek
5	Dissected uplands on intermediate intrusives	Undulating timbered uplands on granodiorite and associated intermediate intrusives.	North, east and south of the study area
6	Miscellaneous alluvial deposits	Stream levees, prior streams, benches, terraces, distributary channels, local creek flood plains etc.	Burdekin River levee and along parts of Bonnie Doon Creek

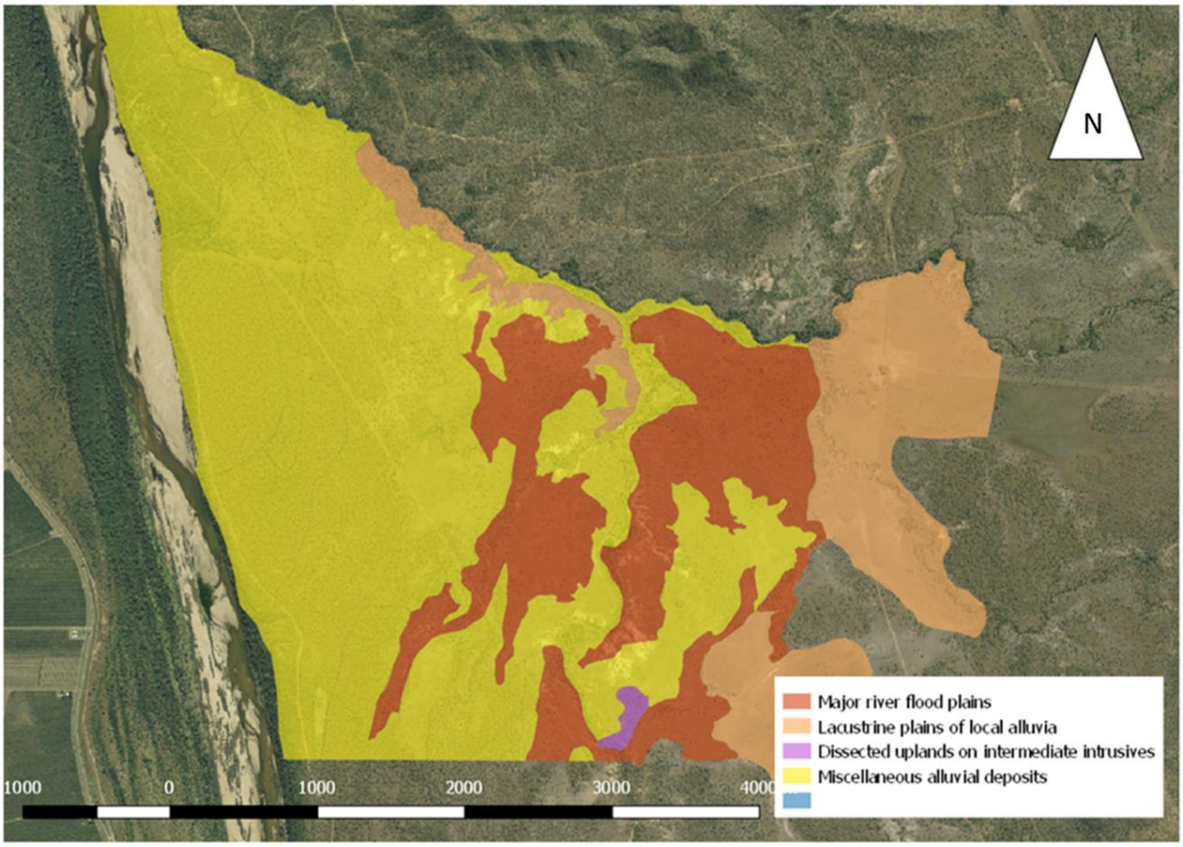


Figure A2.4. Landscape Units for Strathalbyn as defined in Table A2.4.

Crocodile Station soil and geomorphological investigations

Within the study area, the soil materials have been characterised, mapped and correlated to Soils of Cape York (Biggs and Philip, 1995). This is a local soil classification that groups similar soil profile descriptions into areal units (map polygons). Figure A2.5 shows the natural soil distribution at Crocodile when classified using this local soil profile class classification.

The soil map incorporates SPCs from previous soil survey information from the Cape York Land Use Study (CYPLUS) and the Lakeland Irrigation Area where applicable.

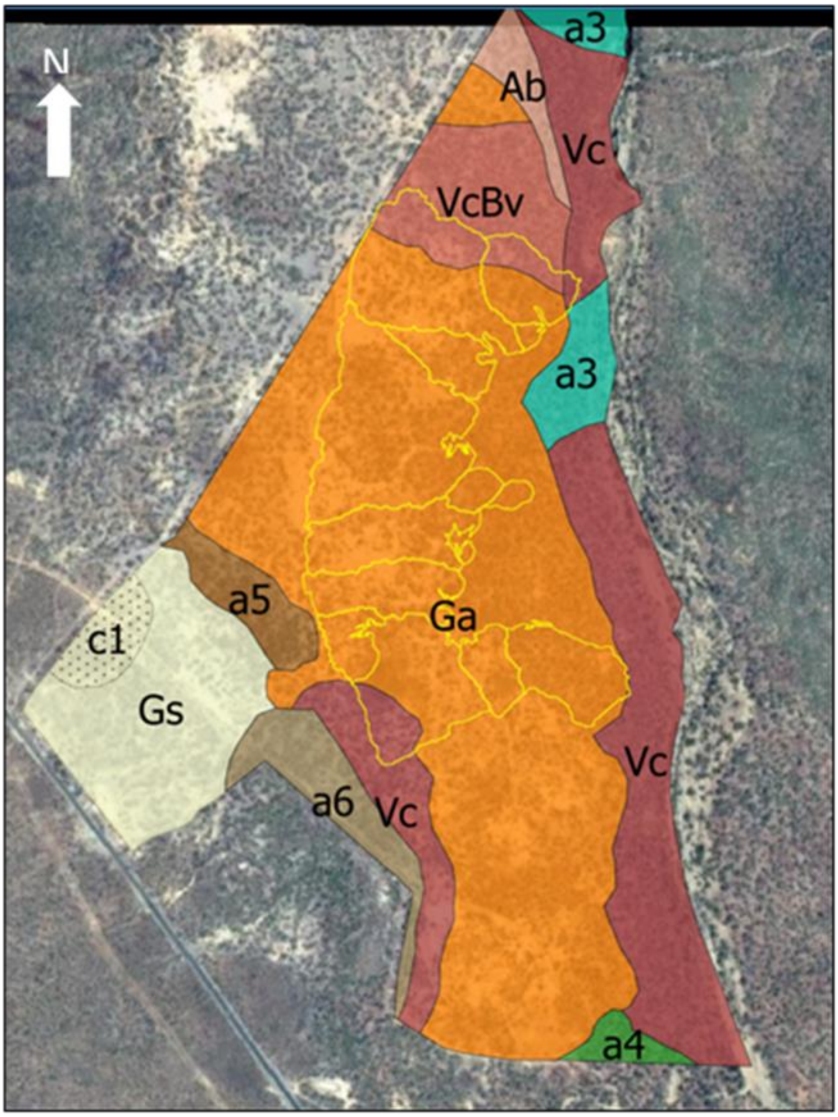


Figure A2.5. The soil map of Crocodile station using the local SPC classes augmented by those identified especially from the area.

The map represents soils that are morphologically different from each other based on material texture, colour, pedality, coarse fragments, parent material, pH, layering, vegetation and boundary characteristics. It is expected that each of these soils will also have distinct or functionally-different analytical (chemical) properties. By associating the soils in the study area with the Soils of Cape York (Biggs and Philip, 1995) where possible, we can use some of known analytical soil properties found during the mapping of Cape York within this area.

For this project we have selected a limited number (four) of sites that represent the dominant soils within the study area near gully erosion areas for additional full analytical analysis.

To enable a quick overview of the study area, the variety of soils found can be summarised using the Australian Soil Classification (ASC) soil orders and sub-orders. The dominant soils are Yellow, Brown or Grey Sodosols and Red Chromosol with also Brown Dermosol and Red Kandosol present.

Yellow, Brown or Grey Sodosols are soils that have a clear/abrupt soil texture change between the A and brown B horizons and are sodic but not strongly acid (pH>5.5) within the upper 0.2m of the B horizon and are not strongly subplastic. There are two SPC's, one (*Greenant*) formed on the older alluvia possibly originating from Earls (Redbank) Creek and one (*Gibson*) formed on colluvial sediments on the lower slopes of the Byerstown Range.

Greenant has a shallow sandy to loamy hard setting surface whereas *Gibson* has a deeper sandy A horizon. *Greenant* subsoils are strongly sodic, saline, magnesic and have an alkaline pH and are extensively eroded whereas *Gibson* subsoils are less sodic and saline but still magnesic and have an acid to neutral pH and few divergent linear gullies.

Red Chromosols are soils that have a clear/abrupt soil texture change between the A and brown B horizons and are non-sodic and not strongly acid (pH>5.5) within the upper 0.2m of the B horizon and are not strongly subplastic. There is one SPC (*Victor*) formed on the older alluvia possibly originating from Earls (Redbank) Creek. It occurs either side of the *Greenant* SPC on the elevated parts of the plain as narrow bands. Considerable amounts of this soil have eroded and deposited onto the floor of large gullies within the enclosure.

Brown Dermosols are soils with structured B horizons and no strong contrast in texture between the A and B horizons and are not Vertosols, Hydrosols, Calcarosols or Ferrosols.

There is one SPC (*Antbed*) formed on the older alluvia within the enclosure that occurs downslope of Victor. It has a sodic, slightly saline and magnesic subsoil making it particularly erodible.

Red Kandosols are soils with a well-developed B2 horizon in which the major part is massive or has only a weak grade of structure and a maximum clay content in some part of the B2 horizon which exceeds 15% (i.e. heavy sandy loam, SL+). There is one SPC (*Mitchel*) formed on the older alluvia within the enclosure near the Laura River and associated with *Victor*. It is quite sandy and only just qualifies as a Kandosol.

Crocodile Station Reference Sites

Soil Type: Victor
Site No: 110
A.M.G. Reference: 241929mE 8265827mN ZONE 55
Geology: Quaternary alluvial sediment
Australian Soil Classification: Bleached, Mesotrophic, Red, CHROMOSOL.
Great Soil Group: Red podzolic soil
Principle Profile Form: Dr2.41
Type of microrelief: Termite mounds
Condition of surface soil when dry: Hard setting

Surface coarse fragments: Very few, small ironstone pebbles
Slope: 1 %
Landform element type: Plain
Landform pattern type: Plain
Vegetation: Tall woodland, *Eucalyptus leptophleba, Erythrophleum chlorostachys* and *Eucalptus brassiana*

Profile morphology:

Horizon	Depth (m)	Description
A1	0.00 to 0.05	Dark yellowish brown (10YR44); clayey sand; massive structure; weak strength when dry; sharp change to
A2e	0.05 to 0.15	Bleached, brown (7.5YR44); sandy loam; massive structure; strong 2-5mm platy structure; very weak strength when dry; abrupt change to
B1	0.15 to 0.28	Strong brown (7.5YR56); few (2-10%) medium (5-15mm) faint red mottles; sandy light clay; strong 2-5mm subangular blocky structure; very firm strength when dry; clear change to
B21	0.28 to 0.41	Yellowish red (5YR46); few (2-10%) fine (<5mm) distinct yellow mottles; light clay; moderate 2-5mm subangular blocky structure; very firm strength when dry; clear change to
B22	0.41 to 0.75	Red (2.5YR46); few (2-10%) fine (<5mm) distinct yellow mottles; light medium clay; strong 2-5mm polyhedral structure; strong strength when dry; gradual change to
B23	0.75 to 1.10	Red (2.5YR56); common (10-20%) fine (<5mm) distinct yellow mottles; light medium clay; strong 10-20mm prismatic breaking to 2-5mm polyhedral structure; strong strength when moderately moist
B31	1.10 to 1.30	Light yellowish brown (2.5Y64); many (20-50%) medium (5-15mm) prominent red mottles; clay loam sandy; strong 2-5mm polyhedral structure; strong strength when moderately moist
B32	1.30 to 1.45	Light yellowish brown (10YR64); many (20-50%) medium (5-15mm) prominent red mottles; clay loam; strong 10-20mm prismatic structure; very few (<2%) fine (<2mm) ferruginous nodules; strong strength when moderately moist

Depth	Aqueous 1:5 soil/water extract			Particle size fractions					Exchangeable (Alcoholic cations)								Dispersion ratio		Soil moisture		
	pH	EC	Cl	Fine Seds	CS	FS	SI	CLA	CEC	Ca	Mg	Na	K	ESP	Ca/Mg	CEC/Clay	R1	R2	ADMC	DLL	NO_3
m		ds/m	mg/kg	%<20µm	%	%	%	%	cmol/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	%					%	%	mg/kg
B0-.1	5.7	0.03	<20																		3
0-.05	5.7	0.01	<20	22	18.4	61.3	11	10.9	1.65	1.09	0.31	<0.080	0.21	NA	3.5	0.15	0.86	0.30	<1.5	6.2	<1
.2-.28	5.5	0.01	<20	37	15.3	51.3	12.9	24.2	1.76	0.84	0.79	<0.080	0.09	NA	1.1	0.07	0.81	0.43	<1.5	9.0	<1
.5-.6	5.5	0.02	25	59	8	33.8	11.3	48	4.84	2.3	1.85	0.16	0.12	NA	1.2	0.10	0.44	0.18	1.6	15.3	<1
.8-.9	5.6	0.02	34	56	7.8	37	18	37.7	4.94	2.74	1.93	0.16	0.11	NA	1.4	0.13	0.16	<0.10	<1.5	13.5	<1
1.3-1.4	5.6	0.15	227	59	8.8	32	24.8	34.2	7.40	3.07	3.65	0.54	0.14	NA	0.84	0.22	0.39	<0.10	<1.5	13.2	<1

Depth	Org C	Tot N	Extractable P		Replaceable K	Extractable S	Total P	DTPA Extractable			
			Acid	Bicarbonate				Fe	Mn	Cu	Zn
m	%	%	mg/kg	mg/kg	cmol/kg	mg/kg	%	mg/kg			
B0-0.10	1	0.073	14	<2	0.34	3	<0.013	39.1	37.2	0.2	0.4

Soil Type: Antbed
Site No: 120
A.M.G. Reference: 242444mE 8265961mN ZONE 55
Geology: Quaternary alluvial sediment
Australian Soil Classification: Mottled-Bleached, Eutrophic, Grey, DERMOSOL.
Great Soil Group: Solodic soil
Principle Profile Form: Gn3.06
Type of microrelief: Termite mounds
Condition of surface soil when dry: Firm

Surface coarse fragments: None
Slope: 2 %
Landform element type: Hillslope
Landform pattern type: Plain
Vegetation: Tall woodland, *Eucalyptus leptophleba* with a mid stratum of *Erythrophleum chlorostachys* and *Grevillea striata*

Profile morphology:

Horizon	Depth (m)	Description
A1	0.00 to 0.05	Dark yellowish brown (10YR44); very few (<2%) fine (<5mm) faint orange mottles, very few (<2%) fine (<5mm) faint dark mottles; fine sandy clay loam; massive structure; very firm strength when dry; clear change to
A2e	0.05 to 0.15	Olive yellow (2.5Y66); few (2-10%) fine (<5mm) faint orange mottles and very few (<2%) fine (<5mm) faint dark mottles; clay loam fine sandy; massive structure; very firm strength when dry; abrupt change to
B1	0.15 to 0.55	Brownish yellow (10YR66); few (2-10%) medium (5-15mm) distinct red mottles and few (2-10%) fine (<5mm) distinct grey mottles; fine sandy light clay; moderate 5-10mm subangular blocky structure; very firm strength when dry; clear change to
B21	0.55 to 0.85	Pale brown (10YR63); few (2-10%) medium (5-15mm) distinct red mottles and few (2-10%) fine (<5mm) distinct yellow mottles; light medium clay; strong 2-5mm prismatic parting to strong 2-5mm angular blocky structure; strong strength when dry; clear change to
B22	0.85 to 1.18	Light brownish grey (10YR62); few (2-10%) medium (5-15mm) distinct yellow mottles and few (2-10%) fine (<5mm) distinct red mottles; light medium clay; strong 5-10mm prismatic structure; strong strength when dry; abrupt change to
B3	1.18 to 1.50	Yellowish brown (10YR56); few (2-10%) coarse (15-30mm) distinct red mottles and few (2-10%) fine (<5mm) distinct orange mottles, few (2-10%) fine (<5mm) distinct grey mottles; fine sandy light medium clay; strong 5-10mm prismatic structure; very few (<2%) fine (<2mm) manganiferous root linings; strong strength when moderately moist; many clay skins

Depth	Aqueous 1:5 soil/water extract			Particle size fractions					Exchangeable (Alcoholic cations)								Dispersion ratio		Soil moisture		
	pH	EC	Cl	Fine Seds	CS	FS	SI	CLA	CEC	Ca	Mg	Na	K	ESP	Ca/Mg	CEC/ Clay	R1	R2	ADMC	DLL	NO_3
m		ds/m	mg/kg	%<20μm	%	%	%	%	cmol/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	%					%	%	mg/kg
B0-.1	6.4	0.06	26																		3
0-.05	5.7	0.03	24	22	13.1	58.3	12.7	19.2	2.81	1.44	1	<0.080	0.33	NA	1.44	0.15	0.82	0.48	<1.5	9.4	<1
.2-.3	5.7	0.01	<20	37	9.8	40.3	11	41.2	3.84	1.36	2.24	<0.080	0.2	NA	0.61	0.09	0.66	0.30	<1.5	14.4	<1
.6-.7	5.9	0.08	114	59	4.7	26.3	22.9	51.2	7.59	0.81	5.77	0.85	0.16	11	0.14	0.15	0.65	0.26	<1.5	18.4	<1
1-1.1	7.3	0.32	473	56	8.4	20.7	26.4	46.2	11.9	0.44	7.19	4.07	0.2	34	0.06	0.26	0.99	0.84	<1.5	16.7	<1

Depth	Org C	Tot N	Extractable P		Replaceable K	Extractable S	Total P	DTPA Extractable			
			Acid	Bicarbonate				Fe	Mn	Cu	Zn
m	%	%	mg/kg	mg/kg	cmol/kg	mg/kg	%	mg/kg			
B0-0.10	1.3	0.095	9	7	0.74	3	<0.013	26.0	33.9	0.2	0.6

Soil Type: Greenant
Site No: 126
A.M.G. Reference: 241652mE 8266407mN ZONE 55
Geology: Quaternary alluvial sediment
Australian Soil Classification: Hypocalcic, Mottled-Hypernatric, Grey, SODOSOL.
Great Soil Group: Solodized solonetz
Principle Profile Form: Dy5.43
Type of microrelief: Termite mounds
Condition of surface soil when dry: Firm

Surface coarse fragments: None
Slope: 1 %
Landform element type: Plain
Landform pattern type: Plain
Vegetation: Tall woodland, *Eucalyptus leptophleba* with *Erythrophleum chlorostachys*

Profile morphology:

Horizon	Depth (m)	Description
A1	0.00 to 0.03	Dark greyish brown (10YR42); loamy sand; massive structure; very weak strength when dry; abrupt change to
A2e	0.03 to 0.30	Pale brown (10YR63); sand; massive structure; loose when dry; sharp change to
B21	0.30 to 0.55	Dark greyish brown (10YR42); common (10-20%) medium (5-15mm) distinct orange mottles; sandy light clay; strong 20-50mm prismatic structure; many (20-50%) fine (<2mm) manganiferous root linings; strong strength when dry; few clay skin; clear change to
B22	0.55 to 0.86	Light olive brown (2.5Y54); common (10-20%) medium (5-15mm) distinct orange mottles and very few (<2%) medium (5-15mm) distinct red mottles; sandy light medium clay; strong 20-50mm prismatic structure; strong strength when dry; few clay skin; clear change to
B23	0.86 to 1.20	Yellowish brown (10YR56); light medium clay; strong 20-50mm prismatic breaking into strong 5-10mm angular blocky structure; very few (<2%) fine (<2mm) calcareous soft segregations; strong strength when dry; common clay skin; clear change to
B24	1.20 to 1.40	Strong brown (7.5YR56); many (20-50%) fine (<5mm) distinct red mottles; light clay; strong 20-50mm prismatic parting into strong 2-5mm subangular blocky structure; few (2-10%) medium (2-6mm) manganiferous soft segregations; strong strength when dry; common clay skin

Depth	Aqueous 1:5 soil/water extract			Particle size fractions					Exchangeable (Alcoholic cations)								Dispersion ratio		Soil moisture		
	pH	EC	Cl	Fine Seds	CS	FS	SI	CLA	CEC	Ca	Mg	Na	K	ESP	Ca/Mg	CEC/Clay	R1	R2	ADMC	DLL	NO_3
m		ds/m	mg/kg	%<20µm	%	%	%	%	cmol/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	%					%	%	mg/kg
B0-.1	5.6	0.02	<20																		<1
0-.1	5.5	0.02	<20	19	32.2	52.1	11.3	7.3	1.09	0.56	0.21	<0.08	0.09	NA	2.67	0.15	0.75	0.43	<1.5	4.3	<1
.4-.5	6.2	0.41	593	32	23.9	38.2	11.2	30.9	6.15	0.29	3.38	2.39	0.09	38.9	0.09	0.20	0.91	0.92	<1.5	12.3	<1
.7-.8	8.7	0.49	705	49	19.1	37.3	11.3	37.7	7.59	<0.600	3.17	4.67	0.14	66.7	0.19	0.20	0.97	0.86	<1.5	13.8	<1
1.1-1.2	9	0.67	1000	69	8	29.8	26.4	42.8	11.9	<0.600	4.02	7.58	0.13	84.2	0.15	0.20	0.99	1.00	<1.5	17	<1

Depth	Org C	Tot N	Extractable P		Replaceable K	Extractable S	Total P	DTPA Extractable			
			Acid	Bicarbonate				Fe	Mn	Cu	Zn
m	%	%	mg/kg	mg/kg	cmol/kg	mg/kg	%	mg/kg			
B0-0.10	1	0.049	20	4	0.21	2	<0.013	83.1	7.8	0.1	0.3

Soil Type: Gibson
Site No: 129
A.M.G. Reference: 241568mE 82655745mN ZONE 55
Geology: Quaternary colluvial sediment
Australian Soil Classification: Hypocalcic, Hypernatric, Yellow, SODOSOL.
Great Soil Group: Solodic soil
Principle Profile Form: Dy2.43
Type of microrelief: Termite mounds
Condition of surface soil when dry: Hard setting

Surface coarse fragments: None
Slope: 3 %
Landform element type: Fan
Landform pattern type: Hills
Vegetation: Tall woodland, *Eucalyptus leptophleba*

Profile morphology:

Horizon	**Depth (m)**	**Description**
A1	0.00 to 0.08	Brown (10YR53); loamy sand; massive structure; very weak strength when dry; abrupt change to
A2e	0.08 to 0.40	Bleached, light olive brown (2.5Y54); sand; massive structure; very weak strength when dry; sharp change to
A31	0.40 to 0.50	Yellowish brown (10YR54); few (2-10%) medium (5-15mm) distinct orange mottles; sandy clay loam; weak structure; very firm strength when dry; clear change to
A32	0.50 to 0.68	Light olive brown (2.5Y54); few (2-10%) medium (5-15mm) faint orange mottles; sandy clay loam; weak structure; very few (<2%) fine (<2mm) manganiferous root linings; strong strength when dry; abrupt change to
B2	0.68 to 1.16	Light yellowish brown (2.5Y64); few (2-10%) medium (5-15mm) distinct red mottles; sandy light medium clay; strong 5-10mm angular blocky structure; very few (<2%) fine (<2mm) manganiferous root linings; very firm strength when moderately moist; few clay skin; clear change to
B3	1.16 to 1.32	Light olive brown (2.5Y54); few (2-10%) fine (<5mm) distinct dark mottles; sandy light medium clay; very few (<2%) small (2-6 mm) sub-rounded quartz pebbles; moderate 50-100mm prismatic structure; few (2-10%) fine (<2mm) manganiferous root linings; strong strength when moderately moist; many clay skin

Depth	**Aqueous 1:5 soil/water extract**			**Particle size fractions**					**Exchangeable (Alcoholic cations)**								**Dispersion ratio**		**Soil moisture**		
	pH	**EC**	**Cl**	**Fine Seds**	**CS**	**FS**	**SI**	**CLA**	CEC	Ca	**Mg**	**Na**	**K**	ESP	**Ca/Mg**	**CEC/Clay**	**R1**	**R2**	**ADMC**	**DLL**	**NO_3**
m		**ds/m**	**mg/kg**	**%<20µm**	**%**	**%**	**%**	**%**	cmol/kg	cmol/kg	cmol/kg	cmol/kg	cmol/kg	%					**%**	**%**	**mg/kg**
B0-.1	5.9	0.49	696																		<1
0-.1	5.1	0.14	203	23	21.8	56.8	14.4	9	1.32	.31	0.37	<0.08	0.19	NA	0.84	0.15	0.86	0.66	<1.5	4.6	<1
.2-.3	5.5	0.1	143	22	24	56.1	12.8	8.8	1.37	<0.14	0.71	0.163	0.05	11.9	0.10	0.16	0.88	0.68	<1.5	4.4	<1
.9-1	6.9	0.34	475	35	20.7	48.1	12.6	22.6	5.54	0.23	3.43	1.79	0.09	32.3	0.07	0.25	0.94	0.94	<1.5	9.2	<1

Depth	**Org C**	**Tot N**	**Extractable P**		**Replaceable K**	**Extractable S**	**Total P**	**DTPA Extractable**			
			Acid	**Bicarbonate**				**Fe**	**Mn**	**Cu**	**Zn**
m	**%**	**%**	**mg/kg**	**mg/kg**	**cmol/kg**	**mg/kg**	**%**	**mg/kg**			
B0-0.10	1.1	0.065	10	7	0.35	8	<0.013	59.4	19.6	0.1	0.8

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