

Quantifying the effectiveness of gully rehabilitation on water quality: results from demonstration sites in the Burdekin catchment

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ACRONYMS

BACI	Before, After, Control, Impact
DAF	Department of Agriculture and Fisheries [Queensland]
DEM	Digital Elevation Model
DES	Department of Environment and Science [Queensland]
DOD	DEM of difference
DPI	Department of Primary Industry [Queensland]
EMCs	Event Mean Concentrations
EOD	End of the Dry season
EOW	End of the Wet season
FRP	Filterable Reactive Phosphorus
GBR	Great Barrier Reef
LDC	Landholders Driving Change
Lidar	Light Detection and Ranging
NESP	National Environmental Science Program
NQDT	NQ Dry Tropics
NRM	Natural Resource Management
PCDs	Porous Check Dams
PSA	Particle Size Analysis
P2R	Paddock to Reef
RRRC	Reef and Rainforest Research Centre Limited
RSS	Rising Stage Samplers
RTK	Real Time Kinematic
TLS	Terrestrial laser scanner
TN	Total Nitrogen
TSS	Total suspended sediment
TWQ	Tropical Water Quality

ABBREVIATIONS

cm	centimetre
ha	hectare
kg/ha	kilograms per hectare
kg/y	kilograms per year
km	kilometre
km²	square kilometres
mg/L	milligrams per litre
mm	millimetre
t/ha/y	tonnes per hectare per year
t/y	tonnes per year
t/m³	tonnes per cubic metre
ug/L	micrograms per litre
µm	micrometre

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PREFACE

This document represents the 2019/20 annual wet season report for NESP Project 5.9 (Gully rehabilitation effectiveness) and the Landholders Driving Change (LDC) contracts LRP17-003 and LME17-009. This report presents the 2019/20 monitoring results for control/treatment gully rehabilitation projects on seven properties in the Burdekin catchment. For four of those properties, the data represents the cumulative monitoring results that were initiated in 2016/17. The funding for the implementation of rehabilitation works, and the subsequent monitoring of these activities, came from a range of sources (Table 1). The focus of this report is on the monitoring of land condition, runoff and water quality response following various gully rehabilitation treatments.

This report is written as a stand-alone report, and all the pasture, land condition, runoff and water quality data has been updated to include the 2019/20 wet season data where available. There is considerable repetition from previous reports, as we have attempted to ensure consistent and repeatable methods between years. This allows comparison between the baseline or pre-treatment data and subsequent post-rehabilitation data (Bartley et al., 2017; Bartley et al., 2018a; Bartley et al., 2019).

It is important to note that the 2019/20 wet season was one of the driest on record for the Burdekin region and rainfall was well below average for several sites. This meant that the Virginia Park and Meadowvale gullies experienced no runoff events in 2019/20. Subsequently no new runoff or water quality data are presented for these sites. Several of the treatment sites (Strathbogrie treatment and Glen Bowen treatment) also did not produce any measurable runoff or water quality samples, which is likely to be a combination of low rainfall and treatment effects. Pasture and land condition data were still collected and presented for all sites. Due to the COVID-19 travel restrictions, the end of 2019/20 wet season terrain scans (using the terrestrial laser scanner) for the initial four NESP sites were not completed in time for this report as key staff associated with this instrument are based in NSW.

A list of the peer reviewed journal publications that have been linked to this project over the last five years are presented in Appendix D. Several papers have had major NESP TWQ Hub funding contributions (e.g. included NESP TWQ Hub funded equipment, data, travel time or extensive writing time) and other papers had only minor NESP TWQ Hub funding contributions (e.g. staff writing time). Based on the data presented in this report, several other publications are in preparation for submission in 2021.

Table 1: Property name, length of monitoring data and funding source for each site

Property name	Years of monitoring data	Funding sources (for monitoring and rehabilitation)
Virginia Park	4 years	P2R, NESP
Meadowvale	4 years	NESP
Strathbogrie	4 years	NESP, LDC
Minnievale	4 years	NESP, Reef Trust
Mt Wickham	3 years	LDC, NESP
Glen Bowen	1 year	LDC
Mt Pleasant	1 year	LDC

EXECUTIVE SUMMARY

Gully erosion contributes ~40% of the excess fine sediment to the Great Barrier Reef from just ~0.1% of the catchment area, however, the methods and approaches for reducing this erosion source are not well tested in this region. Gully erosion is a complex and spatially variable process influenced by soil properties, terrain, surface runoff, sub-surface drainage and vegetation. There is significant government investment in GBR water quality improvement focused on reducing gully erosion, and there is an urgent need to evaluate the most cost-effective methods for reducing the sediment and particulate nutrients generated and delivered from this erosion source.

The studies reported here were designed to evaluate the effectiveness of a diversity of rehabilitation options for a range of gully types found within rangeland systems of the Burdekin catchment. To allow comparison across the various projects, a consistent approach to monitoring and evaluation was used across all sites and studies.

The evaluation presented here was based on gully monitoring on seven properties from the Burdekin Natural Resource Management (NRM) Region; two properties in the Upper Burdekin catchment, one in the Don, two in the Bogie and two in the Bowen catchment. The rehabilitation options implemented on the treatment gullies varied and included activities such as fencing, livestock management, small sediment trapping check dams within the gullies, diversion banks upslope of gully heads, and larger engineered approaches including re-shaping and rock grade control structures (Table 2).

To quantify the effectiveness of the various treatment options a suite of monitoring equipment and sites has been set up on both a treatment and control gully at each location. The monitoring metrics include (i) estimates of land condition, vegetation cover, biomass and species diversity on the hillslopes above each gully as well as within the gullies, (ii) repeated terrain scanning to estimate changes in erosion and deposition (primarily in gully headcut areas), and (iii) water quantity and quality monitoring that provided the measurement of flow depth, velocity, runoff volume, turbidity, sediment and nutrient concentration and sediment particle size. Water quality samples from these sites have also been shared with other projects looking to connect water quality metrics at the property scale to catchment and marine condition. The monitoring periods varied for each of the properties depending on the implementation date of the rehabilitation. The paired monitoring periods varied between one and four years. The hydrological reporting period presented in this report is focused on the summer wet season 1st November 2019 until 30th April 2020, however, where appropriate data from all sampled wet seasons are presented.

(1) Key findings from the monitoring sites

(a) Spatial variation of erosion and water quality in gullies

- Across the sites, annual average soil loss from gullies is strongly dependent on the drainage area above the gully head-cuts. Catchment area is a surrogate for runoff volume or energy and is the strongest predictor of sediment yield found in this study; however, other studies have also found soil properties and vegetation condition to be important. Therefore, the

catchments above gullies should be a continued focus of grazing management or remediation interventions.

- The total suspended sediment (TSS) concentrations varied considerably between control sites with the highest median concentrations measured at Glen Bowen (53,000 mg/L) and Mt Wickham (~47,000 mg/L), and the lowest concentrations at Mt Pleasant (60 mg/L). The other sites had median concentrations between ~1,300 and ~6,300 mg/L. Mt Wickham and Glen Bowen gullies have both formed on sodosol dominated landscapes.
- Total nitrogen (TN) concentration values are highly variable between sites, and between events within sites, and not as responsive as sediment to rehabilitation treatment. TN concentrations show a similar pattern of variation between sites although the differences are of smaller magnitude than for TSS.
- There are differences in the sediment yields (t/ha/yr) estimated using different measurement approaches (loads monitoring vs terrain analysis). A multiple lines of evidence approach is encouraged until further data is collected to resolve these differences.

(b) Calculating rehabilitation effectiveness

- When sites have water quality and runoff data collected from periods both before and after treatment, from control and treatment sites, statistical analysis can be used to calculate the effectiveness of the rehabilitation on erosion control (as described in Section 3.7 and 3.8). This approach takes in account variations in response due to inter-annual rainfall variability between wet seasons.
- If water quality samples have been adequately sampled across the flow event hydrograph for the main events in all seasons at both control and treatment sites (including first flush and peak events) then it is suitable to use concentration data to evaluate rehabilitation effectiveness.
- However, comparison of changes in the sediment loads between sites is the most appropriate metric to use to evaluate treatment effectiveness, as this represents the total tonnes of fine sediment delivered or saved due to the rehabilitation. It is acknowledged that runoff and load data are notoriously challenging to obtain and highly uncertain in these flashy systems, however, loads are considered important for gold standard monitoring.
- When using control and treatment data, without coincident before data at each site, or using before and after data at a treatment site, without a control site to compare to, it is possible to detect changes, but it is difficult to attribute these to the treatment effects alone. The changes could be influenced by variations in rainfall, runoff or individual gully dynamics. For sites without before data, indicative trends can be identified, but longer time frames (e.g. >5 years) will likely be required to detect statistically significant changes that are independent of rainfall/runoff variability.

(c) Livestock management and revegetation

- Most sites have shown some improvement in % cover or biomass following treatment; however, gully catchment land condition remains in C or D class for most sites. This is because the pasture species are primarily dominated by the exotic perennial grass Indian couch, forbs, and/or exotic legumes. Indian couch produces less biomass and is more

sensitive to seasonal climate variations than native perennials, resulting in relatively poor infiltration.

- The 'fencing off only' rehabilitation site (Meadowvale) has shown improved gully floor/channel vegetation biomass, which is increasing the sediment trapping potential of the site.
- Grazing management during and following rehabilitation needs to be carefully monitored to ensure treatments are not compromised. In most cases it is important to give treated areas a spell from grazing to allow vegetation to recover from the initial disturbance associated with rehabilitation. Grazing can then be reintroduced using an adaptive management approach.

(d) Porous Check Dams

- The sites that have had fencing and porous check dams installed (Virginia Park and Minnievale) are showing improvements in the vegetation metrics in the gully floor/channel and gully walls. This increased cover, in conjunction with the sediment check dam structures, has resulted in high (>90%) sediment trapping. However, the material that is being trapped is predominantly coarse (>63 μm) sediment.

(e) Hillslope runoff diversions above the gully

- The treatment at Strathbogie focused on hillslope runoff diversion banks which have effectively 'starved' the active gully and statistically improved the runoff and water quality metrics for this site. Given the site has statistically improved water quality and sediment yields following treatment, an effectiveness value of ~0.95 was calculated for this treatment. However, this first year was relatively dry, and the test will be whether the diversion banks concentrate surface runoff and cause gully initiation elsewhere. Subsequent wetter years will be an important test for this site. The land condition is still relatively poor and should be the focus for the long-term resilience of this site. Hence, this effectiveness value needs to be used with caution, and can be considered preliminary.
- Hillslope diversions always require careful design, placement and maintenance of the structures to prevent the breaching of the structures or the initiation of new gullies where diverted water accumulates. Ripping and seeding is also known to have a relatively short-lived influence on pasture and runoff, and should not be considered a replacement for improved grazing land management.

(f) Runoff management within a gully

- The Mt Pleasant site implemented a landscape rehydration project that aimed to reduce the erosive force of runoff within the treatment gully. This project appears to have had some success; however, the changes between the treatment and control site are small, as the property was already in relatively good condition compared to other sites. When properties have good vegetation metrics, and relatively mature and in-active gully systems, gully rehabilitation is not worth doing for water quality benefits alone. There is negligible improvement in terms of water quality and sediment savings relative to other more active gully sites, however, there may be other benefits including increased ecological habitat.

(g) Gully reshaping, structural control and revegetation

- The larger scale rehabilitation works at Mt Wickham have resulted in statistically improved vegetation metrics on the hillslope and within the gully after just two wet seasons. There are also statistically significant improvements in total suspended sediment (TSS) concentrations following the major earth works at the treatment site. Sediment loads have also declined following treatment, relative to the un-treated control. Given the site has statistically improved water quality and sediment yields following treatment, the effectiveness value was calculated as ~0.85 for this treatment. Additional years of data will determine how variable this effectiveness value is for a broader range of rainfall seasons.
- The larger scale rehabilitation works at Glen Bowen have shown early signs of success with significantly improved cover and biomass on the treatment site. Visually, the water leaving the treatment site is relatively clear and considerably less turbid than the control site which reached sediment concentrations as high as 64,000 mg/L. The vegetation will need to be carefully managed at the treatment site due to the low rainfall during the establishment phase.

(2) Key messages for management and policy

- This type of research will continue to deliver improvements in understanding for many years as an increasing range of climates are experienced and as the composition of revegetation continues to develop. These studies require a high level of expertise, and a lot of luck with respect to rainfall and instrumentation behaviour, to produce reliable results.
- While the quantitative data on sediment reductions will continue to emerge, the qualitative information such as terrain monitoring of gully erosion, photographs of event runoff, vegetation responses and treatment intactness provides early information to support gully rehabilitation.
- The P2R program has been modelling possible/potential water quality improvement following land management rehabilitation for more than a decade; however, there is very little measured data available to constrain model predictions. This study presents some of the first control/treatment field experiments that are measuring changes in water quality on the ground. The data from these projects will be critical for scenario analysis using the P2R modelling.
- Due to the variability in erosion rates within and between gully types, cost-effectiveness values will vary between sites, even when the same treatment is used. The key to ensuring remediation resources are allocated cost-effectively is (i) to match the treatment \$ value proportionally to sediment loss, and (ii) prioritise sites with high current erosion rates, and high delivery to coastal systems.

(3) Recommendations for other rehabilitation projects

- Due to the high variability in rainfall and site characteristics in these landscapes, whenever possible, measurements should be collected from both control and treatment sites for at least one, preferably two, wet seasons prior to rehabilitation works being undertaken. This provides much greater statistical power to detect and quantify changes in shorter time frames. It also allows for instrumentation breakdowns, which do occur in these challenging and remote conditions.

- Some sites are more suited to quantitative evaluation of rehabilitation effectiveness than others. It is important to have comparable treated and untreated control gullies (e.g. the same soil, vegetation, rainfall, terrain, morphology, instrumentation) otherwise monitoring design and site selection may introduce additional bias into the statistical analysis that reduces the ability to detect a change.
- Where funding permits, the same instrumentation should be used at both control and treatment sites. Using cheaper cut-down monitoring equipment reduces the number of samples collected, and subsequently reduces the statistical power to detect changes between control and treatment sites.

Table 2: Summary of the treatment history and monitoring results for all sites; *represents early indicator, pending further data, NA = not available.

		Virginia Park	Meadowvale	Strathbogrie	Minnievale	Mt Wickham	Glen Bowen	Mt Pleasant
	Burdekin basin	Upper Burdekin	Upper Burdekin	Bogie	Don	Bowen	Bowen	Bogie
	Managing organisation	CSIRO	CSIRO	NQDT	Greening Aust.	NQDT (Verterra)	NQDT (Neilly Group)	NQDT (Mulloon Institute)
	Gully type	Linear hillslope gullies and scalds	Linear hillslope gullies and scalds	Linear hillslope gullies	Linear hillslope gullies and scalds	Scalds and major alluvial gullies	Scalds and major alluvial gullies	Linear hillslope gullies and scalds
	Average annual long-term rainfall (mm) from nearest BOM site	~ 660 mm	~ 680 mm	~ 750 mm	~ 880 mm	~600 mm	~ 725 mm	~ 690 mm
	Soil type	Red Chromosol	Red Chromosol	Black Vertosol	Sodic Hypocalcic Red Dermosol	Hypernatric Brown Sodosol	Brown or Yellow Sodosols	Black and Brown Chromosols and Brown Sodosols .
	Catchment area (ha) above monitoring station at treatment site	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha
	Primary treatment	- Disc plough above the treatment gully - Fenced off gully (electric fence) - Porous check dams installed in the gully (n=6)	- Four strand cattle exclusion fence around the gully - ~30% of the gully catchment has long term cattle exclusion	- Five hillslope flow diversion banks with two drains - Fencing - Small rock revetment near headcut	- Hillslope ripped, and seeded (creeping blue grass, V8 stylo, R.Rhodes etc) - Fencing - Total of 200 timber porous check dams installed	- Major earth works, soil treatment, rock chute structures - Fencing - Significant re-veg using mixed exotic species	- Major earth works, soil treatment, rock chute structures + earth bund, water points - Fencing - Significant re-veg using mixed exotic species	- Landscape rehydration - Four v-notch log rock sill structures and an earth bank to divert flows - Fencing and trough
	Grazing management in treatment paddock	Historically this site has undertaken wet season spelling and forage budgeting.	No grazing management outside of enclosure areas.	No grazing management.	Grazing Mgt Plan. Reduced stock numbers in treatment paddock.	Cattle have been excluded since works began, but future grazing proposed.	Cattle excluded during rehab. Low stock numbers and short duration graze proposed.	Exclusion for limited periods and then rotational grazing.
	No. years treatment in place	10	3	1	4	2.5	1	1
	No. years of control/treatment monitoring	3-4	3-4	4	4	3	1	1
	Total cost (\$) of on-ground works	\$3.5k	\$3.8k	~\$44k	~\$27k	\$595k	~\$840k	\$95k
Measured improvement at treatment site compared to control.	Land condition	Improved	Improved	Declined	Improved	Improved	No significant effect	No significant effect
	Vegetation (hillslope + gully)	Improved	Improved	No significant effect	Improved	Improved	Improved	Improved
	Erosion rate (headcut)	Improved	Improved	Improved*	Improved	NA	NA	NA
	Sediment concentrations	Improved	No significant effect	Improved	Improved	Improved	Improved*	No significant effect
	Sediment loads	No significant effect	No significant effect	Improved	No significant effect	Improved	NA	No significant effect
	Treatment effectiveness value			0.95		0.85		

1.0 INTRODUCTION

There is considerable evidence demonstrating that excess sediment and associated nutrients from catchments adjacent to the Great Barrier Reef (GBR) are having a deleterious influence on seagrass beds (Waycott et al., 2005) and inshore coral reef ecosystems (De'ath et al., 2012). Gully erosion covers just 0.1% of the catchment area draining to the GBR, however, sediment source tracing, erosion mapping and load monitoring indicates that gully erosion supplies ~40% of the fine sediment (silt and clay, <63 µm particle size) exported from river basins to the GBR lagoon (Olley et al., 2013; Wilkinson et al., 2015a). The area occupied by gullies is estimated to have increased ~ 10 fold since European settlement in parts of Northern Australia (Shellberg et al., 2010), and the length of gullies in GBR catchments is now estimated to be in excess of 87,000 km (Wilkinson et al., 2015a).

In tropical Australia, gullies can be broadly differentiated into two types: large alluvial gullies (McCloskey et al., 2016; Shellberg et al., 2016) and the smaller, more ubiquitous linear or hillslope gullies (Wilkinson et al., 2018). Both gully forms are likely to be a major anthropogenic sediment source to the GBR. Gully erosion is known to be related to soil properties (Wilkinson et al., 2015a; Castillo and Gómez, 2016), surface and sub-surface runoff (Vanmaercke et al., 2016), terrain attributes (Chaplot, 2013) and vegetation above and below the ground (Prosser and Slade, 1994; Gyssels et al., 2005; De Baets et al., 2009). Although the specific location, causes and timing of gully erosion in tropical Australia are not fully understood, emphasis has now turned to understanding the cost-effectiveness of gully rehabilitation options, with the longer-term goal of reducing sediment and particulate nutrient delivery to the GBR.

Gully erosion has been a problem across many parts of the world since 750 AD (Doolittle, 1985) and gully rehabilitation, using structures like check dams, have been used for centuries in some areas (Quinonero-Rubio et al., 2016; Wei et al., 2016). There is evidence from other parts of the world that gully rehabilitation can be effective on smaller linear gullies (Polyakov et al., 2014; Nichols et al., 2016; Guyassa et al., 2017) and on larger alluvial or badland systems (Hevia et al., 2014; Ranga et al., 2016). There is, however, very limited data on the effectiveness of various gully rehabilitation approaches in the tropical catchments draining to the GBR.

Hundreds of millions of dollars are spent each year on catchment and stream rehabilitation across the globe in an effort to reduce the amount of sediment and nutrients delivered to ecologically sensitive receiving waters (Bernhardt et al., 2005; Kondolf et al., 2008; Kurth and Schirmer, 2014; Wohl et al., 2015). However, measuring the effectiveness of these investments is challenging due to the variability in erosion processes and long lag times between rehabilitation implementation and water quality (Zhang et al., 2017) or ecological response (Kroon et al., 2014). In 90% of stream restoration projects in the USA, there was no monitoring of project effectiveness and limited data were collected to determine which activities were successful and those that were not (Bernhardt et al., 2005). This greatly limits the transferability of approaches between locations and makes calculating the cost-effectiveness of such programs very challenging.

This program is focused on using a combination of vegetation management and structural control approaches. This is because vegetation (grass) management, on its own, is unlikely to

meet the current water quality goals within the time frames required (Bartley et al., 2014), and engineered gully structures are known to have a limited lifespan (Gellis et al., 1995) or high failure rate (Nyssen et al., 2004). Long term studies have shown that downstream water quality can be improved using a combination of engineering and vegetation management (Guyassa et al., 2017; Zhang et al., 2017; Bartley et al., 2020).

This project aims to provide measured evidence of the effectiveness of these gully rehabilitation approaches for landholders interested in protecting and enhancing forage productivity, and for the organisations investing in activities to reduce sediment and nutrient loads delivered to the Great Barrier Reef. The project aims to (i) provide new knowledge about the links between gully rehabilitation, vegetation and land condition, erosion rates and water quality and (ii) to help quantify the effectiveness of rehabilitation strategies used in the Reef Trust and Landholders Driving Change (LDC) projects.

The study is focused in the Burdekin basin, as this catchment is the highest contributor of anthropogenic sediment to the GBR (Kroon et al., 2012; Bainbridge et al., 2014; Bartley et al., 2015). This report presents the experimental design and study site description in Section 2 and site methods in Section 3. The results that are common to all sites are presented in Section 4.0, and then the results for each individual property are given in Section 5. A discussion of the key findings and recommendations for future work are given in Section 6.

2.0 STUDY SITES AND EXPERIMENTAL DESIGN

2.1 The Burdekin catchment

All the sites presented in this study are in the Burdekin Region (Figure 1). The Burdekin catchment is ~130,000 km² and drains into the GBR Lagoon south of Townsville on the east coast of Australia. It has the largest mean annual runoff of any of the GBR catchments at 10.29×10^6 ML and is the largest contributor of anthropogenic derived fine sediment to the GBR lagoon (Kroon et al., 2012). The Burdekin river directly influences ~47,000 km² of marine area which includes ~246 coral reefs and 73 seagrass beds (Devlin et al., 2012), however, the flood plume from the Burdekin catchment can extend as far north as Cairns in high runoff years (Brinkman et al., 2014; Waterhouse et al., 2015).

2.2 Selection of experimental sites

The key question that we were asking in this study was, ‘is there a measurable improvement in the land condition, erosion and water quality leaving remediated gully sites compared to sites left un-treated?’ Experience elsewhere shows that experiments able to quantify an improvement in water quality generally have the following attributes (Melland et al., 2018):

- Control sites paired with treatment sites.
- Before data or baseline data (often at least 2 years of baseline data) at both control and treatment sites.
- Constituent loads data which requires robust measurements of discharge (Q) and water quality concentrations.
- Coincident events between control and treatment sites. This means that treatment and control sites should be located as close to each other as possible so that rainfall (and hopefully) runoff conditions are similar.

These attributes include the key features of a BACI (before, after, control, impact) experimental design (Green, 1979). We applied a BACI design where possible, but at some site's circumstances prevented pre-treatment data being collected. This reduces the statistical power to measure the effect of a change that can be directly attributed to the ‘treatment’ at those sites. It is very difficult to obtain control and treatment sites in natural or agricultural settings that are going to have exactly the same physical characteristics such as drainage area and topography (slope and degree of surface convergence). Where-ever possible, we selected treatment and control sites with the same soil type and vegetation. Landholder input and the suitability of sites for monitoring equipment installation and access also influenced site selection.

Our experimental design aimed to cover a range of soil types and management practices. We focused on the catchment areas regarded as high priority for gully erosion control, such as the Bowen Bogie River catchments, as well as building on extensive baseline monitoring in the Upper Burdekin River catchment. Additional sites are included in this report to progressively increase the range of site conditions across which treatment effects are being evaluated (see Table 3).

Monitoring was undertaken at seven properties in the Burdekin catchment: two in the Upper Burdekin (Virginia Park and Meadowvale), two in the Bogie (Strathbogie and Mt Pleasant), two in the Bowen (Mt Wickham and Glen Bowen) and one in the Don catchment (Minnievale). All sites are commercial grazing properties and represent a range of property sizes (from 930 to 39,000 ha). The general soil type for the properties are shown in Figure 1 and a description of the sites is given in Table 3.

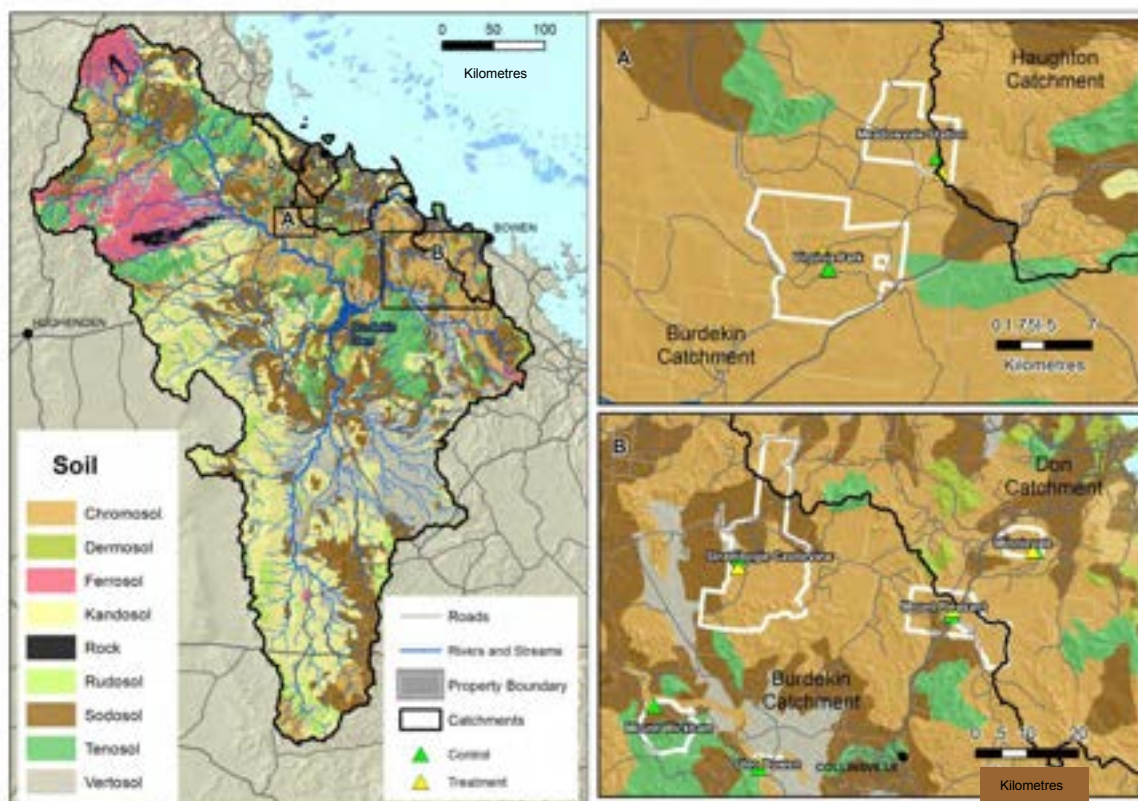


Figure 1: (left) Map of the Burdekin Region showing the underlying soil type at each of the properties (Source: Atlas of Australian Soils); and (right) the location of the properties within the Burdekin Region.

Table 3: Description of the seven study sites documented in this study.

Property	Virginia Park	Meadowvale	Strathbogie	Minnievale	Mt Wickham	Glen Bowen	Mt Pleasant
Management Unit (sub-catchment)	Upper Burdekin	Upper Burdekin (and Haughton)	Bogie	Don	Bowen	Bowen	Bogie
Local stream name and catchment size of gullies	Treatment and Control both on Weany Creek (1400 ha)	Treatment in headwaters of Haughton river (1400 ha), Control on Wheel Creek (1000 ha)	Treatment and Control both on side arm (1300 ha) of Capsize Creek	Treatment site on Mary Creek (1500 ha) Control site on Side arm of Four Mile Creek (1400 ha)	Treatment (3.03 ha) and Control 14.14 ha) sites both drain into Sandalwood Creek which connects with the Bowen river	The treatment gully (~5.3 ha) drains directly to Bowen River. The control gully (5.0 ha) drains into a small creek then into the Bowen.	Both the treatment (220 ha) and control (160 ha) sites drain into an unnamed creek before reaching the Bogie River
Size of property (ha)	~7000 ha	~3000 ha	~39,000 ha	~3750 ha	~7790 ha	~930 ha	~14,000 ha
Soils	Red Chromosol	Red Chromosol	Black Vertosol	Sodic Hypocalcic Red Dermosol	Hypernatric Brown Sodosol	Brown or Yellow Sodosols	Black Chromosols on foot-slopes. Brown Chromosols on upper slopes of Treatment site and Brown Sodosols on upper slopes of control site.
Geology	Granite and Granodiorite	Granodiorite	Granite, Basalt	Granodiorite	Granite and Granodiorite	Mafic Intrusives	Quaternary Alluvium on lower slopes and Tonalite and Micro Gabbro intrusives on upper slopes

Property	Virginia Park	Meadowvale	Strathbogie	Minnievale	Mt Wickham	Glen Bowen	Mt Pleasant
Terrain (% slope property)	2-3%	2-3%	6-7% (due to high relief in south)	3-4%	10%	1.7%	4.5%
Average annual long term rainfall (mm) derived from nearest BOM site	~ 660 mm	~ 680 mm	~ 750 mm	~ 880 mm	~ ~600 mm	~ 725 mm	~ 690 mm
Vegetation over- story	Widely spaced Narrow-leafed Ironbark and Bloodwood	Widely spaced Narrow-leafed Ironbark and Bloodwood	Widely spaced Narrow-leafed Ironbark and Bloodwood	Widely spaced Narrow-leafed Ironbark and Bloodwood	Widely spaced Narrow-leafed Ironbark and Bloodwood + Popular gum	Widely spaced Narrow-leafed Ironbark and Bloodwood + Popular gum	Narrow-leafed Ironbark, Blackbutt and Red Bloodwood, some acacia
Vegetation groundcover	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch	Couch dominated, but wider range of pasture species at this site
Gully type	Linear hillslope gullies and scalds	Linear hillslope gullies and scalds	Linear hillslope gullies	Linear hillslope gullies and scalds	Linear hillslope gullies, scalds and major alluvial gullies (incl. tunnel erosion)	Scalds and major alluvial gullies	Linear hillslope gullies
Lat Long Treatment Gully	-19.8916, 146.5127	-19.8389, 146.5910	-20.2214, 147.5566	-20.1934, 148.0720	-20.4624, 147.4019	-20.572624 147.593225	-20.305059, 147.929184
Lat Long Control Gully	-19.9029, 146.516	-19.8288, 146.5882	-20.204, 147.5581	-20.1943, 148.0776	-20.4650, 147.4071	-20.560498 147.591485	-20.295261, 147.932524

2.3 Treatments applied at each site

The Gully and Stream Bank Toolbox, a technical guide prepared for the Reef Trust Gully and Stream Bank Erosion Control Program, outlines a range of treatment options suitable for gully rehabilitation in the GBR catchments (Wilkinson et al., 2019a). The treatment options are broadly based on evidence of the effectiveness of studies elsewhere in the world (Bartley et al., 2020), as we have limited effectiveness data from Australian studies.

In many parts of the world there is debate as to whether gully rehabilitation should focus on managing erosion within gullies as this is often the major sediment source, or on managing the catchments above the gullies as the main source of runoff (Chen and Cai, 2006). The global experience reviewed in Bartley et al., (2020) suggest that a decline in sediment yield is likely to occur faster when the rehabilitation treats both the area above the catchment as well as the gully feature. Treating the catchment above the gully reduces the runoff and thus erosive energy from the upslope catchment, slowing the gully erosion rate. Treating the gully channel may further limit erosion from side-walls and facilitates sediment trapping within the gully complex. Combined, these processes will reduce the amount of sediment (or sediment yield) leaving the gullied catchment.

The global experience reviewed by Bartley et al., (2020) also suggested that it is important to combine both engineering and vegetation management. Engineering structures (e.g. retention terraces, diversion banks, check dams) are central in the initial phase of rehabilitation in order to help stabilise the site and manage runoff and erosion. Especially in harsh plant growth conditions (e.g. low rainfall, degraded soils, very steep slopes) engineering structures are often required to create conditions that allow the establishment of vegetation. This is because, in the long term, vegetation is the most important factor. Without improvements in the vegetative biomass above and within the gully, significant long-term reductions in sediment yield (compared to their natural trajectory) are unlikely. Using a combination of measures also provides insurance against the failing of certain (engineering) structures such as the breaching, bypassing or filling up of check dams.

The treatment options and implementation of the rehabilitation treatments at each site was generally the responsibility of a third party or 'delivery' partner (summarised in Table 1). The choice of treatments was undertaken through consultation with the delivery partners, landholders and a range of consultants. A discussion of this merits and challenged of this approach in terms of project delivery is presented in Wilkinson, (2019b) and will not be discussed further in this report. CSIRO organised the treatments at Meadowvale which was funded by the NESP TWQ Hub program, and at Virginia Park which was funded by the Paddock to Reef Program (P2R, in 2010). The treatments implemented across the seven properties represent a spectrum of rehabilitation options, from simple and low cost (Virginia Park and Meadowvale) to mine site style rehabilitation (Mt Wickham and Glen Bowen). A summary of the approaches and the cost of the treatments are outlined in Table 5.

Table 4: Property name, length of monitoring data, funding source and delivery partner and consultants for each site.

Property name	Years of monitoring data	Funding sources (for monitoring and rehabilitation)	Delivery partner	Key consultants involved in rehabilitation
Virginia Park	4-8 years	P2R, NESP	CSIRO	
Meadowvale	4 years	NESP	CSIRO	Ramsay fencing
Strathbogrie	4 years	NESP, LDC	NQDT	On Property Management Solutions (OPMS)
Minnievale	4 years	NESP, Reef Trust	Greening Australia	
Mt Wickham	3 years	NESP, LDC	NQDT	Verterra
Glen Bowen	1 year	LDC	NQDT	Neilly Group
Mt Pleasant	1 year	LDC	NQDT	Mulloon Institute

Table 5: Description of treatment history at each site up until May 2020.

Activity	Virginia Park	Meadowvale	Strathbogie	Minnievale	Mt Wickham	Glen Bowen	Mt Pleasant
Managing organisation	CSIRO (P2R)	CSIRO	NQDT	Greening Aust.	NQDT (Verterra)	NQDT (Neilly Group)	NQDT (Mulloon Institute)
Year control site monitoring began	2016	2016	2016	2016	2018	2019	2019
Year treatment was initiated	2010	2017	2019	2016	Early 2019	Late 2019	Late 2019
Year treatment site monitoring began	2010	2016	2016	2016	Early 2019	Late 2019	Late 2019
No. years treatment in place	10	3	1	4	2.5	1	1
Catchment area (ha) above monitoring station at treatment site	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha
Primary treatment	- Disc plough above the treatment gully - Fenced off gully (electric fence) - Porous check dams installed in the gully (n=6)	- Four strand cattle exclusion fence around the gully - ~30% of the gullied catchment has a long-term cattle enclosure	- Five hillslope flow diversion banks with two drains - Permanent 3 barb fence - Small rock revetment	- Hillslope ripped, and seeded (creeping blue grass, V8 stylo, R.Rhodes etc) - Fencing - Total of 200 timber porous check dams installed	- Major earth works, soil treatment and rock chute structures installed - Permanent 4 barb fence - Significant re-veg using mixed exotic species (see Appendix C)	- Major earth works, soil treatment, rock chute structures installed + earth bund - Permanent 3 barb fence + pipeline and off-site waterpoints - Significant re-veg using mixed exotic species (see Appendix C)	- Four v-notch log rock sill structures installed and an earth bank to divert flows - Permanent 4 barb fence around a 60 ha paddock - Off-site watering trough installed
Grazing management in treatment paddock	Historically this site has undertaken wet season spelling and forage budgeting.	No grazing management outside of enclosure areas.	No grazing management.	Grazing Mgt Plan. Reduced grazing duration in treatment paddock.	Cattle have been excluded since works began, but future grazing proposed.	Cattle excluded during rehab. Low stock numbers and short duration graze proposed.	Exclusion for limited periods and then rotational grazing.
No. years treatment in place	10	3	1	4	2.5	1	1
No. years of control/treatment monitoring	3-4	3-4	4	4	3	1	1
Total cost (\$) of on-ground works*	\$3.5k	\$3.8k	~\$44k	~\$27k	~\$595k	~\$840k	\$95k

2.4 Metrics used to measure gully rehabilitation effectiveness

Each site has a somewhat different mix of individual treatments (Table 5), however, we have attempted to use a consistent evaluation methodology across all sites. To capture the changes in different parts of the gullied landscape, monitoring was focused on changes that occurred (i) on the hillslope above the gully (ii) within the gully channel and (iii) at the gully outlet or downstream of the treatments. In an ideal monitoring situation, changes to runoff would also be undertaken on the hillslope above the gully, however, this was cost prohibitive. Therefore, vegetation metrics representing factors such as cover, biomass, species diversity and land condition, were measured to represent potential improvements in runoff. High cover and biomass on hillslopes are known to enhance infiltration and reduce runoff in these landscapes (Roth, 2004; Bartley et al., 2006; Sanjari et al., 2009; Silburn et al., 2011). Similarly, good vegetation cover and biomass on and within the gully channel has been shown to be important for reducing gully erosion rates (Wilkinson et al., 2018). The approach is summarised in Table 6 and the general conceptual framework for the study is outlined in Figure 2 (after Koci et al., Accepted). The detailed methods are provided in Section 3.

Table 6: Variables used to evaluate the success and effect of individual treatments and their cumulative effects on downstream water quality.

Hillslope above the gully	Within the gully channel	Cumulative impact representing changes to the hillslope and gully
Vegetation cover and biomass	Vegetation cover and biomass	% runoff
Land condition	Terrain changes in headcut section (erosion and deposition)	Sediment and nutrient concentrations and particle size
		Sediment and nutrient loads

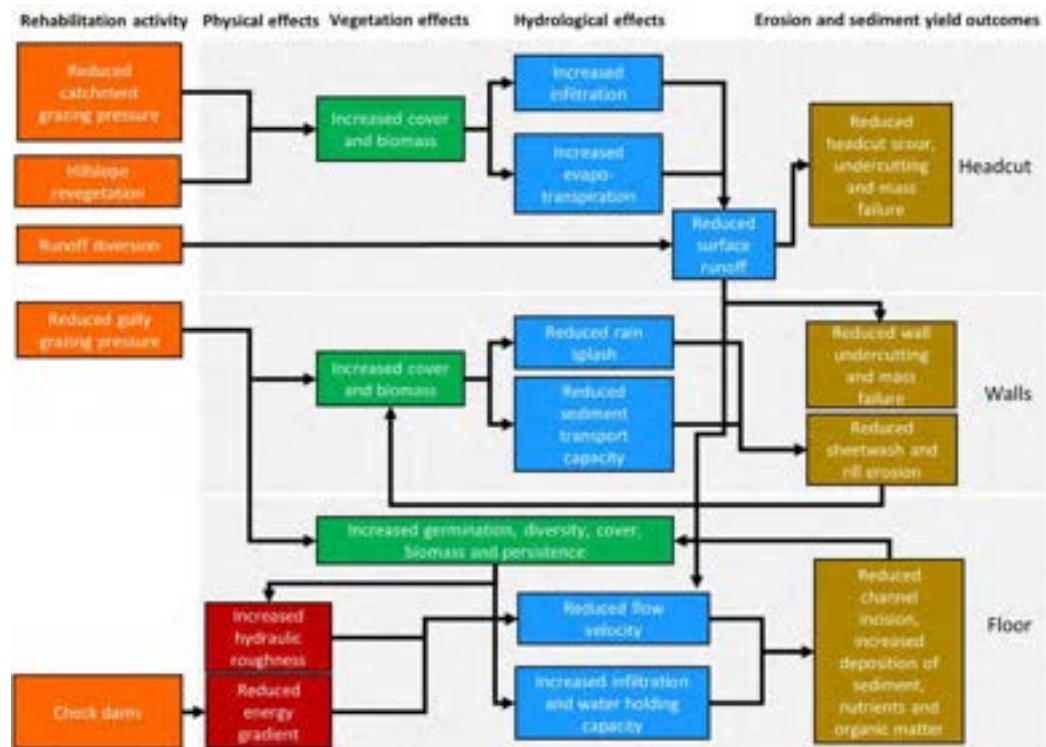


Figure 2: Conceptual framework of the potential effects and outcomes of gully rehabilitation activities used to develop the research questions investigated in this study (after Koci et al., Accepted).

3.0 METHODS

3.1 Soil description

Detailed soil descriptions and chemical analysis were undertaken by different groups at each of the field sites following the Australia Soil Classification system (Isbell, 2002). Queensland State Government and CSIRO staff were responsible for the soil analysis at Virginia Park, Meadowvale, Strathbogrie, Minnievale and Mt Wickham. Soil chemical analysis for these sites were undertaken at the Queensland Department of Environment and Science Labs in Brisbane, and all the data are stored in Queensland Globe (P2REEF-<https://qldglobe.information.qld.gov.au/>). Detailed descriptions of the soils at Glen Bowen were presented in Stout et al., (2019) and for Mt Pleasant by Hardy (2019). Bulk density of surface soil was collected at each field site and used to convert erosion volumes into tonnes of sediment.

3.2 Vegetation and land condition

Vegetation metrics were measured on the hillslope above each of the gullies at the end of the dry season ('EOD', October–December) and then again at the end of the wet season ('EOW', April). Landscape and vegetation condition transects were installed upslope of the uppermost head section on both the treated and control gullies at all sites (Figure 3). Transects were oriented along slope contours and varied in length and spacing for each site depending on gully-head catchment size. Four to five transects were used at each treatment and control location. Each transect has a permanent marker at the beginning and end to facilitate repeat measures. Pasture metrics were recorded along each transect using a 1m² quadrat based on the methods of Tothill et al., (1992), with placement of quadrats dependent on transect length at each site (a total of 30 quadrats were sampled for each treatment/control area). Metrics included the main pasture species (most dominant 5 species) and/or functional group composition and frequency, above-ground pasture biomass (DMY), total cover, litter cover, basal-area percentage, defoliation level and key soil surface condition metrics (Tongway and Hindley, 1995).

Landscape condition was also calculated along each transect using PATCHKEY (Abbott and Corfield, 2012). The condition assessments were aggregated to reflect ABCD landscape condition as used across grazed landscapes in the GBR catchments (Aisthorp and Paton, 2004; Chilcott et al., 2005; Bartley et al., 2014). Cover and biomass estimates were calibrated against standard quadrats taken at each site using classified quadrat photographs and cut samples. Biomass standards were oven dried to attain dry matter yield, removing vegetation water retention error between treatments.

Gully vegetation cover and biomass were also measured within each gully, on the gully walls and gully floor. The sampling methodology for the in-channel gully surveys was similar to the hillslope survey. A minimum of three transects were measured across each gully. At each transect, percent cover, biomass and dominant cover type was assessed using 0.25 m² (0.5 x 0.5m) quadrats. Three quadrats were assessed on each wall (six in total) and six quadrats assessed in the deepest part of the channel in the gully floor. Box plots of the percent cover and biomass data at the end of each wet season for control and treatment sites were analysed

using Sigmaplot Version 14. No gully channel surveys were conducted at the Glen Bowen site as all the rehabilitation was almost exclusively on the alluvial gully surface.

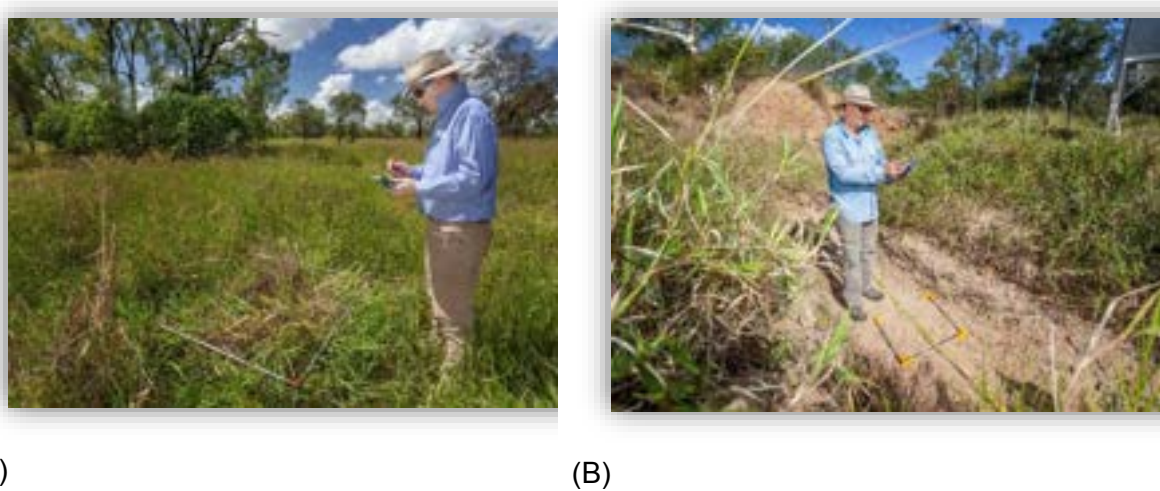


Figure 3: Example of vegetation sampling for percent cover and biomass on (A) the hillslopes above the gullies and (B) on the gully floor/channel.

3.3 Terrain analysis

Terrain mapping of the NESP gullies was used to (i) provide metrics of the gully width, gully slope and shape for the purpose of flow modelling, and (ii) estimate the amount of erosion or soil loss (and deposition) between years. For the hillslope gully sites, terrain analysis was focused on the gully headcuts. At the alluvial sites, terrain analysis is focused on the entire gully complex. Soil erosion can generate both fine ($<63\ \mu\text{m}$) and coarse ($>63\ \mu\text{m}$) sediment. Terrain analysis, expressed as digital elevation models (DEMs) of difference (DODs) will capture erosion of the entire soil profile, including fine and coarse material. The water quality monitoring (Section 3.5) will focus on the fine sediment only.

(i) RTK surveys

The slope of gully beds, hillslope above the gully, and locations of reference markers were surveyed using an RTK (real time kinematic) GPS system (Ashtech, ProMark 200) with a tolerance of $\pm 12\ \text{mm}$ in the horizontal plane and $15\ \text{mm}$ in the vertical. The slope of the gully bed was surveyed by traversing the entire length of the gully collecting survey points along the deepest part of the channel and identifying key locations such as head-cuts and instrumentation.

(ii) RIEGL Terrestrial laser scanner

The terrestrial laser scanner (TLS) instrument used in this study was the RIEGL VZ400. The TLS was registered using five ground control points at each site. The control points consisted of a $50\ \text{cm}$ star picket driven flush into the ground with a concrete collar. Survey bipods with reflectors were then placed over these marks to establish consistent xyz locations between scanners and for repeat surveys. To link RIEGL scans collected on the same day, additional 'mobile' reflectors were placed strategically around the sites. Registration was then performed by matching distances between reflector pairs (see Goodwin et al., 2016 for details). The RIEGL has an inbuilt fine-scan option to accurately locate reflector locations and is used to

register separate scans into the same coordinate system with errors typically < 1 cm. These datasets are then projected into real world coordinates using the internal GPS and digital compass. The number of scans captured between sites varies due to differing morphological complexity and area to be mapped. Note that TLS scanning has not occurred at Mt Wickham, Glen Bowen or Mt Pleasant. Aerial Lidar surveys will likely be used to detect the larger scale changes at the alluvial gully sites by other partners in the LDC program. Considering the survey time TLS monitoring was typically confined to the top half of the gully feature containing the headcut.

(iii) Zebedee

The Zebedee is a portable, handheld laser scanner that consists of a rotating (ZebRevo) or spring mounted (Zeb1) 2D laser scanner and an inertial measurement unit (IMU) connected to a backpack mounted control module. The system uses Simultaneous Localisation and Mapping (SLAM) technology to reconstruct and track the position of objects in the environment as the scanner passes through. The raw data from the scanner was processed using proprietary software to create a 3D point cloud with a manufacturer stated range extending up to 35 m with a precision of 1–3 cm. The error associated with this application was presented in Bartley et al., (2016) where it was estimated to be $\pm 0.09 - 0.12$ m. Subsequent analysis suggests that a conservative estimate of error of 0.1 m (Henderson et al., In Prep) applies to this approach.

Repeat scans of gully sections were conducted by traversing in and around the target area, including reference markers, with locations measured using RTK GPS, to create a closed loop survey for the generation of a DEM with real world coordinates. Preliminary Zebedee derived DEMs are presented for Glen Bowen control gully (entire gully feature) and Mt Pleasant (headcuts only) in this report.

(iv) Airborne Lidar

Lidar DEMs (0.5-1.0 m resolution) were used to estimate upslope catchment areas and generate digital elevation models for all gullies except those at Mt Pleasant. At the Mt Pleasant site, the Shuttle Radar Topography Mission (1 Arc Second, SRTM) data was used (Gallant et al., 2011).

(v) Detection of elevation change

Digital elevation models (DEMs) were developed for all surveys from the RIEGL scanner by selecting the minimum (ground) elevation from all the points in a 5 cm x 5 cm XY interval. A 3 x 3 median filter was then applied to the resulting grid to remove spurious values. To map gully planform extent, a modified region grow approach was applied to an unclipped RIEGL DEM. This approach utilises a difference from mean elevation (DFME) (Evans and Lindsay, 2010) and a slope layer to detect the gully edges. A 50 cm buffer was then applied to ensure full capture of the gully edges.

To statistically separate 'true' from 'false' elevation changes within the gully, a minimum change of ± 0.1 m was used in the DEM of difference (DOD) analysis to exclude propagated error. This is considered conservative based on the previous work carried out at Virginia Park with this data (Bartley et al., 2016), and is appropriate given the diversity of gully morphologies across these sites (Goodwin et al., 2017).

Table 7: Terrain analysis approach employed and data availability.

Property name	RTK measured at gauging station	Zebedee at headcut ^a or part of erosion surface ^b	Terrestrial laser scanner (TLS) at headcut	Lidar over whole gully	DEM of difference (DOD)	Method for DOD
Virginia Park	√		√	√	√	TLS
Meadowvale	√		√	√	√	TLS
Strathbogie	√		√	√	√	TLS
Minnievale	√		√	√	√	TLS
Mt Wickham	√			√		NA
Glen Bowen	√	√ ^b		√	Prelim	Zeb
Mt Pleasant	√	√ ^a			Next year	Zeb

3.4 Velocity and runoff

An automatic monitoring station was installed at each of the treatment gullies (Figure 4A). The monitoring station recorded rainfall, stage height, velocity, turbidity and water temperature at 1 minute intervals during runoff events. The station also housed an ISCO auto-sampler that collected 1 Litre water samples at programmed intervals across the hydrograph. These samples were processed according to the methods in Section 3.5. A camera was installed at the treatment sites to capture photos during runoff events.

To save on cost, initially each of the control sites were fitted with a simpler tripod monitoring station that measured rainfall, stage height and turbidity. Bulk water quality samples were then collected manually after each (accessible) event using rising stage samplers housed in poly-pipe rocket structures (Figure 4B). However, these simpler (and cheaper) cut down systems have been phased out in more recent installations as they are less reliable and generally collect an insufficient number of samples over the wet season to enable load calculations and statistical comparisons. A description of the sampler used at each site is summarised in Table 8. Data from both the treatment and control sites had telemetered communications to allow remote access of data.

Obtaining velocity and discharge measurements were one of the most challenging aspects of this project. During the NESP study we have undertaken the following approaches to estimate discharge:

- **Wet season 1 (2016/17):** Hec-RAS modelling was applied at all sites, but it was considered inappropriate without measured velocity data to constrain modelled estimates;
- **Wet season 2 (2017/18):** given the modelling didn't work, low cost (~\$2k each) Unidata Starflow QSD ultrasonic doppler sensors were installed above the turbidity sensor at each site in 2017. The sensor measures the velocity of particles or bubbles in the water (presumed to be the same velocity as the water) using the doppler shift between transmitted and received ultrasonic signals. The sensors are mounted facing downstream to reduce the impact of particles damaging the sensor face and debris build up on measurement. Unfortunately, the manufacturer supplied settings didn't provide measured water velocity in natural environments and no data were collected that season. The sensors required reconfiguration from factory default settings to capture data in gully systems.

- **Wet season 3 (2018/19):** the settings in the velocity sensors were corrected and velocity data was collected from 9 out of 10 NESP sites (the only site without velocity data didn't flow). However, the quality of the data was highly variable between sites and the load estimates had high uncertainty.
- **Wet season 4 – (2019/20):** The same Starflow ultrasonic Doppler velocity sensors (~\$2k) were installed at the LDC sites. In addition, six (~\$7k, research grade) acoustic Doppler Sontek IQ sensors were purchased using CSIRO and project funds to calibrate and test the Starflow sensors. These were installed beside the Starflow sensors at Mt Wickham, Mt Pleasant and Glen Bowen prior to the start of the wet season (Figure 4C). A comparison of the results from the different sensors are presented below, and recommendations for future velocity sampling discussed.



Figure 4: (A) Example of a treatment gully set up using an ISCO sampling system (B) example of a control gully set up including rising stage samplers (RSS) and (C) example of LDC instrumentation configuration with two velocity sensors.

3.5 Water quality and particle size

A description of the water quality sampling procedures for this project are outlined in Baker et al., (2016). In brief, following significant runoff events that triggered the samplers, the ISCO bottles were collected and either (i) delivered directly to the lab for immediate analysis; or (ii) the samples were filtered and frozen (if collected within 24 hours), and analysed later when sampling budget allowed. These samples were analysed for TSS and the full suite of nutrients including total nitrogen (TN), total dissolved nitrogen, NH_3 , NO_x , total phosphorus (TP), total dissolved phosphorus and filterable reactive phosphorus (FRP) at the JCU TropWater Laboratory in Townsville. Samples that were not collected within 24 hours were analysed for TSS, and in some cases TN and TP. A sub-set of the samples collected were also sent for particle size analysis. These samples were processed on a Malvern Mastersizer which is a laser diffraction analyser with a lens range of 0.02 – 2000 μm . The quality control process excluded some samples from analysis due to equipment malfunction or damage.

3.6 Loads estimates

To estimate loads of suspended sediment (TSS) and total nitrogen (TN) the following steps were undertaken:

- (1) Depth, velocity and surveyed cross-sectional area data were used to generate a stage-discharge rating curve for each site;
- (2) Linear relationships between TSS and TN sample concentrations and coincident turbidity data were derived for all sites (Table 8). Turbidity data was excluded from this process when (i) the turbidity exceeded the instrument calibration threshold; (ii) turbidity sensor readings were erroneous due to damage or sensor malfunction, or when the sensors were buried. These relationships allowed for estimation of TSS and TN from turbidity. When there was no turbidity data (due to sensor issues or instrument burial), TSS and TN concentrations were infilled using sample interpolation.
- (3) Total suspended sediment (TSS) and total nitrogen (TN) loads were then generated for each event and each water year (generally Nov to April) by multiplying discharge by concentration.
- (4) For all sites flow weighted annual average mean concentrations were generated by dividing the annual load by annual runoff. This provided a flow adjusted assessment of the relative change in concentration between sites.
- (5) For some sites (i.e. Mt Wickham) event mean concentrations (EMCs) were generated for individual events by dividing the event load (T) by event runoff (ML). This provided a flow weighted mean concentration for each event (after Kim et al., 2004).

We have not explicitly dealt with sampling error or uncertainty in the discharge and load calculations which can be high in semi-arid systems (Kuhnert et al., 2012). However, we have provided data quality assessments for all runoff and loads data which are documented in Appendix B.

3.7 Statistical analysis

To compare differences between the vegetation and water quality samples at control and treatment sites following the 2019/20 wet season, a Student's t-test for means and non-parametric Mann-Whitney rank sum test were conducted. Student's t-test were applied when the data were normally distributed. When the data was not normally distributed, a non-parametric Mann-Whitney rank sum test was applied.

For the Strathbogie and Mt Wickham sites, that have both pre and post treatment data, a Two-Way ANOVA was applied to the log transformed data (to ensure distribution normality and equal variance). This allowed us to test the statistical significance of changes between sites (control vs treatment) and time (before and after). All statistical data analysis was complete in Sigmaplot v14.

3.8 Rehabilitation effectiveness calculations

When sites have water quality and runoff data collected from periods both before and after treatment, from control and treatment sites, statistical analysis can be used to calculate the effectiveness of the rehabilitation on erosion control (as described in Section 3.7). This approach takes in account variations in response due to inter-annual rainfall variability between wet seasons.

If water quality samples have been adequately sampled across the flow event hydrograph for the main events in all seasons at both control and treatment sites (including first flush and peak events) then it is suitable to use concentration data to evaluate rehabilitation effectiveness (see Figure 5). However, comparison of changes in the sediment loads between sites is the most appropriate metric to use to evaluate treatment effectiveness, as this represents the total tonnes of fine sediment delivered or saved due to the rehabilitation. It is acknowledged that runoff and load data are notoriously challenging to obtain and highly uncertain in these flashy systems, however, this is still considered as the goal for gold standard monitoring.

For sites that demonstrate a statistically significant change in sediment loads (or adequately sampled concentrations) at the treatment gully relative to the control, Equation 1 can be used to estimate the 'effectiveness' of the treatment.

$$\text{Treatment effectiveness} = \frac{SYC - SYT}{SYC} \times 100 \quad \text{Equation 1}$$

Where SYC and SYT is the total annual sediment yield in t/ha following treatment for a given year or wet season for the Control (C) and Treatment (T) sites, respectively. When using control and treatment data, without coincident before data at each site, or using before and after data at a treatment site, without a control site to compare to, it is possible to detect changes, but it is difficult to attribute these to the treatment effects alone. The changes could be influenced by variations in rainfall, runoff or individual gully dynamics. For sites without before data, indicative trends can be identified, but longer time frames (e.g. >5 years) will likely be required to detect statistically significant changes that are independent of rainfall/runoff variability.

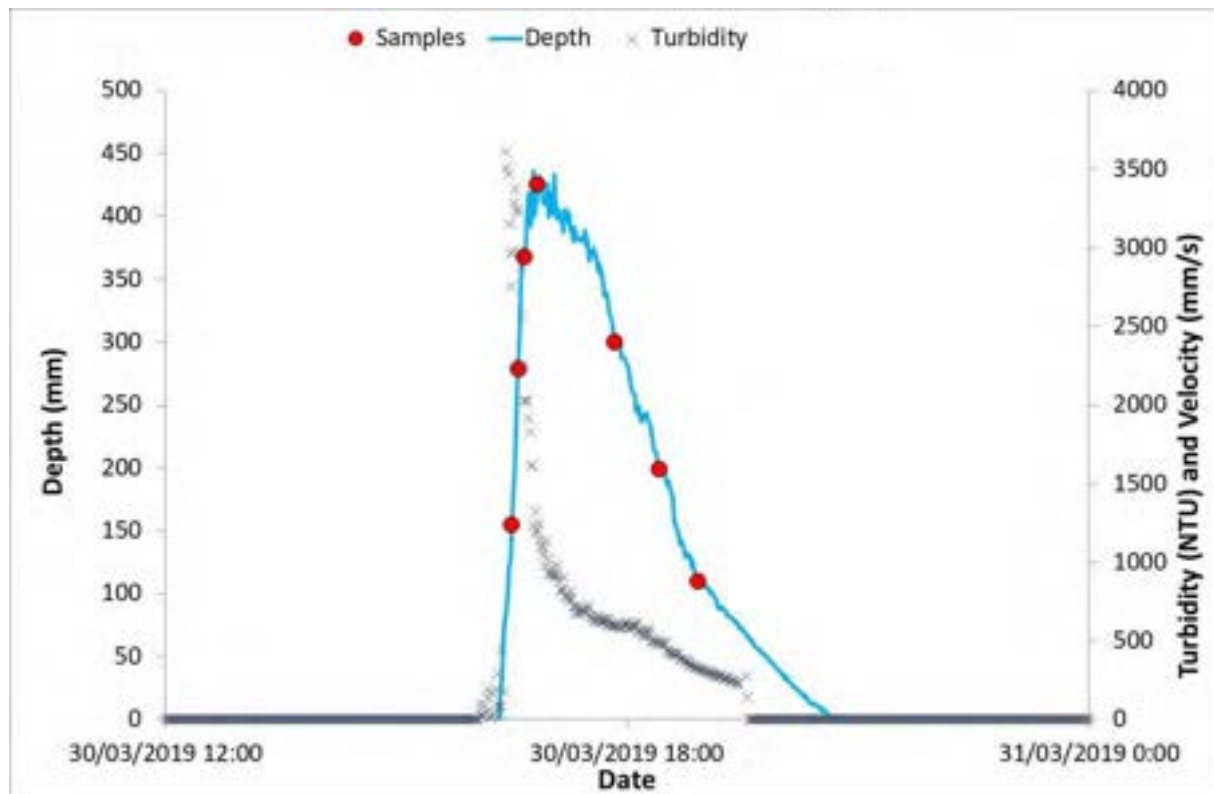


Figure 5: An example of an adequately sampled flow event where water quality samples were collected evenly throughout the event including the rising limb and stage peak (example from Strathbogie Treatment site).

Table 8: Summary of the velocity sensor, water quality sampling approach, Turbidity-TSS and Turbidity- TN relationships for each site.

Property	Gully	Years of data	Velocity approach used to derive rating curve (period of data used)	Water quality sampler used	Turbidity -TSS	Turbidity- TN	Comments
Virginia Park	Control	4	Constant - 200 mm/sec (2018-2019)	RSS	$y = 3.3665x - 920.38$, $R^2 = 0.7978$ (n=6)	$y = 1.9008x + 960.55$, $R^2 = 0.6381$ (n=4)	No new samples or velocity data collected in 2019/20 due to low rainfall/runoff. Loads calculated using existing Turbidity-TSS relationship.
	Treatment (XG5)	4	Starflow QSD (2018-2019)	ISCO	$y = 0.9558x + 9.5912$, $R^2 = 0.9047$ (n=70)	$y = 0.4974x + 1123.7$, $R^2 = 0.6272$ (n=35)	No new samples or velocity data collected in 2019/20 due to low rainfall/runoff. Loads calculated using existing Turbidity-TSS relationship.
	Treatment 2 (XG2)	3	Starflow QSD (2018-2019)	ISCO	$y = 0.8429x + 48.86$, $R^2 = 0.9023$ (n=63)	$y = 1.1376x + 811.83$, $R^2 = 0.7237$ (n=21)	No additional samples collected in 2019/20 due to low rainfall or no runoff
Meadowvale	Control	3	Starflow QSD (2018-2019)	RSS	$y = 1.0946x + 180.78$, $R^2 = 0.836$ (n=7)	$y = 6.4349x - 888.73$, $R^2 = 0.9433$ (n=5)	One sample, but no valid turbidity, depth or velocity due to logger issue during one small flow event.
	Treatment	4	Starflow QSD (2018-2020)	ISCO +RSS	$y = 1.8852x - 250.49$, $R^2 = 0.8623$ (n=71)	$y = 1.2503x + 673.5$, $R^2 = 0.7684$ (n=31)	
Strathbogie	Control (SBT)	4	Starflow QSD (2018-2020)	ISCO	$y = 0.8779x + 325.25$, $R^2 = 0.7759$ (n=32)	$y = 0.6071x + 700.96$, $R^2 = 0.6091$ (n=11)	New cross section profile used after 2019 due to change in channel morphology.
	Treatment (SBT2)	3	Starflow QSD (2018-2019)	RSS then ISCO	$y = 1.2037x + 271.4$, $R^2 = 0.6298$ (n=7)	$y = 1.5332x + 368.44$, $R^2 = 0.9999$ (n=3)	New cross section profile used after 2018 due to channel widening. No samples or velocity data collected in 2019/20 due to new rehabilitation works at treatment
Minnievale	Control	3	Starflow QSD (2018-2020)	RSS	$y = 2.5555x - 2738.6$, $R^2 = 0.7498$ (n=7)	$y = 7.1229x - 9263.8$, $R^2 = 0.4119$ (n=4)	No new samples collected in 2019/20 due to low rainfall or no runoff. Loads calculated using existing Turbidity-TSS relationship.

Property	Gully	Years of data	Velocity approach used to derive rating curve (period of data used)	Water quality sampler used	Turbidity -TSS	Turbidity- TN	Comments
	Treatment	4	Starflow QSD (2018-2020)	ISCO +RSS	$y = 1.1349x + 178.69$, $R^2 = 0.7527$ (n=45)	$y = 2.7793x - 778.48$, $R^2 = 0.684$ (n=25)	
Mt Wickham	Control	3	Starflow QSD (2018-2020)	ISCO	$y = 3.0777x - 5729.8$, $R^2 = 0.8558$ (n=16)	$y = 0.6268x - 2216.7$ $R^2 = 0.7003$ (n=16)	Sontek IQ Std installed but limited flow data due to low rainfall.
	Treatment	2	Starflow QSD (2018-2020)	ISCO	$y = 3.1404x - 1759.7$, $R^2 = 0.9107$ (n=46)	$y = 0.7589x + 1464.3$, $R^2 = 0.7636$ (n=31)	Sontek IQ Std installed but limited flow data due to low rainfall.
Glen Bowen	Control	1	Sontek IQ Std (nil - insufficient data)	ISCO	$y = 3.1386x - 3534.3$, $R^2 = 0.6448$ (n=14)	$y = 0.4187x + 410.58$ $R^2 = 0.712$ (n=6)	Sontek IQ Std installed but insufficient flow data due to low rainfall.
	Treatment	0	Sontek IQ Std (nil -insufficient data)	ISCO			Sontek IQ Std installed but insufficient flow data due to low rainfall. No samples collected likely due to rehabilitation works
Mt Pleasant	Control	1	Sontek IQ Std (2019-2020)	ISCO	$Y = 0.9691x - 30.842$ $R^2 = 0.7985$ (n = 21)	No valid relationship	Discharge only applies to depths above 450 mm. Nitrogen data unsuitable for Turbidity-TN relationship.
	Treatment	1	Sontek IQ Std (2019-2020)	ISCO	$y = 1.6066x - 85.067$ $r^2 = 0.9604$ (n= 25)	No valid relationship	Discharge only applies for flows above ponded depth of 1100 mm. Some erroneous turbidity data replaced with sample interpolation. Nitrogen data unsuitable for Turbidity-TN relationship.

4.0 RESULTS – OVERVIEW ACROSS SITES

4.1 Vegetation and land condition

The average hillslope vegetation metrics for each site are presented in Figure 7. For five out of seven sites, the treatment hillslope had significantly higher percent cover, biomass, basal area and litter compared to the control site, associated with the livestock exclusion or controlled access. The exception was for Strathbogie and Mt Pleasant, where there are currently no major treatments related to the grazing regime at these sites.

Overall, Mt Pleasant has high percent cover and litter, on both control and treatment sites, however, Mt Wickham treatment has consistently high percent cover, biomass, basal area and litter on the treatment site only. Glen Bowen control site has the lowest mean values for each of these attributes.

Table 9 presents the land condition classification results for the hillslopes above each gully in 2019/20. Land condition is dominated by C (poor) and D (very poor) class states for all sites. The individual site results show that in average rainfall years, land condition generally increases over the wet season (Section 0). However, a decrease was observed over the 2019/20 wet season, which was exceptionally dry (see Table 13) and accompanied by considerable *Bothriochloa pertusa* (Indian couch) die-back at most properties (Figure 6).

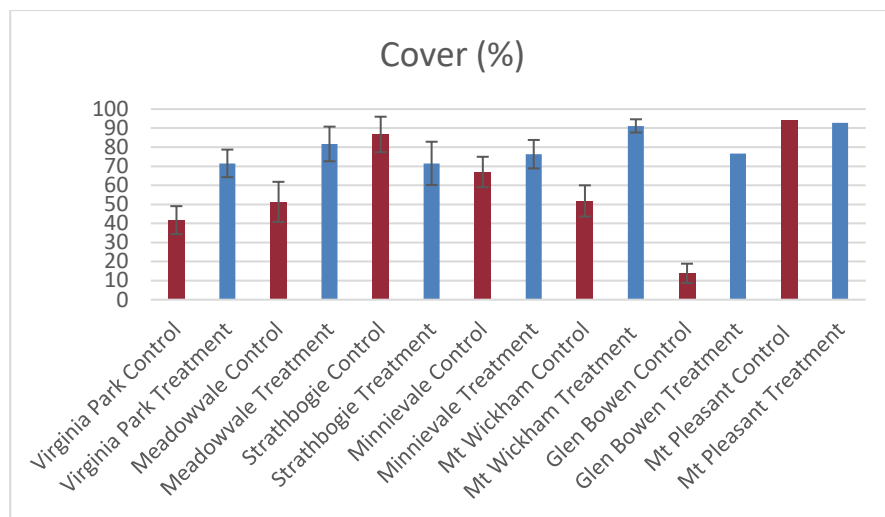
More detailed results for each site are presented in Section 0, however, there are some notable property results. Following the above average wet season in 2018/19 (with 1117 mm of rainfall), the Mt Wickham treatment site transitioned to having ~50% of the hillslope in B condition in just 2 wet seasons. Unfortunately, however, the site only received ~370 mm of rain in 2019/20 and much of the revegetation was drought affected by April 2020. Much of the Rhodes grass had disappeared, and there was an increase in legumes (*Desmanthus*) which had grown and started shading out other grasses. Although the vegetation recovery has been significant at Mt Wickham, it is still a fragile response that is vulnerable to low rainfall conditions and grazing.

The Strathbogie treatment site also had lower land condition following the wet season. While the overall percent cover there is relatively high (~70%), the plant basal area and percent litter is very low and therefore the overall land condition is poor (Table 9).

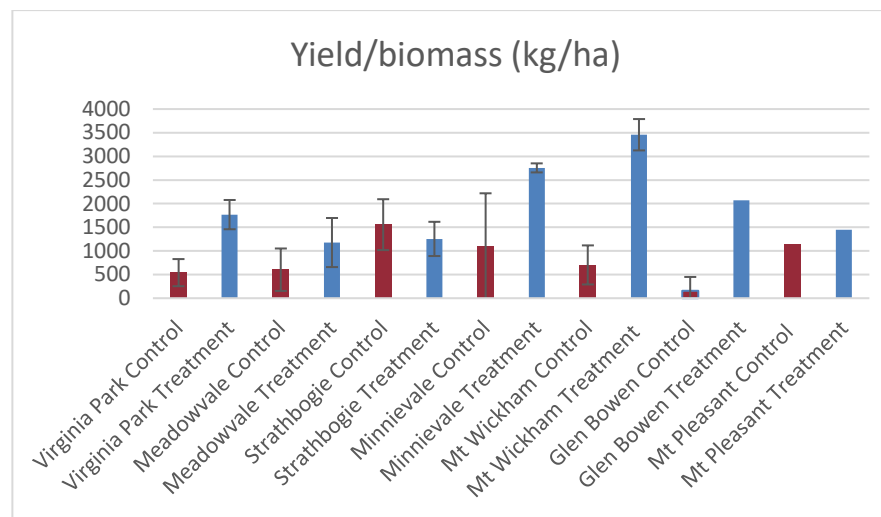
The Glen Bowen treatment site reached cover levels of near 80% following treatment, however, the plant percent basal area and percent litter was still very low following the low rainfall over the 2019/20 wet season. This is associated with a predominance of the annual grasses that have grown from seed mix used at the rehabilitation site. Hence the site remains in D condition. If these annuals do not germinate again next year, this will leave bare earth and litter.



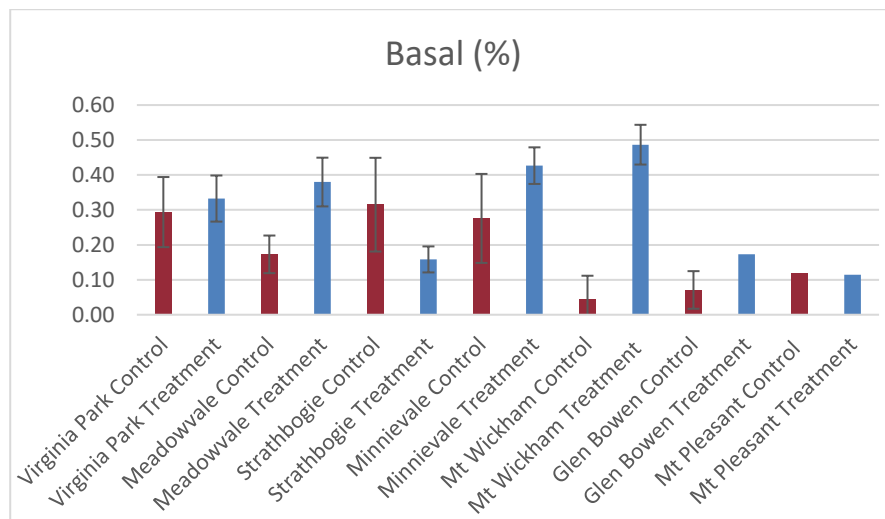
Figure 6: Example of *Bothriochloa pertusa* (Indian couch) die-back observed at most properties.



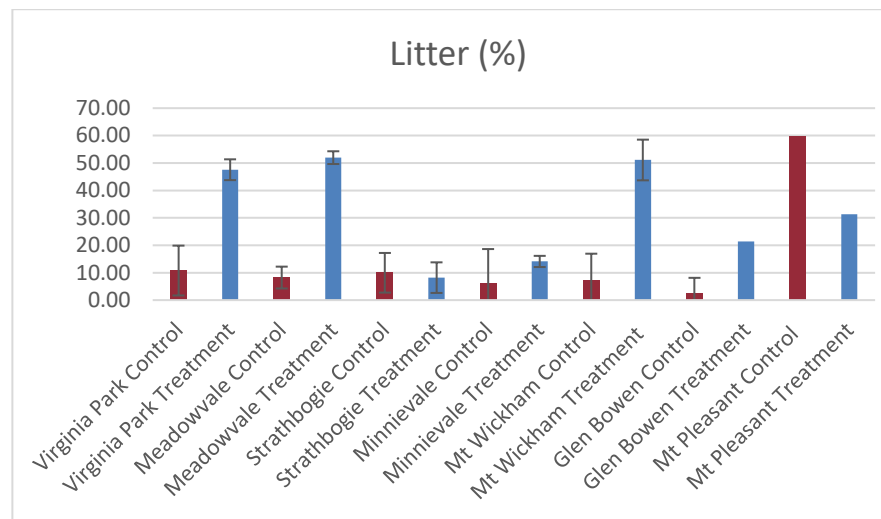
(A)



(B)



(C)



(D)

Figure 7: Average site hillslope vegetation metrics for each site at the end of the 2019/20 wet season (A) percent cover (B) plant biomass or yield (kg/ha) (C) plant percent basal area and (D) percent litter

Table 9: A, B, C, D Land condition classification for each of the properties in this study (pre and post 2019/20 wet season)

	Landscape condition (%)			
	A	B	C	D
Virginia Park				
Treatment: pre-wet (Nov 2019)		2	21	77
Treatment: post wet (April 2020)			44	56
Control: pre-wet (Nov 2019)			28	72
Control: post wet (April 2020)			15	85
Meadowvale				
Treatment: pre-wet (Nov 2019)		1	50	49
Treatment: post wet (April 2020)		3	32	65
Control: pre-wet (Nov 2019)			24	76
Control: post wet (April 2020)			12	88
Strathbogie				
Treatment: pre-wet (Nov 2019)		2	74	24
Treatment: post wet (April 2020)				100
Control: pre-wet (Nov 2019)			28	72
Control: post wet (April 2020)			6	94
Minnievale				
Treatment: pre-wet (Nov 2019)			38	62
Treatment: post wet (April 2020)			22	78
Control: pre-wet (Nov 2019)			48	52
Control: post wet (April 2020)			2	98
Mt Wickham				
Treatment: pre-wet (Nov 2019)	6	51	21	23
Treatment: post wet (April 2020)		1	42	57
Control: pre-wet (Nov 2019)			12	88
Control: post wet (April 2020)			4	96
Glen Bowen				
Treatment: pre-wet (Nov 2019)				100
Treatment: post wet (April 2020)				100
Control: pre-wet (Nov 2019)			2	98
Control: post wet (April 2020)			2	98
Mt Pleasant				
Treatment: pre-wet (Nov 2019)			73	27
Treatment: post wet (April 2020)			7	93
Control: pre-wet (Nov 2019)			66	34
Control: post wet (April 2020)			16	84

4.2 Current rates of gully erosion: terrain analysis

The gully head retreat rates for the 2016/17, 2017/18 and 2018/19 wet seasons are presented in Table 10, and the average erosion, deposition and net change in the volume of sediment for each gully for the study period are presented in Table 11. Note that due to COVID-19 travel restrictions, the 2019/20 terrain data was not able to be collected. The terrain analysis imagery is presented separately for each site in Section 0. Due to issues with site set up at Meadowvale, there is less data available at that site. Only the NESP sites were surveyed with the terrestrial laser scanner (TLS). No TLS data were collected at Mt Wickham, Glen Bowen or Mt Pleasant (see Table 7).

Note that the length of the gully scanned using the TLS is slightly different at each gully (Table 11). Therefore, the average TLS measured erosion rate has been normalised to tonnes of soil lost according the internal gully area surveyed (t/ha) as well as the upslope catchment area above the scan (t/ha) (Table 11). This makes it more appropriate to compare the relative amounts of soil lost between treatment and control sites, however, caution is needed when extrapolating these results to other gullies as they represent a combination of head-cut and sidewall erosion which will be the most active part of the gully.

The results demonstrate that the head-cut retreat (m) and erosion rate (t/ha/y) was highest at the Strathbogie treatment site (prior to treatment implementation), with ~28 m of head-cut movement and 2363 t/ha/y of total (fine + coarse) sediment loss using the internal gully area and 5.98 t/ha/y based on the upslope catchment area. These total sediment losses translate to high fine sediment loss at this site (Table 11). The result from Strathbogie highlights the natural variability in erosion rates that can occur between gullies in the same landscape independent of treatment (9.65 m – 28.06 m;

Table 10). The Strathbogie rehabilitation was not installed until late 2019 and therefore only the runoff and water quality data can be used to evaluate the treatment effects at this site.

There was a very strong relationship between the total average erosion rate and the drainage area above the gully head-cuts ($r^2 = 0.99$; Figure 8); noting that this relationship needs to be interpreted with caution and requires more sites to test this relationship. Nonetheless, this relationship highlights that the catchment area above the gully head is a strong surrogate of discharge which is a primary driver of erosion rate for these gullies.

Table 10: Gully head-cut retreat rates over the three wet seasons using the RIEGL Terrestrial laser scanner.

Property	Gully	Headcut gully retreat rate (m/y)			Average annual movement over measurement period (m/y)
		2016/17	2017/18	2018/19	
Virginia Park	Control	0.35	0.36	0.20	0.30
	Treatment	0.46	0.34	0.19	0.33
Meadowvale	Control	na	0.71	0.90	0.81
	Treatment	na	na	0.73	0.73
Strathbogie	Control	0.75	1.76	9.65	4.05
	Treatment	18.10	7.80	28.06	18.00
Minnievale [#]	Control	0.84	0.48	1.16	0.83
	Treatment	0.50	0.10	0.11	0.24

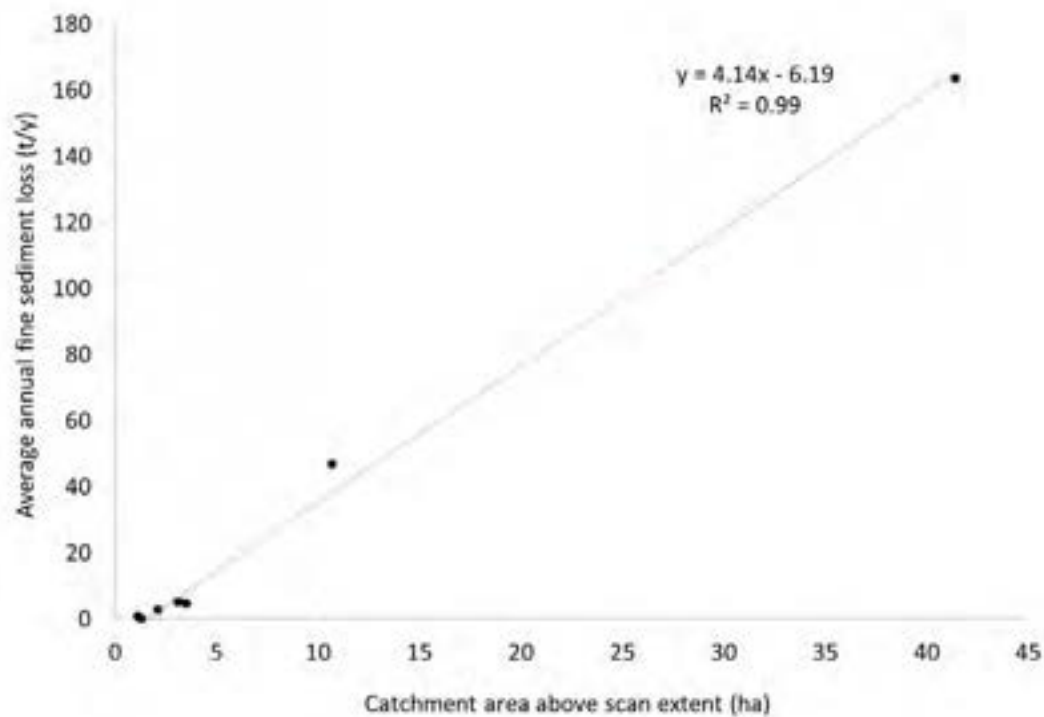


Figure 8: Relationship between upslope gully catchment area of the TLS scan (ha) and the annual average TLS measured total (fine + coarse) sediment loss in tonnes per year (t/y). The results are based on the combined wet season periods (2016 - 2019) for all gully sites at Virginia Park, Meadowvale, Strathbogie and Minnievale. Note that the scanned areas differ slightly between sites, and the t/yr represents the erosion from the head-cut and some gully walls (depending on the length of the scan). These data represent the fine sediment eroded from each site.

Table 11: Annual average gully volumetric change results using the RIEGL terrestrial laser scanner. Negative values represent deposition of sediment. The U_{crit} threshold for defining erosion/deposition was set as 0.1 m at all sites (except Meadowvale where it was 0.15-0.3 due to high biomass interference). Note instrument malfunction reduced the years of survey at Meadowvale. Catchment areas are estimated from 0.5-1 m Lidar DEM.

Attribute	Units	Virginia Park		Meadowvale		Strathbogie		Minnievale	
		Control	Treatment	Control	Treatment	Control	Treatment (before treatment)	Control	Treatment
Bulk density derived from measurements above the control gully	(t/m ³)	1.66		1.50		1.27		1.50	
Average % silt +clay in soil profile above gully	%	32.60		31.60		73.50		41.83	
Years of data represented at each site	Years	3	4	2	1	3	3	3	3
Length of gully surveyed with the TLS	M	27.46	58.52	28.2	138.00	92.20	129.50	41.20	27.20
Erosion	t/y	2.81	6.98	17.90	18.28	70.10	223.35	10.97	4.15
Deposition	t/y	-0.21	-6.89	-1.37	-2.89	-6.16	-0.91	-3.85	-6.24
Net Change or sediment loss	t/y	2.60	0.09	16.52	15.38	63.95	222.44	7.13	-2.10
Deposition as a proportion of erosion (%)	%	7%	99%	8%	16%	9%	<1%	35%	>100%
Gully area (internal surface area based on 2019 survey)	ha	0.0124	0.0397	0.0389	0.0767	0.0975	0.0941	0.0267	0.0137
Total (fine + coarse) soil erosion	t/ha/y (internal area)	225.86	175.92	460.32	238.28	719.04	2372.99	411.19	303.39
Total (fine + coarse) soil deposition	t/ha/y (internal area)	-16.93	-173.72	-17.65	-37.73	-63.14	-9.69	-144.21	-456.74
Net Change or total sediment loss	t/ha/y (internal area)	208.93	2.20	442.67	200.55	655.90	2363.30	266.98	-153.36
Catchment area (ha) upslope of TLS survey	ha	1.1	1.3	3.1	3.5	10.7	41.4	2.1	2.8
Total soil (fine + coarse) erosion	t/ha/y (drainage area)	2.55	5.37	5.77	5.22	6.55	5.39	5.23	1.48
Total soil (fine + coarse) deposition	t/ha/y (drainage area)	-0.19	-5.30	-0.22	-0.83	-0.58	-0.02	-1.83	-2.23
Net Change or total sediment loss	t/ha/y (drainage area)	2.36	0.07	5.55	4.39	5.98	5.37	3.39	-0.75
Fine sediment loss (using upslope catchment area)	t/ha/y (drainage area)	0.77	0.02	1.75	1.39	4.39	3.95	1.42	-0.31

4.3 Rainfall, runoff, water quality and loads

The 2019/20 wet season had below average rainfall at all sites. Due to the low rainfall, several sites did not record any runoff or samples (see Table 12). A summary of the rainfall, runoff, water quality and loads data for the 2019/20 wet season (November 1, 2019 to May 30, 2020) for each of the sites is presented in Table 13 and Table 14. The rainfall and hydrographs for the wet season for each site are presented in Appendix A. Quality codes describing the confidence with the runoff and loads calculations for each site are given in Appendix B (Table 18; Table 19).

To ensure the sites were collecting robust velocity data that is used to determine runoff and sediment and nutrient load estimates, the cheaper (ultrasonic doppler) Starflow sensors were tested against the more expensive (acoustic doppler) Sontek IQ sensors (Figure 9). Overall, the relationship between the Starflow and IQ sensors was better than anticipated ($r^2 = 0.8$). The IQ sensor did provide more robust data, particularly at the high velocities experienced in flashier events. However, this result demonstrated that the Starflow sensors can provide sufficient estimates of mean velocity over the gully cross sections. The results from the relatively dry 2019/20 wet season were collected under low turbidity and low turbulence conditions at most sites. Additional years of data will be useful to evaluate the robustness of the results from both instruments. It is important that the Starflow sensors are appropriately calibrated (not using factory default settings) and checked more regularly than the more expensive sensors.

Table 12: Summary of the runoff, water quality and loads calculations for the 2019/20 wet season

Property	Gully	Discharge data collected in 2019/20	Water quality samples collected in 2019/20	Loads calculated in 2019/20
Virginia Park	Control	Low rainfall and runoff	No	Yes, using TSS-turbidity relationship from previous year
	Treatment	Low rainfall and runoff	No	Yes, using TSS-turbidity relationship from previous year
Meadowvale	Control	One small runoff event, no data due to logger issue	No	No
	Treatment	Low rainfall and runoff	No	Yes, using TSS-turbidity relationship from previous year
Strathbogie	Control (SBT)	Yes	Yes	Yes
	Treatment (SBT2)	Rehabilitation reduced or cut-off runoff. No data collected.	No	No
Minnievale	Control	Yes	No	Yes, using TSS-turbidity relationship from previous year
	Treatment	Yes	Yes	Yes
Mt Wickham	Control	Yes	Yes	Yes
	Treatment	Yes	Yes	Yes
Glen Bowen	Control	Low rainfall. Runoff detected but below velocity threshold.	Yes	No
	Treatment	Low rainfall +rehabilitation reduced or cut-off runoff. No data collected.	No	No
Mt Pleasant	Control	Yes	Yes	Yes
	Treatment	Yes	Yes	Yes

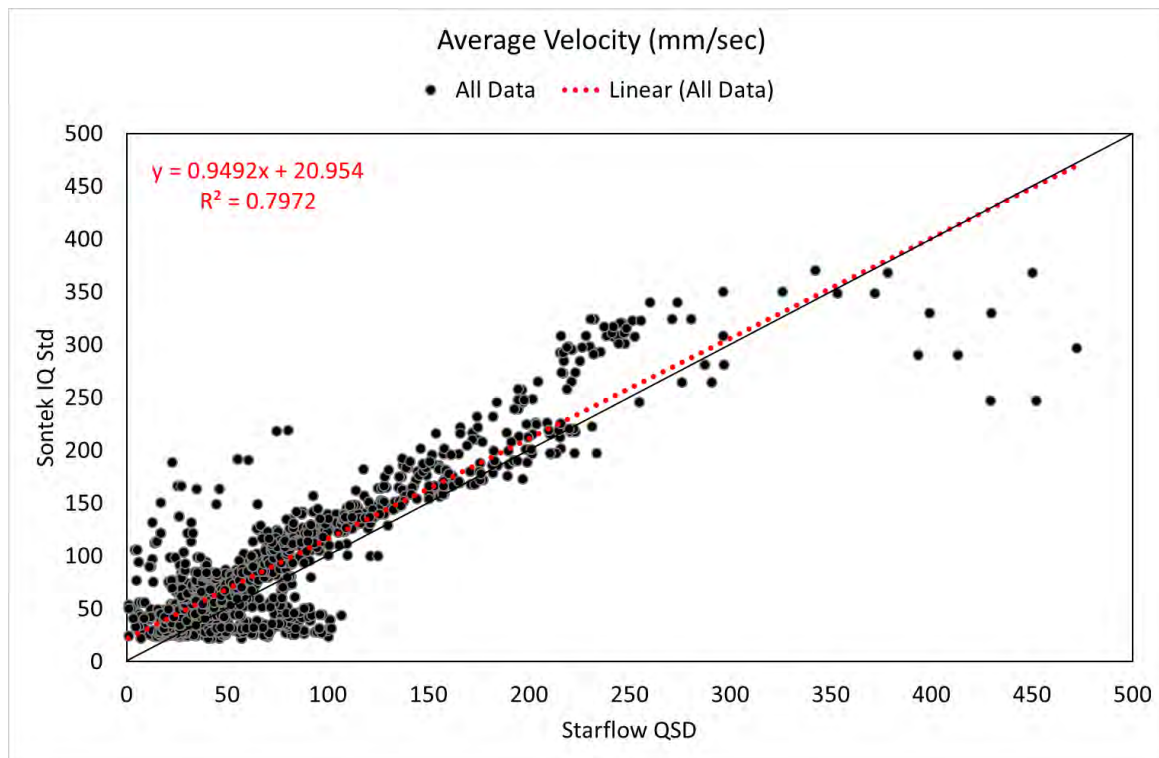


Figure 9: A comparison of the velocity data measured at coincident time steps using the Starflow QSD and Doppler IQ sensors at the sites with flow data during the 2019/20 wet season.

4.3.1 Water quality concentrations (TSS and TN data)

An evaluation of the treatment effects measured at each site are presented for each property in Section 0. A comparison of the Total Suspended Sediment (TSS) and Total Nitrogen (TN) concentrations between the control gullies for all sites are presented in Figure 11. A comparison of data from the control gullies demonstrates the diversity of TSS and TN concentrations that occur in gullies (in the Burdekin catchment) under non-treatment conditions.

The highest TSS concentrations in the 2019/20 wet season were measured at Glen Bowen and Mt Wickham which were many times higher than all other sites (Figure 11A). The TN values were much more similar between the sites, although Mt Wickham (control site) still had the highest median TN concentrations (Figure 11B). The relative differences between sites are generally consistent with results from earlier years.

Due to the initial budget constraints when installing the water quality monitoring equipment at each site, it was decided that the treatment site would receive the more expensive fully automated (ISCO) sampler set-up, and the control site would receive a cheaper rising stage sampler (RSS) that collected two samples in any given event. To test that the RSS samplers were sampling the water (and thus constituents) in a similar way to the ISCO samplers, coincident RSS samplers were also located with ISCO samplers at three treatment sites. Coincident samples from the RSS and ISCO sampler at Meadowvale (n = 5 samples), Strathbogie (n = 1) and Minnievale (n = 5) were compared (Figure 10). The results demonstrate that there is a reasonable comparison between measurement approaches for TSS concentrations below 2000 mg/L, however, the agreement is generally poor at higher TSS

concentrations. Based on this result, and the small number of water samples collected in each event by RSS samplers, it is now recommended that all sites have paired instrumentation using ISCO samplers. Paired control and treatment ISCO systems are now installed at Strathbogie and Mt Wickham, Glen Bowen and Mt Pleasant.

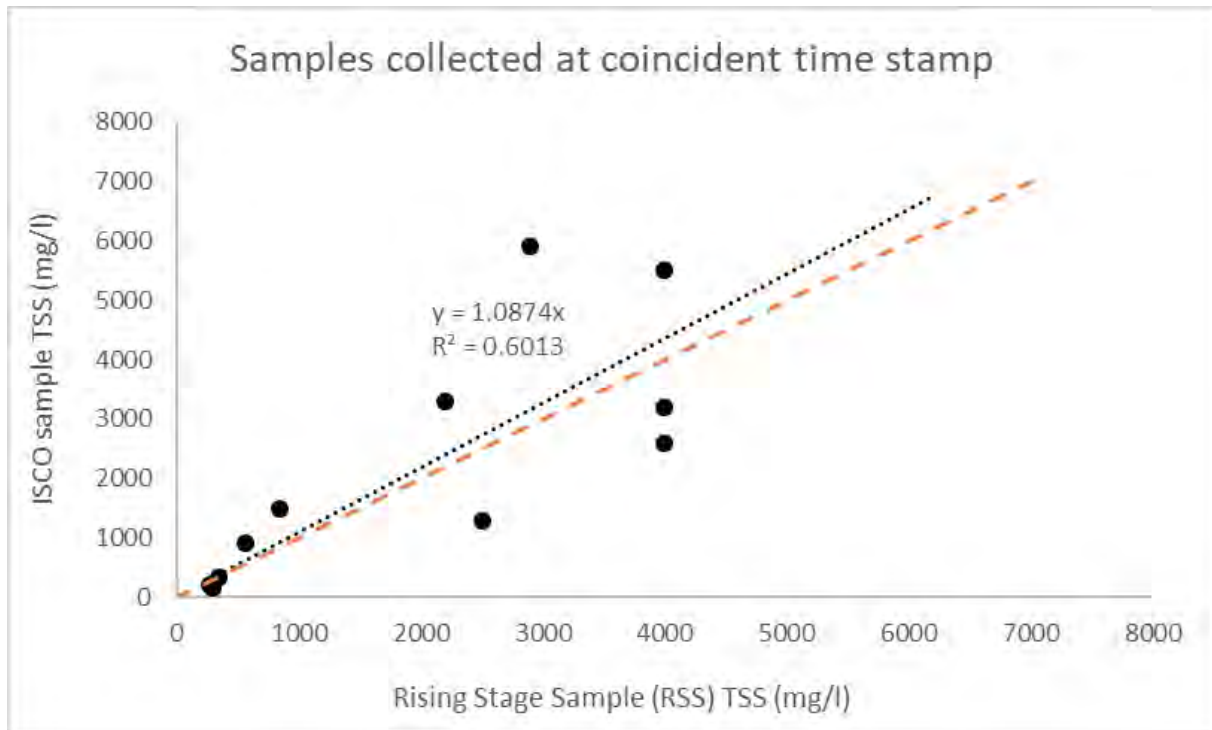
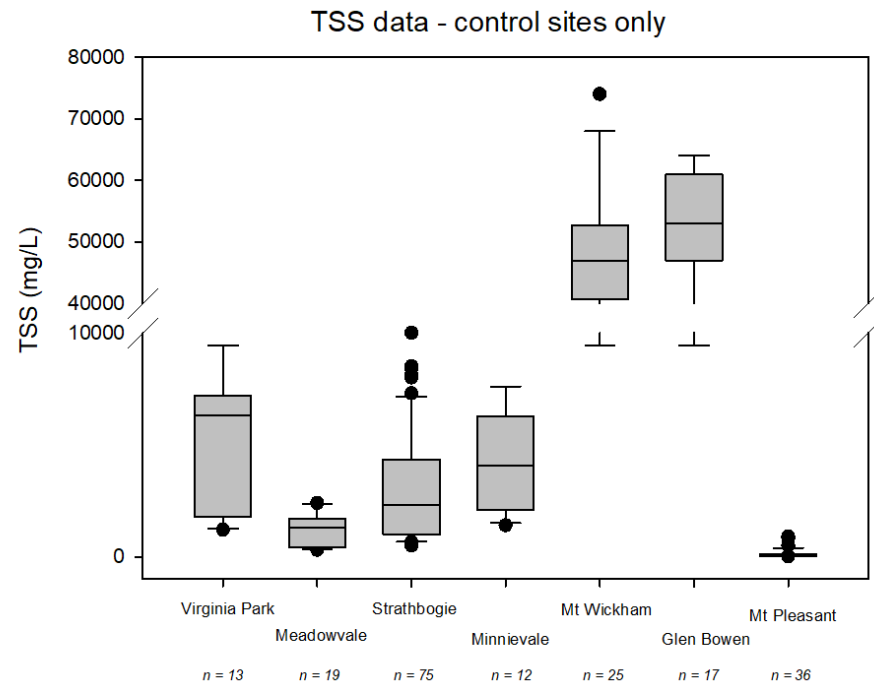
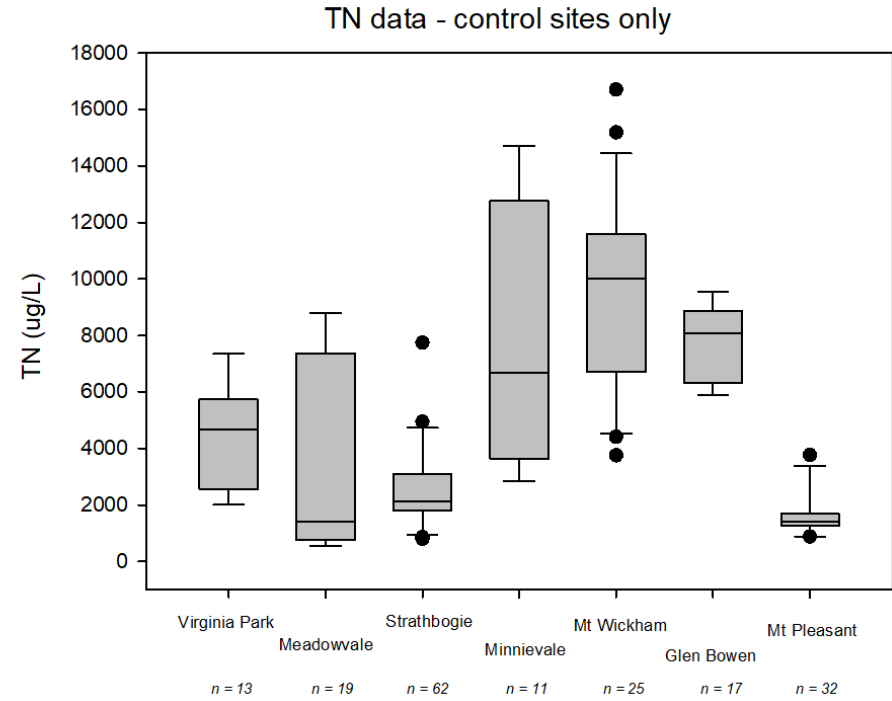


Figure 10: Comparison of water samples collected at the same stream location at the same time using (i) a rising stage sampler and (ii) and an ISCO water sampler. Orange dashed line is the 1:1 line.



(A)



(B)

Figure 11: (A) comparison of TSS data from all un-treated gullies for all years of data (B) comparison of TN data from all un-treated gullies for all TN data at each site (2016 - 2020).

4.3.2 Sediment particle size

Particle size analysis (PSA) is primarily used to help identify the very fine-grained component of sediment that is likely to travel into the GBR Lagoon. The <16 µm sediment (rounded to ~20 µm) is considered to be the most ecologically detrimental for the GBR (Bainbridge et al., 2018). Therefore, sites that are eroding fine grain soil will be a higher priority for rehabilitation.

The results of the PSA data from all sites is shown in Figure 12. Six out of seven sites have median particle size of less than 20 µm, with Strathbogie, which resides on vertosol soils, having the finest particle sizes at ~5 µm. In comparison, the Meadowvale site in the Upper Burdekin has much coarser particle sizes associated with the granitic soil at this site.

There is a weak negative power relationship with TSS concentration and particle size for the hillslope gully sites (Figure 13A; $r^2 = 0.25$) suggesting that sites with higher TSS concentration tend to have finer particle size. This tendency is removed when data from the alluvial gully sites are included (Figure 13B).

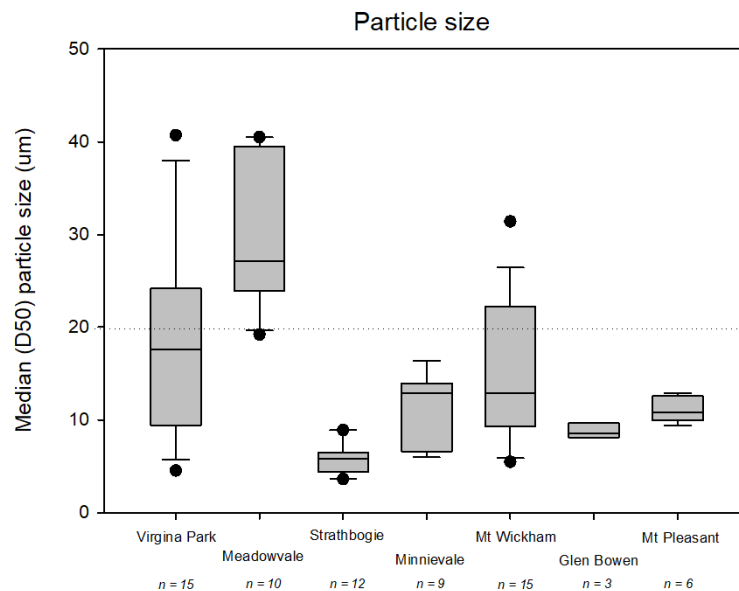


Figure 12: Particle size of suspended sediment collected at each site over the entire study period. Note that sediment <20 µm (dotted line) is considered to be the most ecologically detrimental for the GBR (Bainbridge et al., 2018).

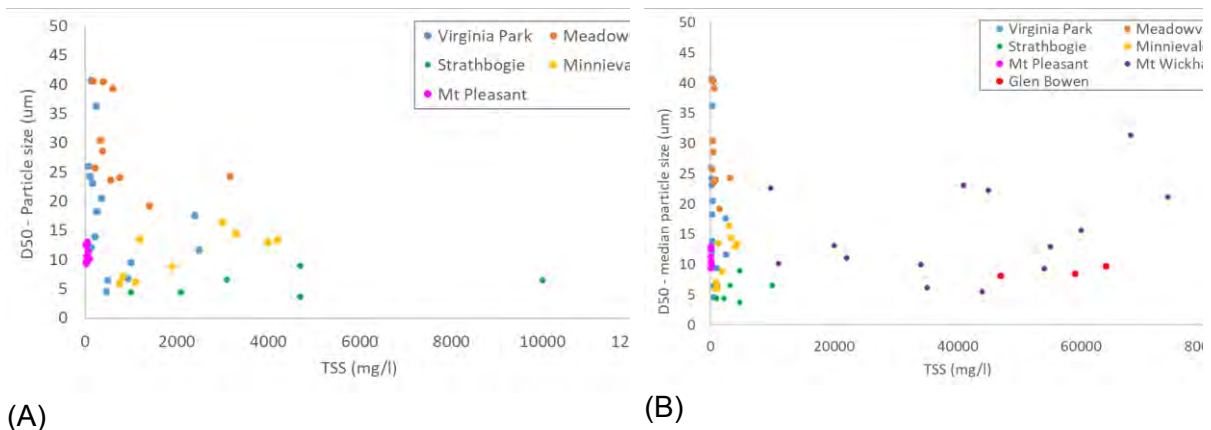


Figure 13: Relationship between TSS (mg/L) and particle size (D50) for (A) the hillslope gullies only and (B) for all gullies including the two alluvial gully sites (Mt Wickham and Glen Bowen)

4.3.3 Velocity, runoff and sediment and nutrient loads

Table 13 and Table 14 show the sites for which data was collected in 2019/20, and detailed results for each property are given in Section 0. The absolute concentration of the measured TSS concentrations from the lab analysis were presented in Figure 11. In Figure 14, the flow weighted mean sediment concentrations are presented. These are calculated as the total annual sediment load (t/y) divided by the total flow for that year (L). This provides a 'flow weighted' estimate of the average TSS concentration at each site (mg/L). A comparison of the t/ha sediment loads and flow weighted mean TSS concentrations for the sites that collected suitable data in 2019/20 are shown in Figure 14, noting that for many sites, these loads are well below estimates from 2018/19 due to the lower rainfall. The measured fine sediment loads are the highest from the Mt Wickham control site which also have very high mean flow weighted concentrations. The Mt Pleasant treatment site had the lowest sediment loads and concentrations, for both the treatment and control site.

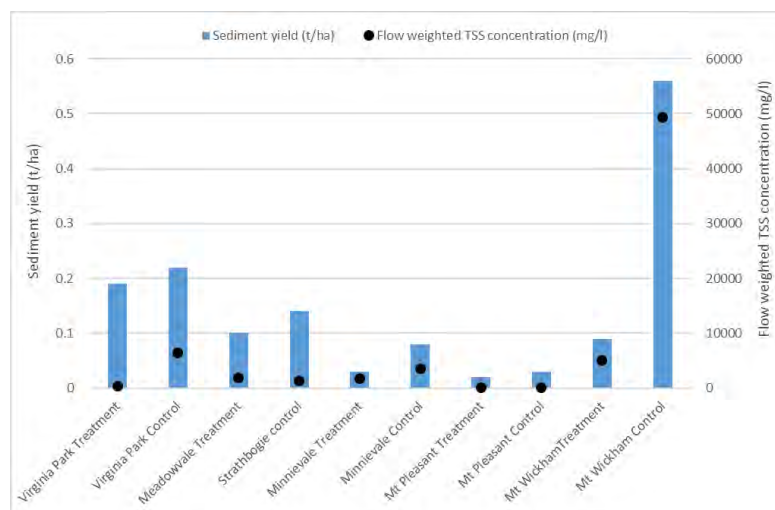


Figure 14: Sediment loads (t/ha) and flow weighted mean concentration (mg/L) measured at the field sites in 2019/20. Noting that the area calculation is based on the contributing catchment area.

Table 13: Summary of rainfall, runoff, water quality concentration and loads for each of the alluvial gully sites for the 2019/20 wet season (July 2019 to May 31st 2020). Catchment area was calculated using Lidar.
^a insufficient rainfall to produce runoff or samples; and ^b no runoff due to treatment effects or na meant it was not suitable to estimate loads for this site.

	Mt Wickham *		Glen Bowen	
	Treatment	Control	Treatment	Control
Site Rainfall (mm) 2019-2020 (Jul-Mar)	370	390	369	337
Long term rainfall (mm) BOM, long term data	626 mm (record length 2000 – 2018)		723 mm (record length 1886-2019)	
Catchment area (ha) above monitoring station	14.1 ^a	3.1 ^a	2.7	2.9
Slope – hillslope above gully (%)	2.2	3.9	4.5	2.5
Hillslope Cover (%) Post- wet	89%	50%	65%	27%
Gully walls (% cover Post- wet	79%	29%	na	na
Gully floor (% cover) Post-wet	42%	3%	na	na
Runoff (mm)	1.8	1.1	0	0
% runoff	0.5	0.3	0	0
Sediment yield (t)	1.2	1.7	0 ^b	0 ^a
Sediment yield (t/ha)	0.09	0.56	0 ^b	0 ^a
Flow weighted annual average sediment concentration (mg/L)	5118	49356	0 ^b	0 ^a
Total Nitrogen yield (kg)	0.8	0.3	0 ^b	0 ^a
Total Nitrogen yield (t/ha)	0.1	0.1	0 ^b	0 ^a

Table 14: Summary of rainfall, runoff, water quality concentration and loads for each of the hillslope gully sites for the 2019/20 wet season (July 2019 to May 31st 2020). Catchment area was calculated using Lidar at all sites except Mt Pleasant where SRTM data were employed. Flow weighted annual average sediment concentration is the total load divided by flow; ^a insufficient rainfall to produce runoff or samples; and ^b no runoff due to treatment effects or na meant it was not suitable to estimate loads for this site; *failed instrument, data in-filled.

	Virginia Park		Meadowvale		Strathbogie		Minnievale		Mt Pleasant	
	Treatment	Control	Treatment	Control	SBT2 - Treatment	SBT – control	Treatment	Control	Treatment	Control
Site Rainfall (mm) 2019-2020 (Jul-Mar)	259	305	350	340*	439	504	506	522	440	449
Long term rainfall (mm) BOM, long term data	650 mm (record length 1899-2016)		650 mm (record length 1899-2016)		725 mm (record length 1886-2016)		841 mm (record length 1961-2016)		687 mm (record length 2000 – 2019)	
Catchment area (ha) above monitoring station	1.3	3.1	5.0	4.2	41.4	19.4	24.9	8.1	258.7	54.8
Slope – hillslope above gully (%)	4.3	3.9	2.9	3.0	2.2	2.1	2.0	2.9	na (no lidar)	na (no lidar)
Hillslope Cover (%) Post-wet	77%	50%	79%	59%	70%	67%	72%	63%	93%	90%
Gully walls (% cover Post-wet)	44%	40%	70%	53%	44%	49%	61%	29%	67%	71%
Gully floor (% cover) Post-wet	59%	6%	41%	23%	25%	40%	30%	12%	47%	6%
Runoff (mm)	50.3	3.5	0.3	0	0	10.7	1.7	2.2	34	35.5
% runoff	19.4	1.1	0.1	0	0	2.1	0.3	0.4	7.6	7.9
Sediment yield (t)	0.2	0.7	<1	0 ^a	0 ^b	2.8	0.7	0.6	6.10	1.8
Sediment yield (t/ha)	0.19	0.22	0.01	0 ^a	0 ^b	0.14	0.03	0.08	0.02	0.03
Flow weighted annual average sediment concentration (mg/L)	375	6439	1899	0	0 ^b	1343	1764	3568	70	93
Total Nitrogen yield (kg)	0.9	0.5	0 ^a	0 ^a	0 ^b	2.9	1.3	1.4	na	na
Total Nitrogen yield (t/ha)	0.66	0.17	0 ^a	0 ^a	0 ^b	0.2	0.1	0.2	na	na

4.4 Comparison of sediment loads measured using terrain analysis and hydrologic instrumentation

Given that a range of approaches have been applied to estimate both baseline and post-treatment sediment yields, it was of interest to compare the results obtained using the different approaches. A comparison of the annual average fine sediment yields derived using (i) the terrain analysis and (ii) loads monitoring, are shown in Figure 15. Interestingly, the net fine sediment loss estimated using the hydrologic loads monitoring instrumentation is ~30% of the load estimated using terrain analysis (i.e. annual TLS scans for most sites or historical air photos + lidar in the case of Mt Wickham). There are several possible explanations for this result:

- There are differences in the gully length or area represented by both techniques (see Figure 16). Despite our initial best efforts to co-locate instrumentation and surveys, a range of factors meant that there were differences in the actual length or amount of gully represented by each approach;
- The gully area measured using the laser scanner is generally smaller and focused on the more active headcut region of the gully (see the TLS image results in for each property e.g. Figure 22). Whereas the hydrologic instrumentation, in most cases, was capturing a larger and longer section of the gully. Thus, there is the potential for some redeposition of fine sediment to occur between the more active headcut region and the stream gauge in any one year;
- The particle size fractions being classed as 'fine' may vary between the different techniques. The fine sediment calculated using the TLS approach is based on the % of silt and clay in the original soil profile as measured using the Queensland Government Soil standard (which is nominally <20 µm). Whereas the ISCO sampler collects suspended sediment in the water column and appears to be primarily capturing sediment that is up to 40 µm, but median values are ~10 µm (see Figure 12).
- It is possible that the hydrologic monitoring is under-estimating sediment loads at some sites. In particular, the velocity sensors appear to be less accurate in highly turbid flows, which may reduce the overall mean velocity and therefore under-estimate sediment loads. Continued calibration of these sensors in a range of environments is needed to ensure robust load calculations.
- This result also reflects some of the error and uncertainty associated with both these measurement techniques. With the TLS approach, errors and uncertainty increases with high biomass or ground cover which is typical after wet years. The water quality and hydrological instrumentation are also prone to uncertainty particularly in years that undergo instrument failure, backwatering or smothering by sediment. Hence, even the 'gold standard' techniques have high uncertainty in these highly variable environments.

In summary, this result suggests that there is merit in continuing to measure and test a range of approaches for estimating sediment yield, at least at focused research sites.

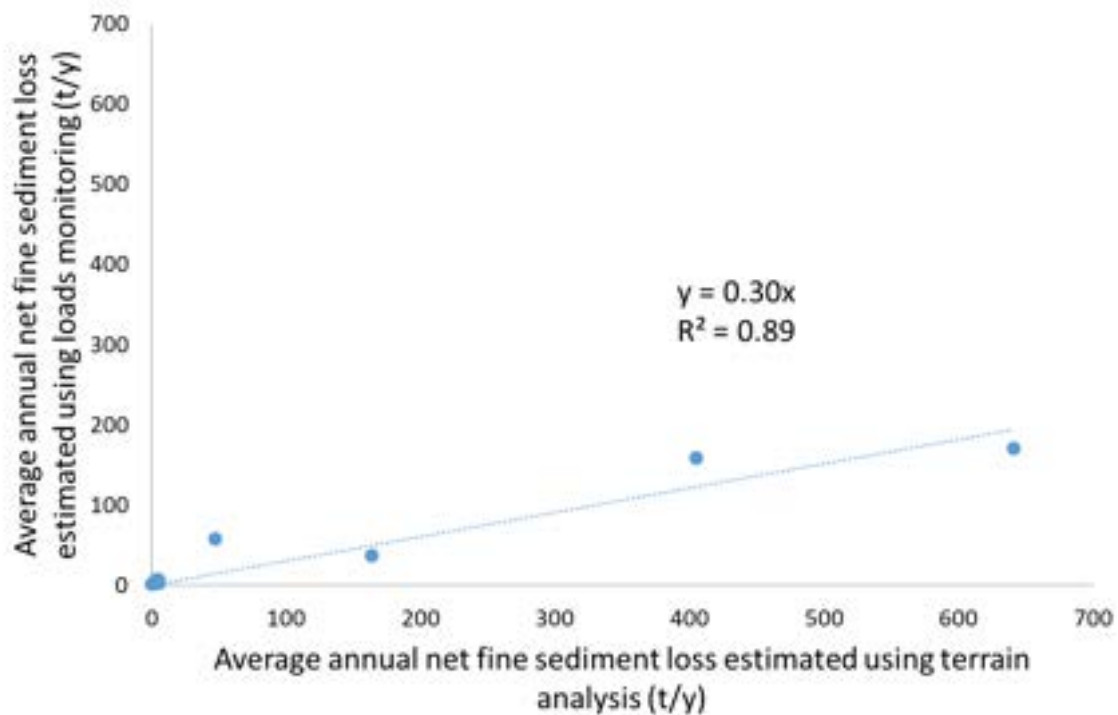


Figure 15: Average annual net fine sediment loss (t/y) estimated using laser scanning (primarily the headcut region) against average annual net fine sediment loss (t/y) estimated using loads monitoring instrumentation. Data from Virginia Park, Meadowvale, Strathbogie, Minnievale control only (Treatment removed as areas different by a factor of 9) and Mt Wickham were included in this analysis. Terrain data for Mt Wickham was derived from Stout et al., (2020) which is based on historical erosion rates combined with airborne lidar rather than ground based TLS annual measured erosion rates.

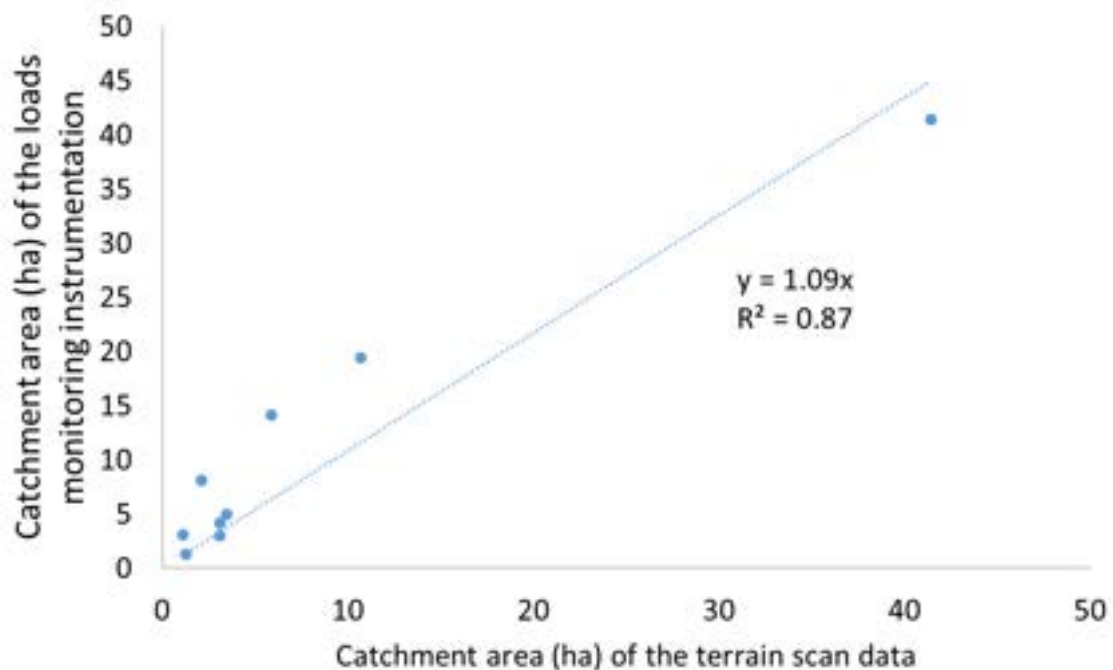


Figure 16: Comparison of the catchment areas represented by the laser scan (or Lidar in the case of Mt Wickham) and the catchment areas represented by loads monitoring instrumentation water quality (WQ). Data from Virginia Park, Meadowvale, Strathbogie, Minnievale control only (Treatment removed as areas different by a factor of 9) and Mt Wickham were included in this analysis.

4.5 Comparison of rehabilitation effectiveness calculations

Table 15 demonstrates the difference in effectiveness values that are calculated using different measured water quality data sets. As described in Section 3.8, if the events are adequately sampled at both control and treatment sites throughout the wet season, and before and after treatment, it is possible to use sample concentrations to estimate treatment effectiveness. However, the recommended approach is to use the sediment yield data for the year that the statistical change was detected.

The three approaches applied here to demonstrate the range in effectiveness values include:

1. Using adequately sampled concentration sample data (not flow weighted);
2. Applying event mean concentration (EMC) data which is the load for that event divided by runoff for that event (after Kim et al., 2004). This approach is more robust than using option #1 and accounts for variability in rainfall and runoff between sites. However, it is not always available for all sites if there have been challenges with the velocity or depth sensors during events.
3. Using the loads data from control and treatment sites for all years of data collection. Loads are calculated by using continuous interpolated TSS from a turbidity trace (Leigh et al., 2019) and coincident discharge data.
4. Using the loads data from control and treatment sites for the final year of data collection when the change in load is most pronounced.

Importantly, the effectiveness values presented are indicative only and are likely to change with additional years of monitoring. A preliminary evaluation of the cost-effectiveness for several of these field sites was presented in Bartley et al., (2018b). That evaluation was not repeated in this report.

Table 15: The sediment reduction effectiveness values calculated at Mt Wickham and Strathbogie using different data metrics. Noting that * represents sites that have had 100% change following treatment, but given we only have one wet season of post-treatment data at this site, a 95% value is considered more appropriate until further data is collected.

Approach	Effectiveness value as %	Mt Wickham	Strathbogie
1	Measured concentrations, most recent year only	~93	~95*
2	Event mean concentration, most recent year only	~90	~95*
3	Sediment yield using all years of measured data (average of SYC – average SYT)/average SYC	~77	~70
4	Sediment yield using most recent year only	~84	~93

5.0 RESULTS – BY PROPERTY

5.1 Virginia Park

5.1.1 Treatment progress

The Virginia Park treatment site represents the longest running of all the treatment sites. This is the 10th wet season of erosion monitoring at this treatment site, and the results build on previous work funded in the Paddock to Reef (P2R) program (Wilkinson et al., 2013; Wilkinson et al., 2014; Wilkinson et al., 2015b; Wilkinson et al., 2018). The key results from this study have been written up for journal publication (Koci et al., Accepted). A fence around this treatment gully, and instream structures, were installed in 2010 (Figure 17). About 30% of the hillslope above the gully was disc ploughed and seeded in 2010. There are six porous check dams (PCDs) installed within the gully; three are above the water sampling site, and three are below. The PCDs have required no maintenance over the ten-year period, however, with increased organic matter now being trapped in the channel, it is possible that that structures may start to break-down over the coming decade. The backwater area upstream of each PCD has now filled with sediment and has likely reached their maximum effectiveness in terms of sediment trapping (Figure 18). The intention of the PCDs was also to initiate revegetation of the gully floor by trapping some fine sediment and associated seeds. It is the vegetation that will grow in the gully that is considered as a relatively low-cost treatment for long-term stabilisation of these smaller gullies. Figure 18 shows the field sites at Virginia Park under different flow event and non-event conditions over the last three wet seasons. Noting that the amount of vegetation in the gully, including small saplings, have increased over the study.

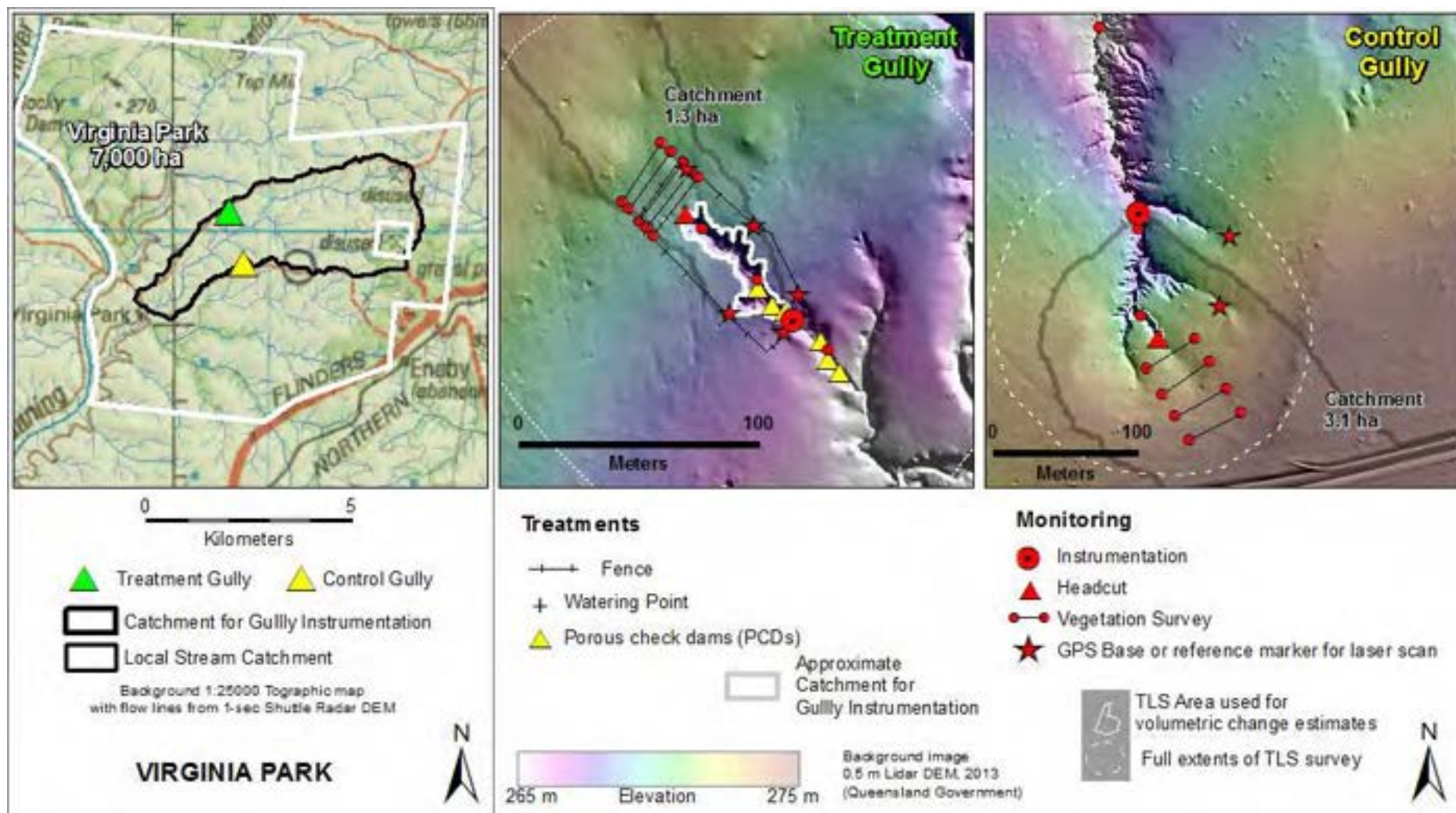


Figure 17: Location of the Virginia Park site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)



(D)



(E)



(F)

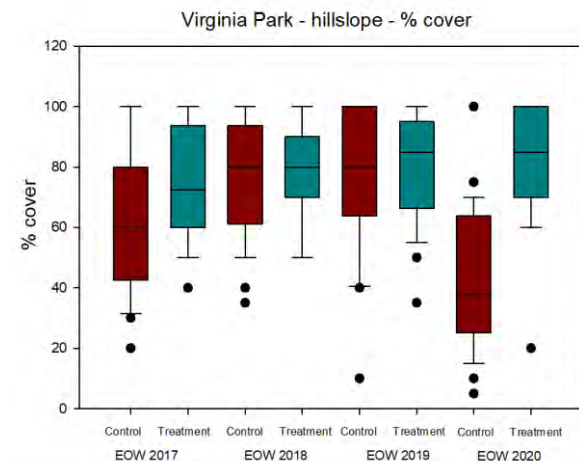
Figure 18: Treatment gully at Virginia Park in (A) 2016 (B) during an event in 2017 (C) at the end of reporting period in April 2017 (D) in April 2018 (E) during an event in 2019 and (F) at the end of April 2020

5.1.2 Vegetation response

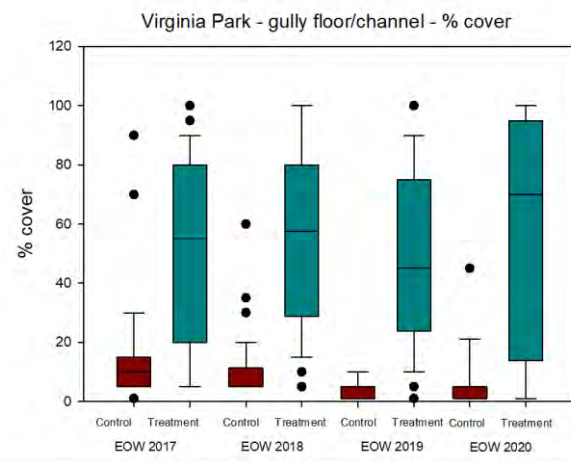
Figure 20 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully at Virginia Park as well as the gully walls and gully floor. The hillslope control site shows a statistically significant decline in cover in 2019/20 and reflects the broader cover and biomass conditions following the below average rainfall during the 2019/20 wet season (Figure 19). The treatment site, which is mostly fenced, now has statistically higher hillslope % cover and biomass than the control over the 2019/20 wet season ($p < 0.001$). There is also a significant treatment difference in the end of wet (EOW) % cover on the gully floor ($p < 0.001$) which is likely to be a direct consequence of the location of the PCD structures, although gully floor biomass has not changed significantly at the treatment site compared to the control ($p = 0.60$). There has not been an increase in gully wall % cover ($p = 0.764$), however, gully wall biomass was higher at the treatment site in 2019/20 compared to the control ($p = 0.036$).



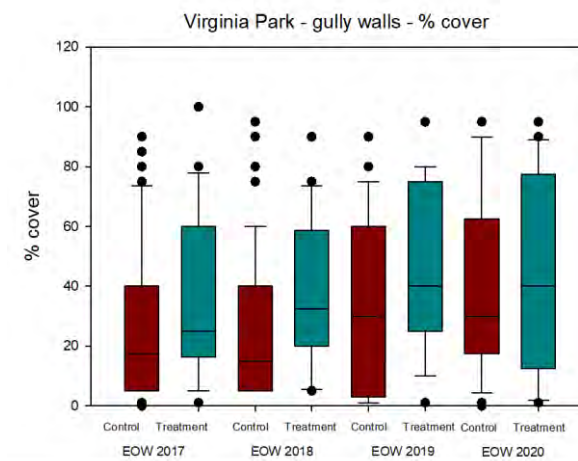
Figure 19: Virginia Park hillslope above (A) control gully and (B) the treatment gully hillslope which has a partial cattle exclusion fence.



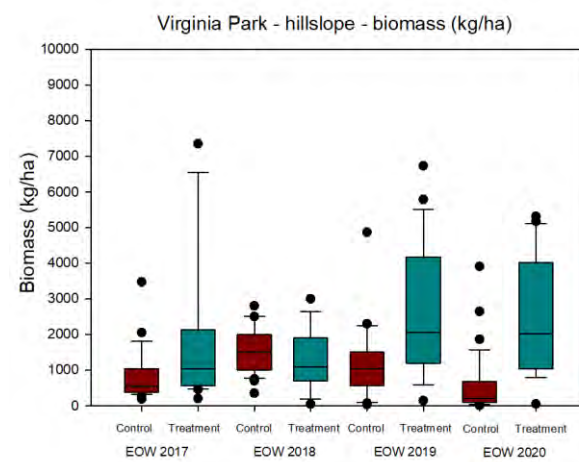
(A)



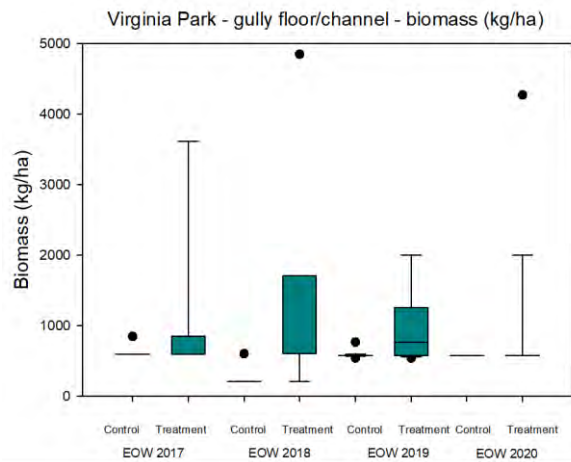
(B)



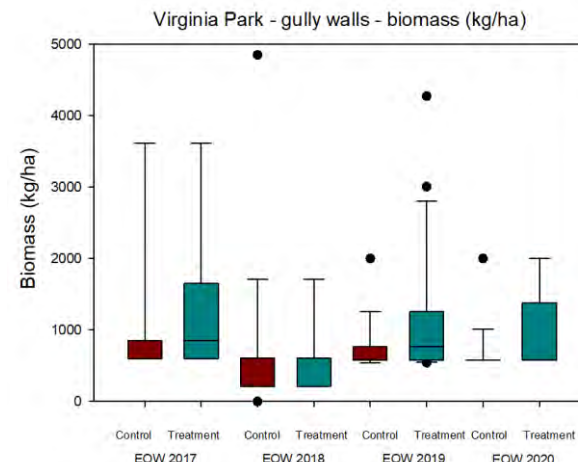
(C)



(D)



(E)



(F)

Figure 20: Virginia Park control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the four year NESP study period. EOW = end of wet season. Note extreme outlier data were excluded at some sites for plotting purposes.

5.1.3 Terrain changes

The terrain analysis results obtained using the terrestrial laser scanner (TLS) were presented in Table 10 and Table 11. The volumetric change in sediment erosion and deposition between the treatment and control site at Virginia Park is presented in Figure 21. Due to COVID-19, this section presents data only up to 2018/19.

The results demonstrate that the amount of sediment lost from the head-cut area is higher at the treatment site compared to the control site. However, the amount of sediment deposited (or trapped) in the gully as a % of erosion varies between 7% for the control, and 99% for the treatment site. The treatment site terrain scan includes ~ 3 of the PCD's installed at this site, suggesting that most of the sediment that was eroding was being trapped or deposited behind the structures. The fact that there is still fine sediment being measured downstream suggests that the hillslope above the gully is a continued source of sediments and nutrients into the gully, and that some of the fine sediment eroded from the gully walls is passing through the PCD's.

Figure 22 presents the TLS results including the DEMs of Difference which show the dominant locations of the erosion (mainly the head-cuts) and the deposition areas. The linear head-cut growth of the treatment site is on average 0.33 m/y (Table 10) which is similar to the control site of 0.30 m/y. Both the control and treatment sites have had a slight decline in head-cut retreat rate over the three-year study period (Table 10). Somewhat counter-intuitively, the reduced head-cut retreat is inversely related to the amount of rainfall received at the site over the last 3 years (Figure 24). That is, there was higher headcut retreat in years with lower rainfall.

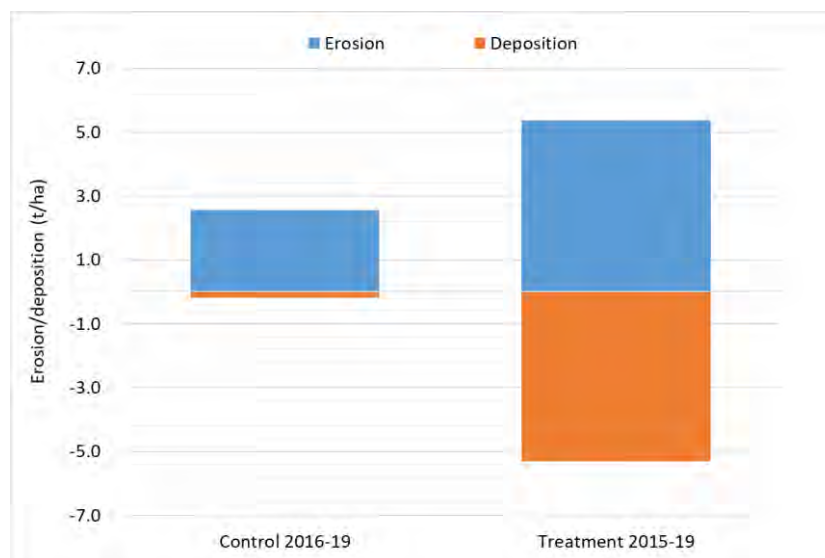


Figure 21: Net total (fine + coarse) sediment movement (t/ha/y) for Virginia Park (using a measured soil bulk density of 1.66 t/m³) for the 2016-19 period. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The area (ha) is based on the upstream catchment area to the end of the TLS scan.

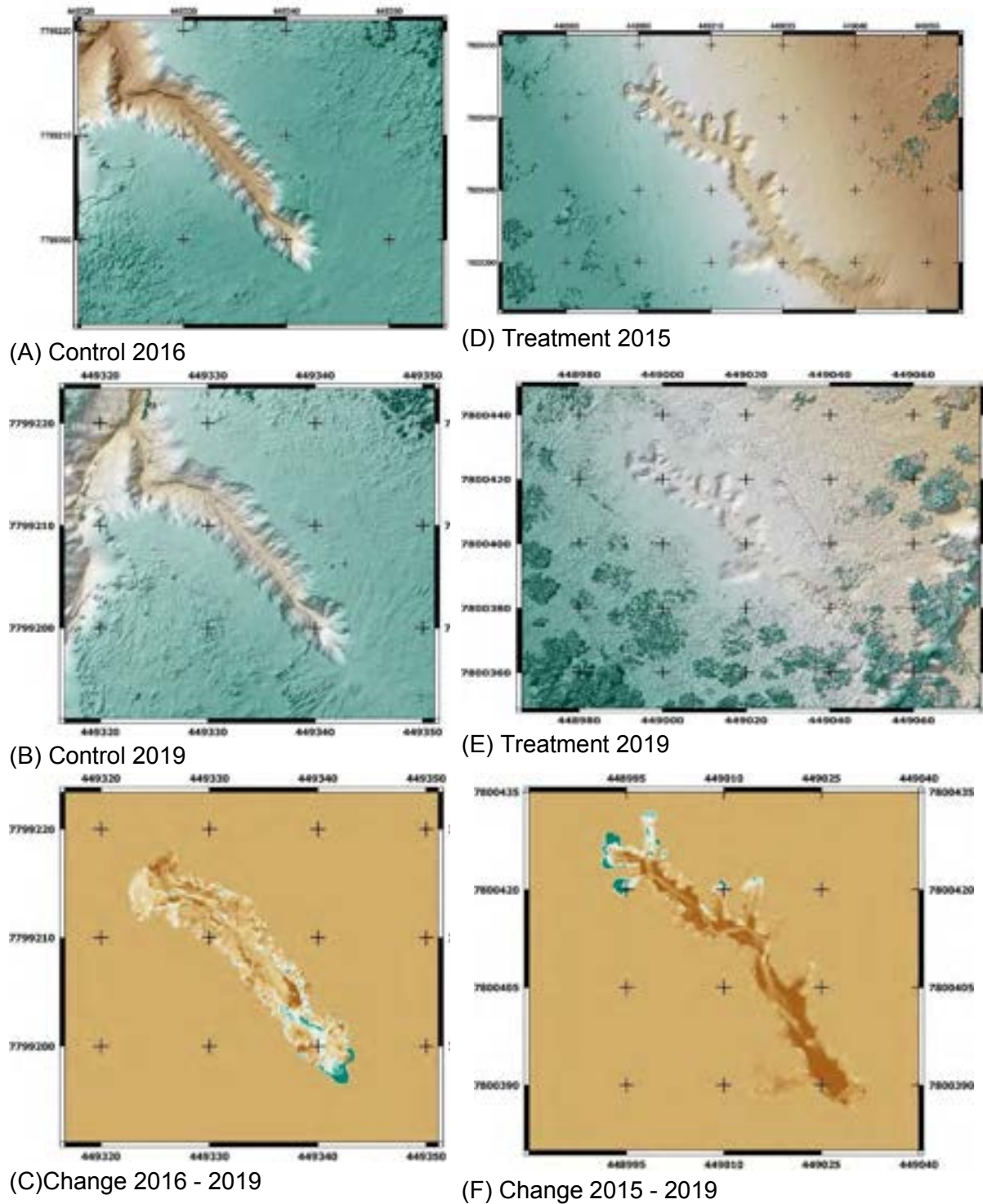


Figure 22: Virginia Park (A) control gully in 2016 (B) control gully in 2019 and (C) DEM of Difference; (D) treatment gully in 2015, (E) treatment gully in 2019 and (C) DEM of Difference as measured by the RIEGL terrestrial laser scanner, where dark green is erosion and brown is deposition.

5.1.4 Water quality, runoff and loads

During the 2019/20 wet season, the treatment site received on 259 mm of rain and there was 305 mm at the control site (Figure 24). This was well below average for this site and both the control or treatment gullies only received small amount of runoff above the sampling threshold in 2019/20. Therefore, no water quality samples were collected and loads estimates were calculated using Turbidity-TSS relationships developed in previous years. Samples were collected at the control site over the last three wet seasons (Figure 23), however, this site experienced large bed level changes, and the velocity sensor was not sufficiently inundated in the later years. Therefore, no rating curve has been developed for the control site, and a constant average velocity was used for this site (Table 8; Figure 24).

During the previous wet seasons, the TSS and TN concentration data suggests that samples from the treatment site are statistically lower than at the control sites during 2018/19 wet season ($p < 0.001$) (Figure 23A). The low number of samples make this comparison difficult in other years, however, the general trend in the median values suggests that the concentrations of TSS and TN are less at the treatment site.

The TSS and TN loads at the treatment site generally follow the rainfall trend with an increase in loads in 2018/19 compared to other years. The TSS loads presented for 2017/18 are lower than expected given the rainfall amount, however, this may reflect the pattern of rainfall distribution over the wet season and/or possibly sensitivities in the rating curve to changes in channel profile.

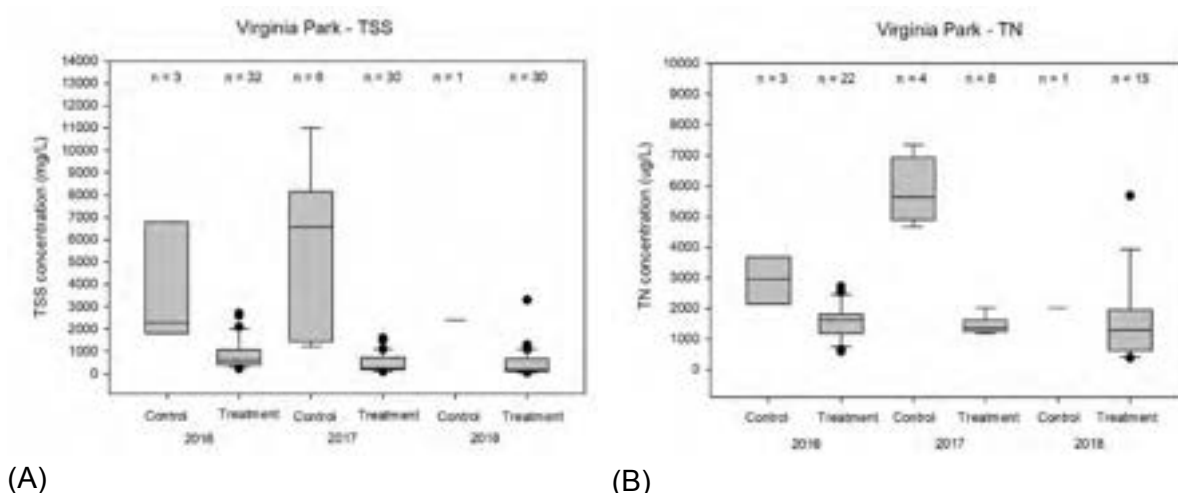


Figure 23: (A) TSS concentration and (B) TN concentrations at Virginia Park for three wet seasons. Year is start of wet season (2016/17, 2017/18, 2018/19)

5.1.5 Summary: Virginia Park

Overall, the fencing and PCD treatments are having a measurable effect on gully floor and wall vegetation cover and biomass. The effect of ploughing and seeding on the hillslope above the treatment gully was not explicitly measured in this study (due to lack of pre-treatment data), however, it may have played a minor role in the initial higher cover and biomass at the treatment site. In 2019/20 the cattle exclusion fence around the gully also prevented cover and biomass on the treated hillslope from declining like that of the control. There has been a reduction in head-cut erosion at the treatment site over the three years, but this reduction has

also occurred at the control gully. The PCD treatments appears to have been effective at inducing deposition behind the structures, however, most of this sediment is coarse ($>63\ \mu\text{m}$) material (Koci et al., Accepted). The combined treatment effects at this site (hillslope disc plough +fencing + PCDs) appear to have had some success at reducing the TSS and TN concentrations in some years.

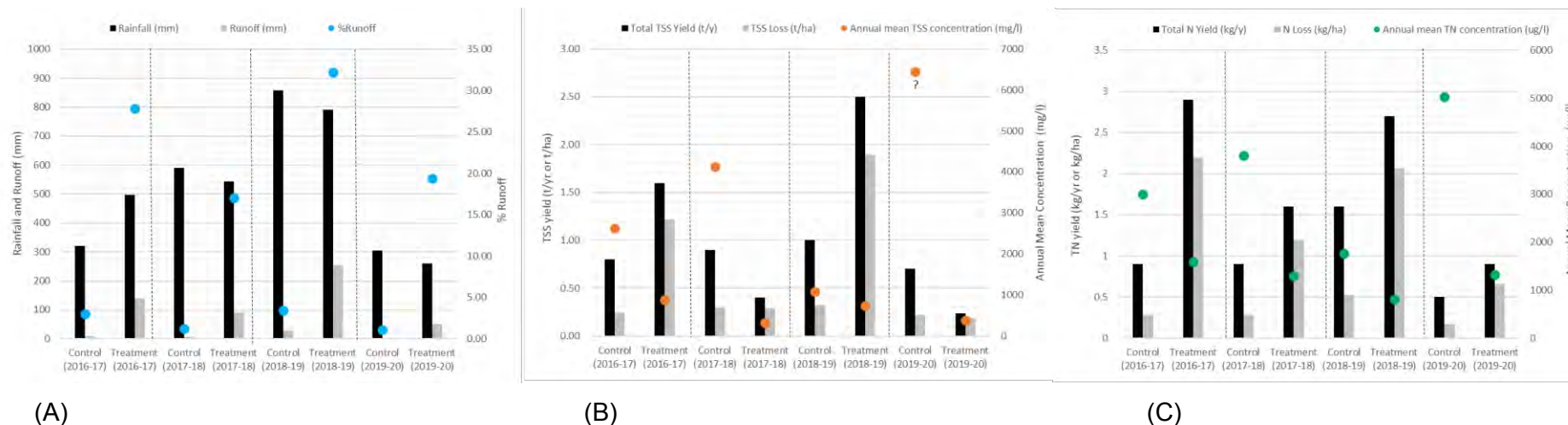


Figure 24: Virginia Park Control and Treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y and t/ha) and flow weighted annual average TSS concentration (mg/L) and (C) Total Nitrogen (TN) loads (kg/y and kg/ha) and flow weighted annual average TN concentration (ug/L). Low runoff was measured, and as a result, no water quality samples were collected in 2019/20. The TSS and TN concentrations are estimates based on Turbidity-TSS curves developed in previous years. As such, the data has low confidence, particularly for the control site. Data quality caveats in Appendix B.

5.2 Meadowvale

5.2.1 Treatment progress

The Meadowvale site has the simplest of all the treatments involving cattle exclusion fencing only. The gully exclusion fence was completed in 2017 and therefore the water quality data collected in 2016/17 represented a before treatment year. The 2017/18 wet season was the first year to evaluate the gully treatment. The cattle exclusion fence is constructed using a combination of four strands of heavy-duty barbed wire and electric fencing, encompassing the gully head and water quality monitoring system (Figure 25).

The treatment gully is adjacent to a re-instated long-term set of hillslope runoff troughs, initially installed by the Queensland Department of Primary Industry (DPI) in the 1980's. The hillslope treatment includes a 4 ha area that has had light or no cattle grazing since 1986, and cattle exclusion since 2002. So approximately half of the hillslope above the treatment gully has had cattle exclusion for more than 15 years (Hawdon et al., 2008).

The control gully at Meadowvale has been monitored over 20 years (1999 – 2020) using erosion pins, topographic survey techniques and vegetation transects. Figure 26 shows the field sites at Meadowvale under different flow event and dry conditions over the last three wet seasons. The improved grass cover in the channel or floor on the treatment gully is visible over the three-year monitoring period.

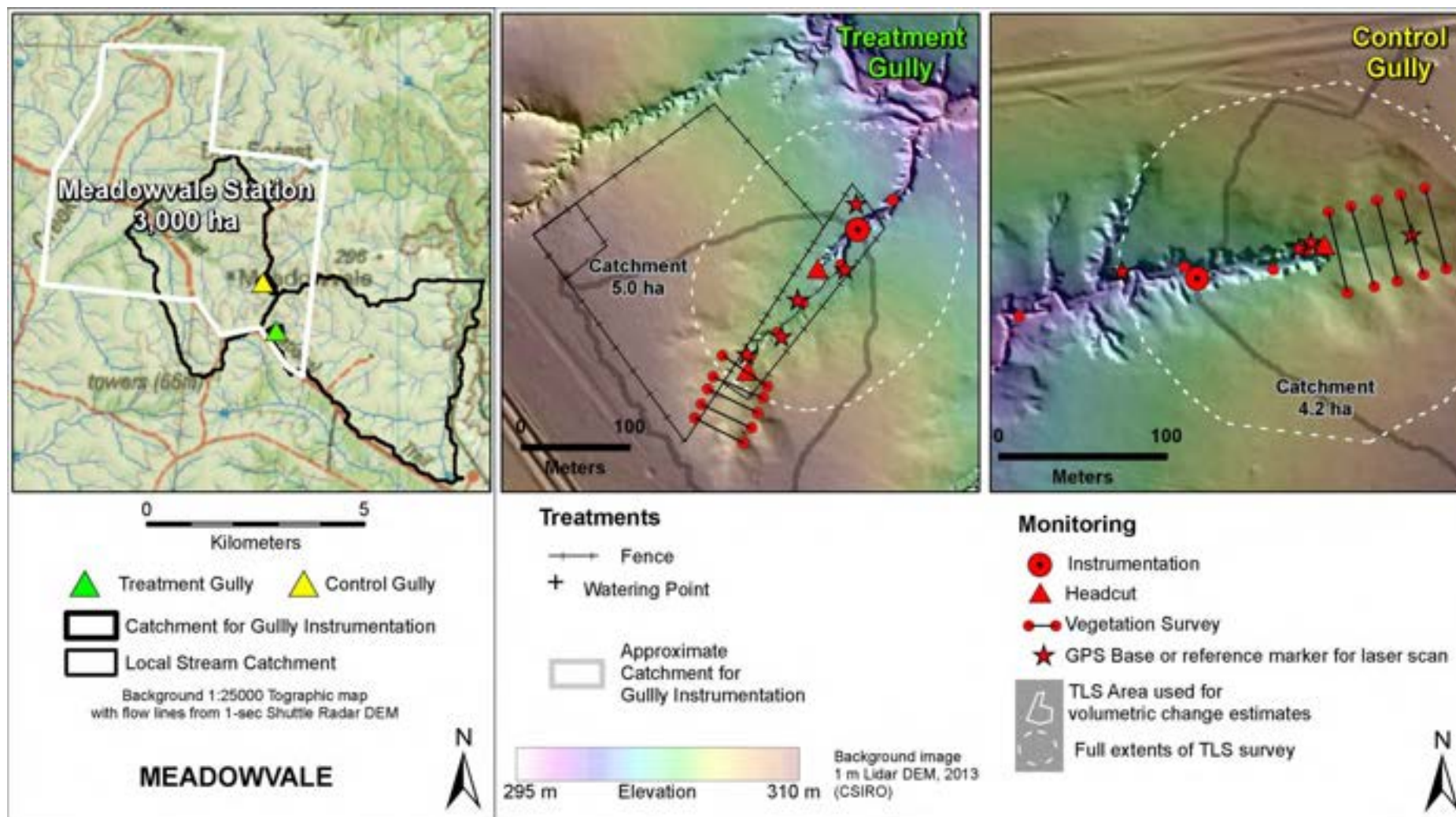


Figure 25: Location of Meadowvale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)



(D)



(E)



(F)

Figure 26: Treatment gully at Meadowvale in (A) 2016 (B) during an event in 2017 (C) at the end of reporting period in April 2017 (D) at the end of reporting period in April 2018 (E) an event in 2019 and (F) at the end of wet season, April 2020

5.2.2 Vegetation response

Figure 28 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully at Meadowvale as well as the gully walls and gully floor. The results demonstrate that there has been a significant increase in hillslope % cover ($p < 0.001$) and biomass ($p < 0.001$) at the treatment site in 2019/20. There is a significant difference in the end of wet (EOW) % cover ($p = 0.001$) and biomass ($p = 0.009$) on the gully floor in 2019/20. There has also been a significant change in % cover ($p = 0.001$) and biomass ($p = 0.009$) on the gully walls during the 2019/20 wet season. The % cover on the gully floor and walls has increased from ~20% at the beginning of the trial (with no fencing) to ~80% in 2019/20 after just three years of cattle stock exclusion. The dramatic change in within gully condition is shown in Figure 26.

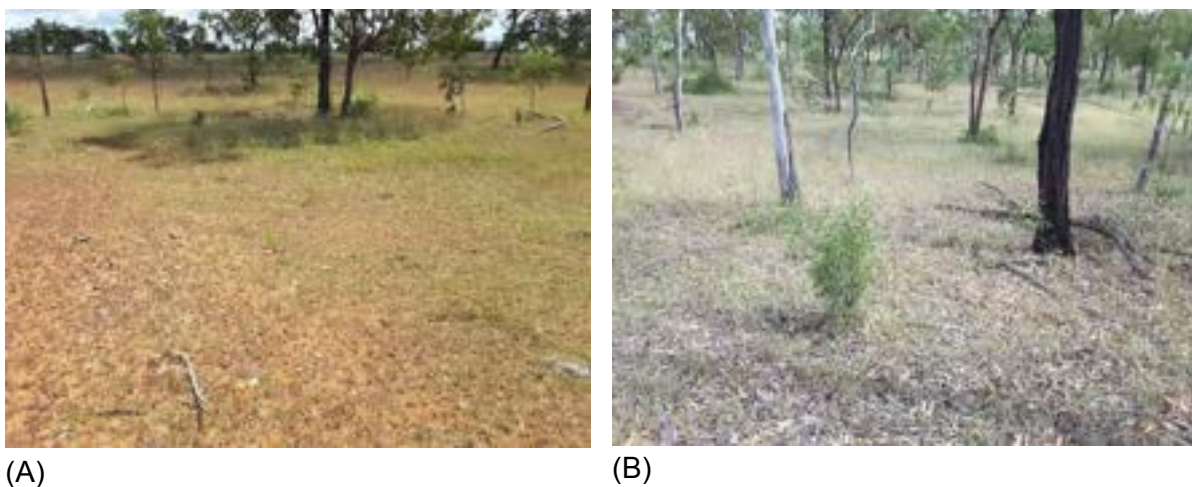


Figure 27: Meadowvale hillslope above (A) control gully (T4) and (B) the treatment gully hillslope (T4) which has a partial cattle exclusion fence.

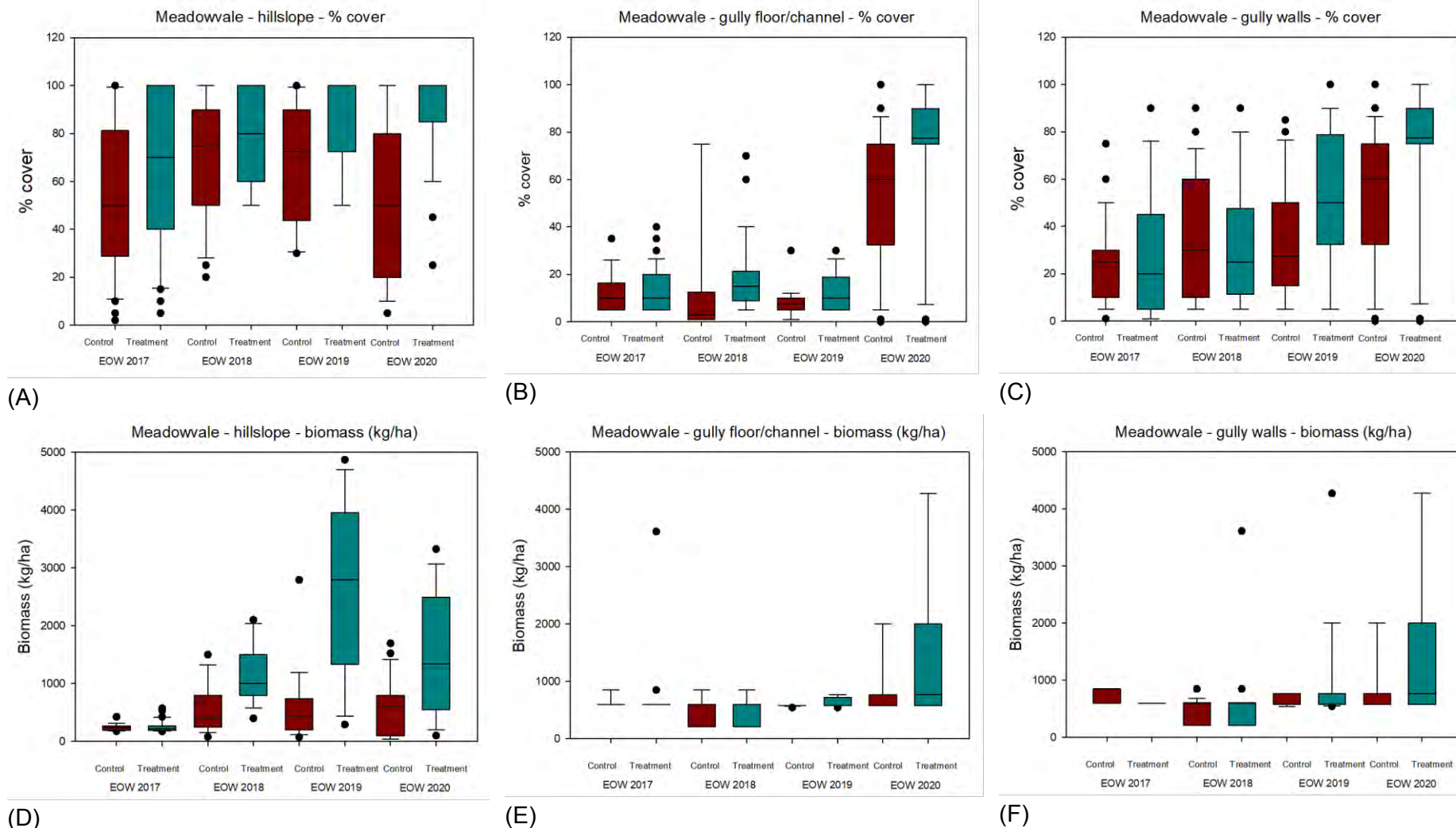


Figure 28: Meadowvale control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the four year NESP study period. EOW = end of wet season. Note extreme outlier data were excluded at some sites for plotting purposes.

5.2.3 Terrain changes

The terrain analysis results obtained using the terrestrial laser scanner (TLS) were presented in Table 10 and Table 11. The volumetric change in sediment erosion and deposition between the treatment and control site is presented in Figure 29. Due to COVID-19, this section presents data only up to 2018/19.

Due to scanning challenges at this site in 2017/18, we have limited change data for the treatment site outside of 2018/19. The results demonstrate that the head-cut retreat rate is similar between the control (0.81 m) and treatment (0.73 m) sites, but the amount of sediment deposited (or trapped) in the gully as a % of erosion varies between 8% for the control gully, and 16% for the treatment site (see Figure 29; Table 10). Figure 30 presents the TLS results including the DEMs of difference which show the dominant locations of the erosion (mainly the head-cuts for the control site) and the deposition areas.

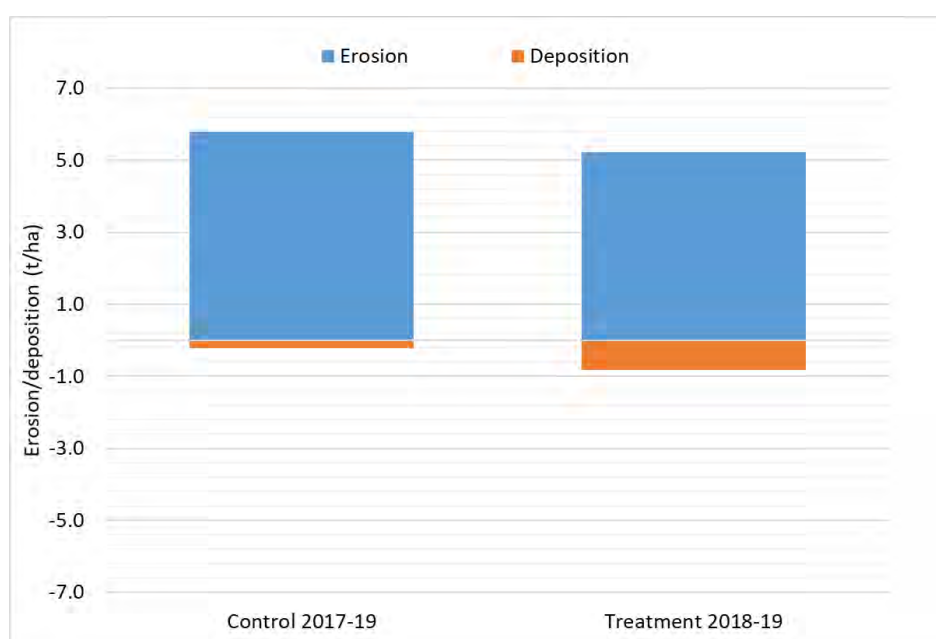


Figure 29: Net total (fine + coarse) sediment movement (t/ha/y) for Meadowvale (using a measured soil bulk density of 1.5 t/m³) for the 2017-19 period for the control and 2018-19 for the treatment. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The area (ha) is based on the upstream catchment area to the end of the TLS scan.

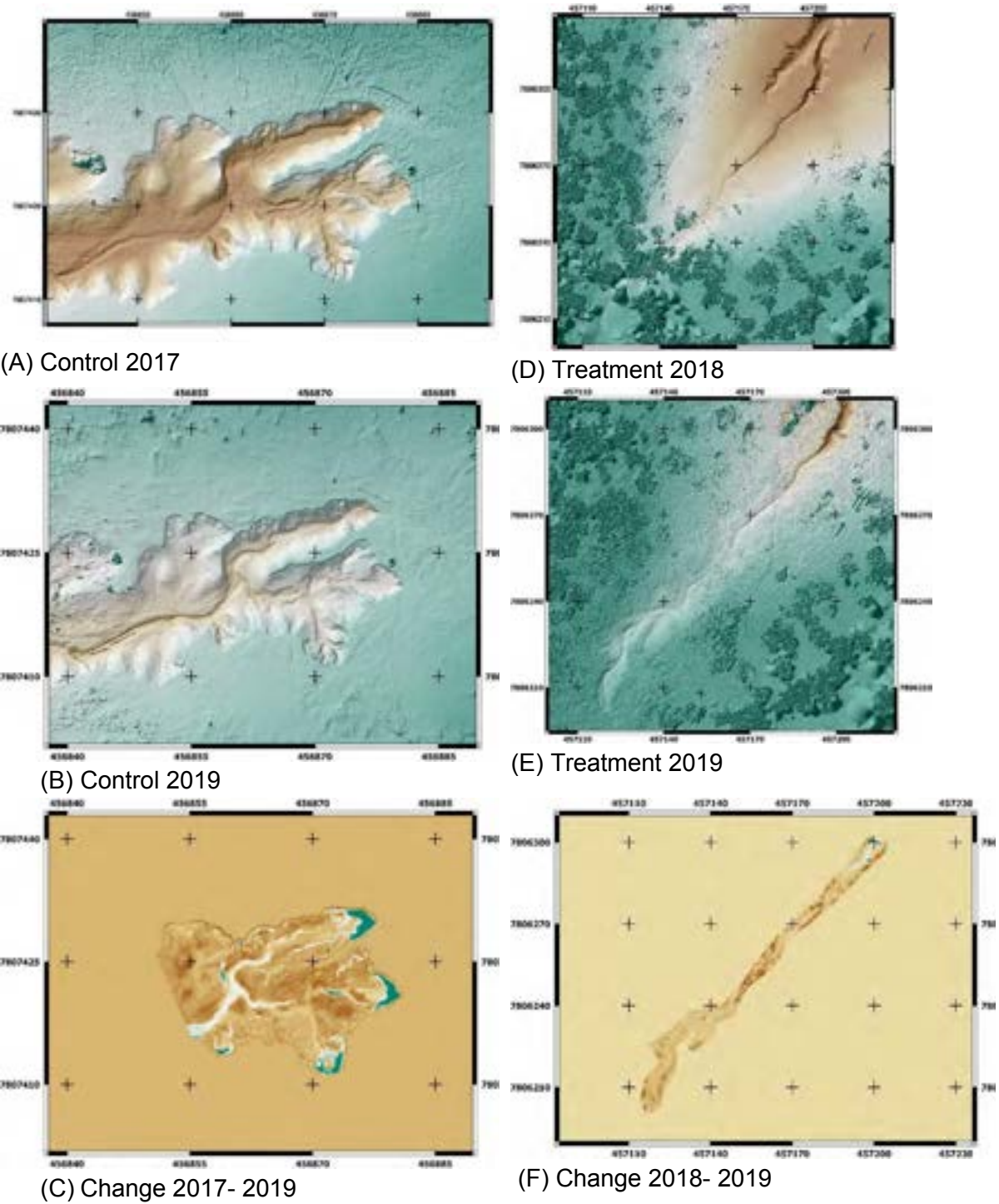


Figure 30: Meadowvale (A) control gully in 2017 (B) control gully in 2019 and (C) DEM of Difference; (D) treatment gully in 2017, (E) treatment gully in 2019 and (C) DEM of Difference as measured by the RIEGL terrestrial laser scanner, where dark green is erosion and brown is deposition.

5.2.4 Water quality, runoff and loads

During the 2019/20 wet season, the Meadowvale treatment site received 350 mm of rain and there was ~340 mm at the control site (Figure 32). This was well below average for this site and the control site did not receive any runoff in 2019/20. There was one small flow event at the treatment site, and only a single water quality sample was collected in 2019/20. The TSS-turbidity relationships developed from previous years were used to derive sediment load data for the treatment site for the 2019/20 wet season. However, the runoff and sediment loads are very low compared to previous years and were too small to display on the axes of the graphs (Figure 32).

The TSS data at the treatment site were statistically lower than at the control sites during 2018/19 wet season ($p < 0.001$) (Figure 31A). Although there were differences in the TN values between treatment and control sites in the first two years of treatment, low sample numbers and problems with green ants nesting in the sensors, make these early data un-reliable. There is no statistical difference in TN concentration values in 2018/19.

The treatment gully has had consistently lower rainfall-runoff ratios (% runoff) than the control site in all years of this study (Figure 32). A large section of the hillslope above the treatment gully includes areas that have been excluded from grazing by cattle and kangaroos since 2002 (17 years) which may partly explain this result. Interestingly, although the rainfall was the highest at the treatment site during the 2018/19 wet season, it had the lowest TSS loads (and TN loads) in the last two wet seasons. This may be due to the treatment effect; however, it may also be because the treatment gully is mature and not as active as the control gully.

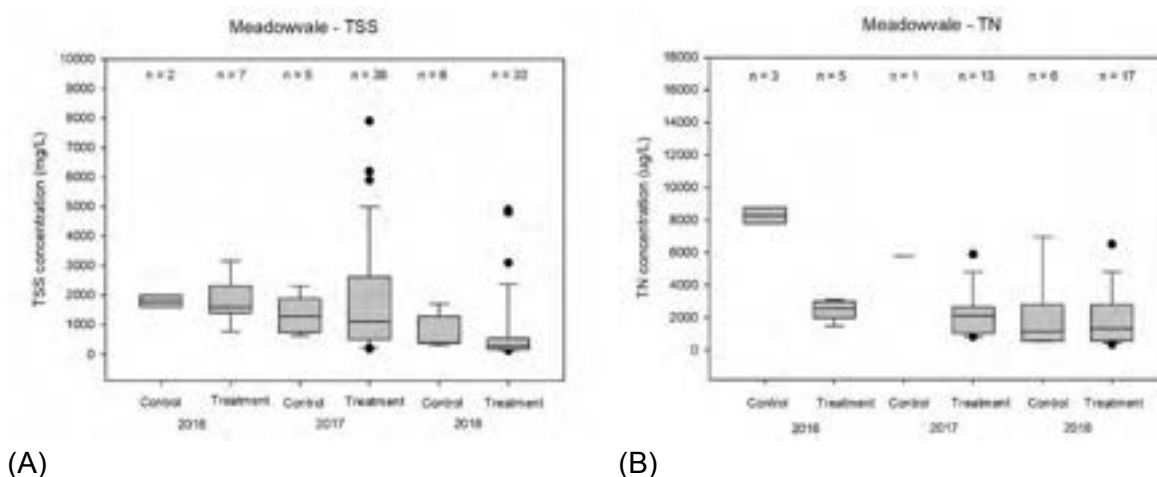


Figure 31: (A) TSS concentration and (B) TN concentrations at Meadowvale

5.2.5 Summary: Meadowvale

After three years of cattle exclusion from this gully using fencing, the cover and biomass metrics for the hillslope, gully channel and gully walls have all statistically improved at the treatment site compared to the control. The treatment site has always had lower % runoff and sediment yield than the control site. This may be because: (i) the treatment gully is actually much older and more mature than the control gully (which can be supported by the fact that the treatment gully has almost reached the ridge top) and therefore it would naturally have

lower erosion rates even in the absence of treatment; or (ii) that the long term grazing exclosure has actually had a positive effect on the hydrology of this hillslope, which is being expressed in the data; or (iii) the vegetation in the gully channel may be starting to trap some of the finer suspended sediment. The annual mean TSS concentration was higher at the treatment site during the first two years of the study, but lower 2018/19. It is likely that the response at this site is due to a combination of these three aforementioned factors.

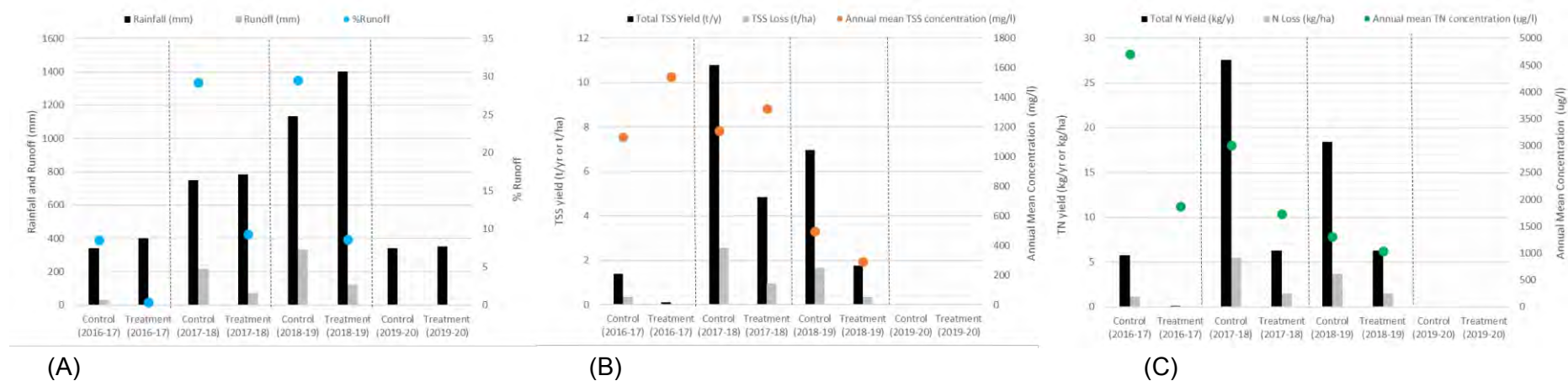


Figure 32: Meadowvale Control and Treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y and t/ha) and annual average TSS concentration (mg/L) and (C) Total Nitrogen (TN) loads (kg/y and kg/ha) and annual average TN concentration (ug/L). Data quality caveats are in Appendix B.

5.3 Strathbogie

5.3.1 Treatment progress

The Strathbogie site was originally a Reef Trust 2 gully rehabilitation site, that is now being managed by NQ Dry Tropics under their Landholders Driving Change (LDC) program. Pre-treatment data was collected at this site on both the control and treatment sites for 3 wet seasons (2016/17, 2017/28, 2018/19), and late in 2019, a series of hillslope interventions were implemented on the Treatment site (Figure 34).

The interventions involved four main activities: (1) hillslope diversion banks, (2) rock revetment on a gully side headcut (3) pasture ripping (using a yeoman's plough) (Figure 33) and (4) permanent 3-barb fencing around the paddock containing both the control and treatment gullies. On the hillslopes above the treatment gully ~5 diversion banks were installed (Figure 34 and Figure 35). Three of the larger diversion banks were above the secondary channel incision (Figure 35A). Two of the smaller diversion banks were directly above the main headcut on the gully (Figure 35B). Two of the diversion banks also had drains located along the diversion bank. In addition to the diversion banks, there were several small rock chutes which were used to treat some of the gully side wall extensions (Figure 35C). The areas above the diversion banks underwent pasture ripping to increase runoff infiltration (Figure 33 and Figure 35D). The entire paddock, containing both the control and treatment gully has also been re-fenced for grazing management, although no specific grazing management strategies had been implemented during the 2019/20 wet season.



Figure 33: Hillslope rehabilitation in progress at Strathbogie Treatment gully hillslope

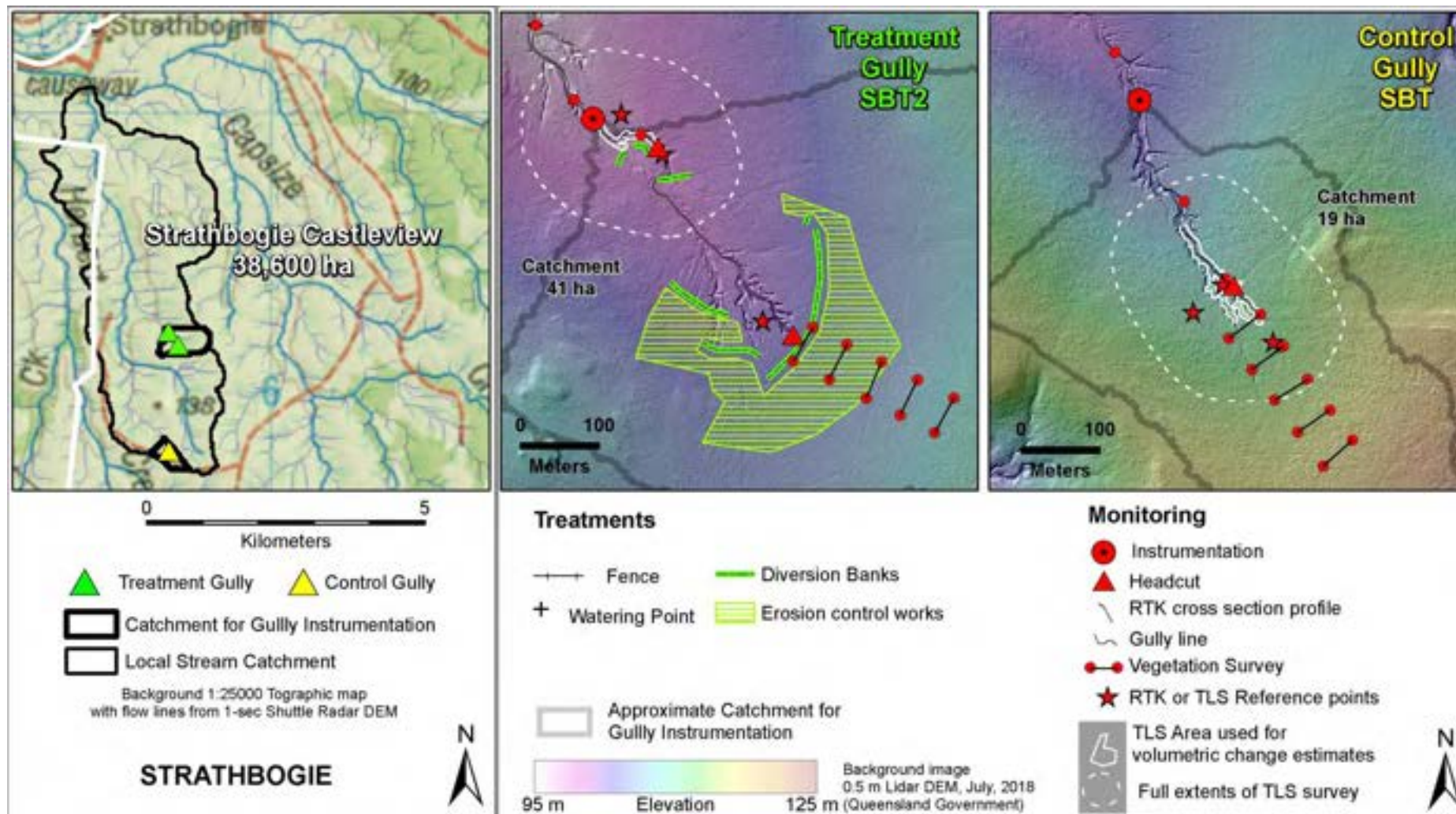


Figure 34: Location of Strathbogie site (left) and the Control and Treatment gullies. The location of the treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)



(D)

Figure 35: Images of the rehabilitation site at the Strathbogie Treatment gully taken during the 2019/20 wet season (Photos: Fruition Environmental)..

5.3.2 Vegetation response

Figure 37 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully at Strathbogie as well as the gully walls and gully floor. There was a significant difference in the hillslope % cover data ($p=0.024$) between the control and treatment sites in 2019/20, with the treatment hillslope having lower % cover than the control hillslope. This is likely due to the impact of the earthworks on the treatment hillslope. Hillslope biomass had not changed significantly between control and treatment sites ($p=0.071$) (Figure 36) which is not a surprising given both sites are located in the same paddock under the same grazing regime. In general, this landscape has quite dramatic shifts in cover and biomass between the dry and wet seasons, as seen by comparing figures Figure 33 and Figure 36. Overall, however, the land condition at this site is poor (D Condition) (Table 9).

The cover or biomass metrics for both the gully channel and the gully walls were not significantly different between treatment and control gullies following the 2019/20 wet season. Indeed, the within gully vegetation metrics were slightly higher at the control site compared to the treatment site. It is possible that in this drier than average year the small amount of runoff that the control gully received provided a beneficial amount of moisture and a seed source. The treatment gully had no direct hillslope runoff into this gully over the 2019/20 wet season due to the treatment works on the hillslope. The channel of the treatment gully has also reached bedrock in the middle and upper reaches which is not an ideal medium for vegetation growth. It will be interesting to see how the vegetation metrics progress over the coming wet seasons.

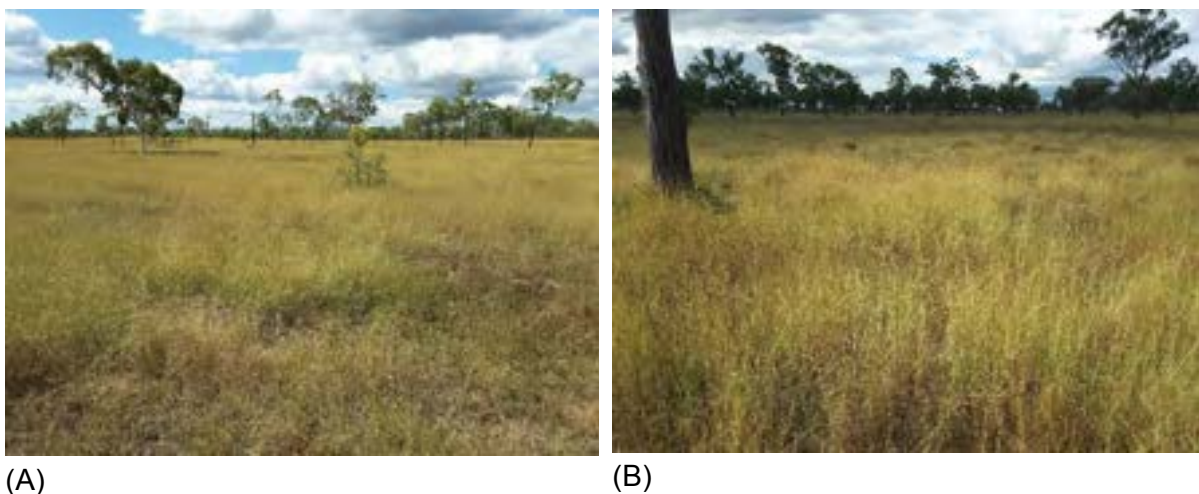


Figure 36: Strathbogie hillslope above (A) control gully (T4) and (B) the treatment gully hillslope (T4) which has a partial cattle exclusion fence.

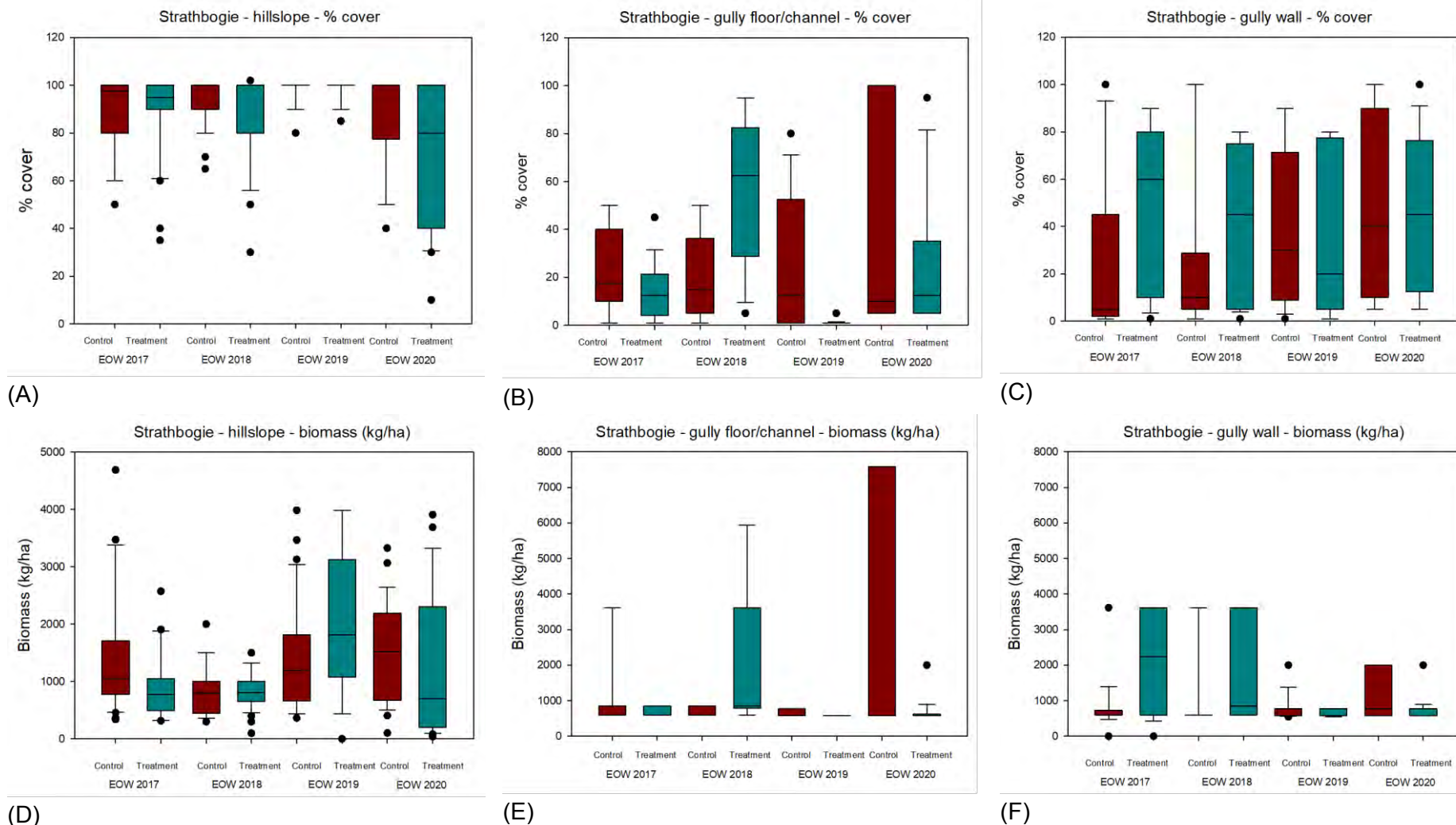


Figure 37: Strathbogie control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the four year NESP study period. EOW = end of wet season. Extreme outlier data were excluded at some sites for plotting purposes.

5.3.3 Terrain changes

The terrain analysis results obtained using the terrestrial laser scanner (TLS) were presented in Table 10 and Table 11. The volumetric change in sediment erosion and deposition between the treatment and control site is presented in Figure 38. Due to COVID-19, this section presents data only up to 2018/19. **The results represent the treatment site BEFORE any treatment was in place.**

The results demonstrate that the amount of sediment lost from the head-cut area is similar for the control and treatment sites when normalised based on the relative catchment area upslope (Figure 38). The treatment gully has a net loss of sediment (erosion minus deposition) of 5.37 t/ha/y compared to 5.98 t/ha/y for the control. Interestingly, the proportion of the eroded sediment being deposited or trapped at this site is very low being ~ 9% at the control site and <1% at the treatment site (before treatment). This suggests that without active treatment, these gullies undergo very little natural trapping or deposition of the relatively fine (<4 μm) sediment.

Figure 39 presents the TLS results including the DEMs of Difference which show the dominant locations of the erosion. Unlike some of the other sites that were dominated by erosion only in the head-cut section, these sites had erosion in the head-cut, but also on the walls of the gully. The linear head-cut growth of the treatment site is on average 18.00 m/y (Table 10) with a massive 28 m of erosion in the 2018/19 wet season alone. Both sites have had their largest head-cut retreat in 2018/19 which coincides with the some of the largest 2-3 day rainfall totals in the region for many decades.

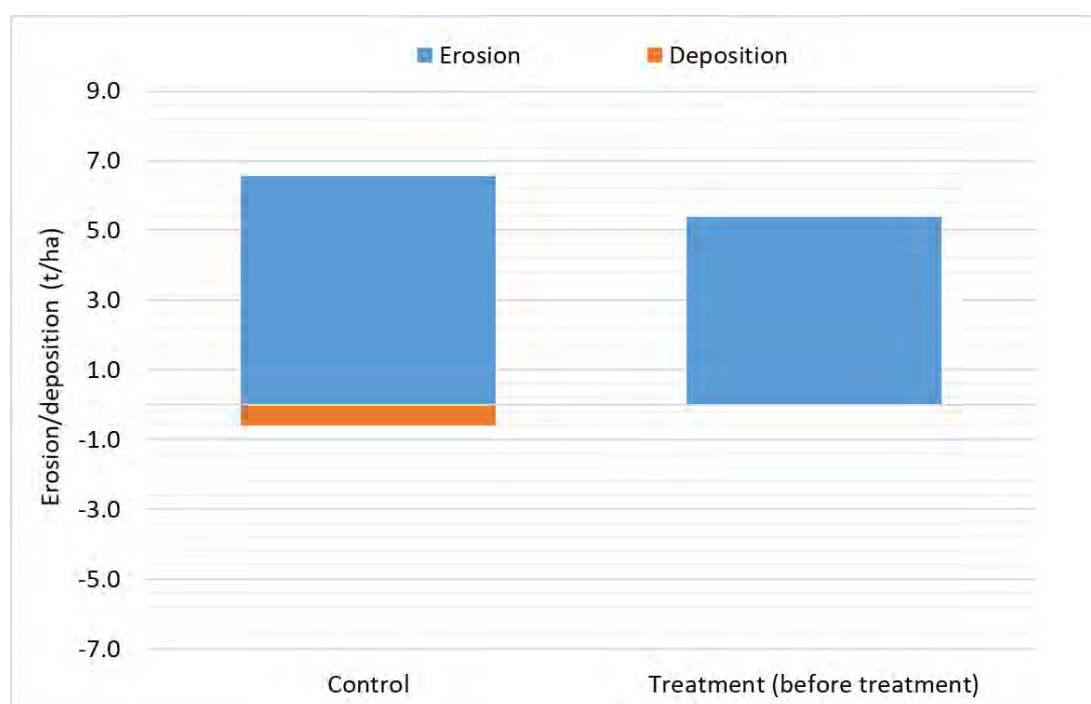


Figure 38: The results represent the treatment site BEFORE any treatment was in place. Net total (fine + coarse) sediment movement (t/ha/y) for Strathbogie (using a measured soil bulk density of 1.27 t/m³) for the 2016-19 period. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The area (ha) is based on the upstream catchment area to the end of the TLS scan.

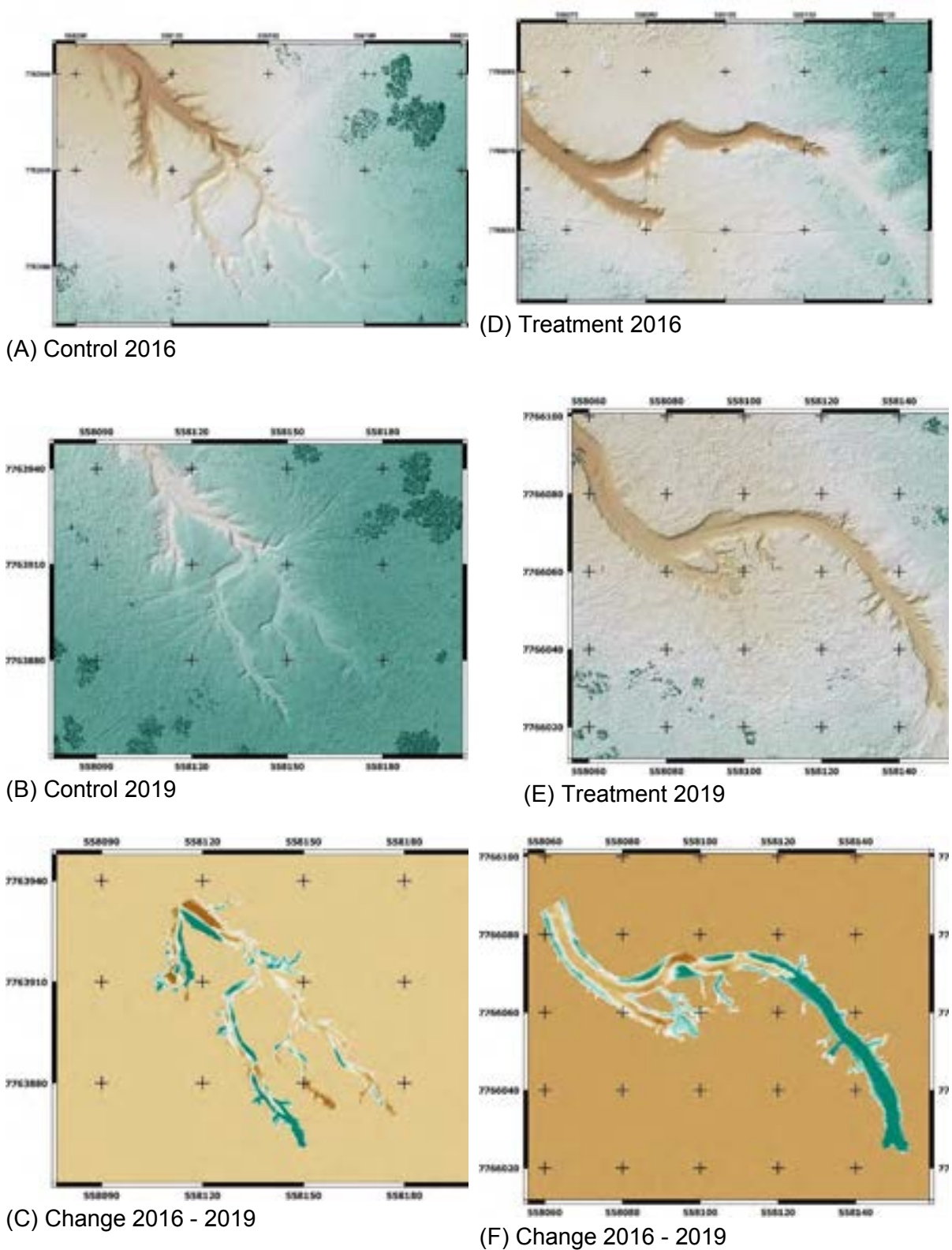


Figure 39: Strathbogie (A) control gully in 2016 (B) control gully in 2019 and (C) DEM of Difference; (D) treatment gully in 2016, (E) treatment gully in 2019 and (C) DEM of Difference as measured by the RIEGL terrestrial laser scanner, where dark green is erosion and brown is deposition.

5.3.4 Water quality, runoff and loads

This site has had quite extreme rainfall patterns, with 2017/18 and 2019/20 having relatively low rainfall totals of <500 mm (Figure 42A), while in 2018/19 the site received ~1400 mm of rain. The extreme rainfall and runoff variability has caused several challenges with instrumentation at this site, particularly in 2017/18 when there was repeated burial (and re-excavation) of the monitoring sensors for parts of the wet season. Resulting, erroneous data has been removed, and no loads data were calculated for 2017/18 at either the control or treatment site. Despite the instrument challenges, the TSS and TN loads generally follow the rainfall trend with an increase in loads in 2018/19 compared to other years. In general, the % runoff, or amount of rainfall that becomes runoff, was higher at the control site than the treatment site, even before treatment was implemented.

In the 2019/20 wet season, following the hillslope rehabilitation, there was no measured runoff or water quality samples recorded at the treatment site.

Figure 43 shows the peak runoff event at the control and treatment sites in 2018/19 wet season, and then the peak events in 2019/20 wet season. Despite the difference in rainfall, the peak event at the control site was similar. However, the treatment site did not flow in 2019/20, and only direct rainfall ponded in the gully. As a result, no samples were collected at the treatment site. Therefore, the sediment yield from this site during 2019/20 wet season was effectively zero.

Figure 40 presents the TSS and TN data collected at the control and treatment sites over the last four years. The initial sampling set-up at this site involved using a rising stage sampler at the treatment (initially control) site. This reduced the number of samples collected at this site. Therefore in 2018, a second ISCO station setup was installed. This increased the number of samples collected at this site.

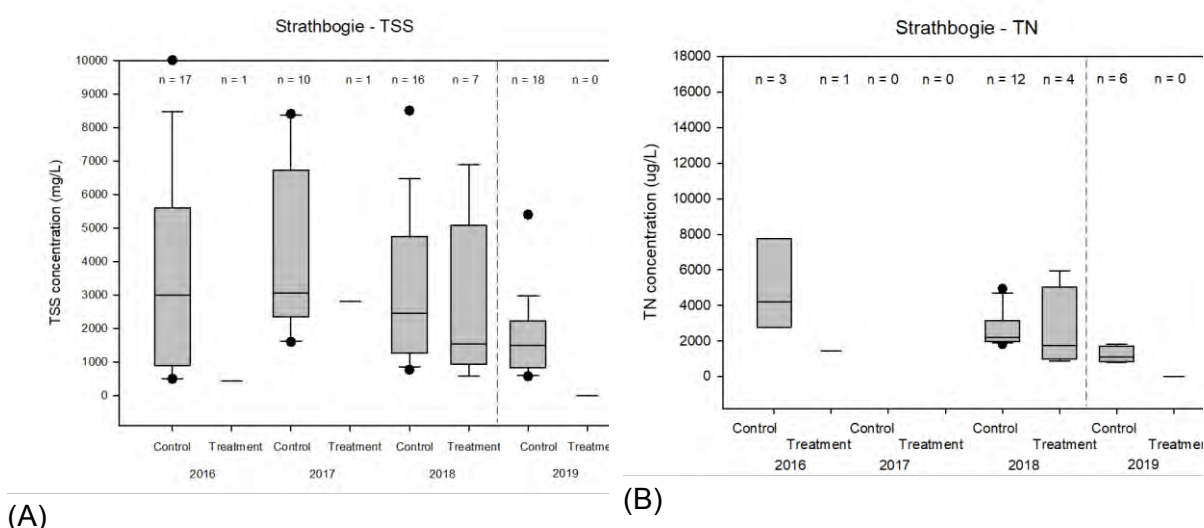


Figure 40: (A) TSS concentration and (B) TN concentrations at Strathbogie for four wet seasons.

As this site had pre-treatment data, we were able to perform several additional statistical analyses to evaluate the effect of the treatment. The TSS data were not normally distributed, so the data were log transformed prior to analysis. The TSS concentrations measured at the

control and treatment site prior to rehabilitation were not statistically different ($p = 0.08$). However, the control site is giving statistically different TSS concentrations in the 'before' and 'after' period, even without intervention ($p = 0.002$). This is likely due to the variable rainfall during the measurement periods with the annual average rainfall for the before period being 801 mm (range between 474-1352 mm) and the after period being 492 mm (between July 2019 and April 2020). This highlights that it is important to have before and after treatment data for both control and treatment sites to adequately assess the treatment effects against the natural variability due to climate.

To test if there was a significant difference in both treatment and time, a two-way analysis of variance was conducted on the TSS data. The treatment site was given a value of 0 for the samples in the period after the treatment period. This resulted in an overall statistically significant result following the treatment period ($p < 0.001$). This suggests that the treatment has had a significant effect on the TSS concentration of samples between these two gullies.

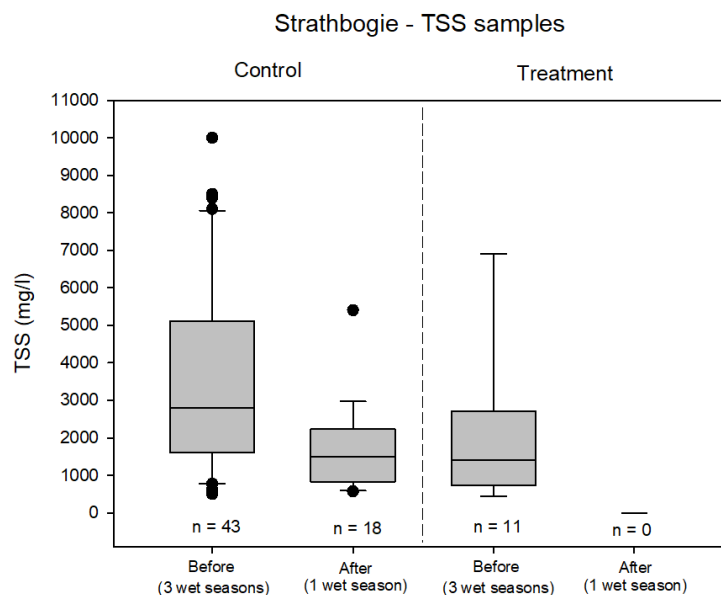


Figure 41: A comparison of the TSS concentrations measured at the Strathbogie control and treatment site before and after the rehabilitation.

5.3.5 Summary: Strathbogie

The results from 2019/20 have shown that there has been a statistically significant improvement in the concentration of sediment (TSS) and nitrogen (TN) at this site following the implementation of the hillslope treatments. This has also been associated with a large reduction in runoff as well as sediment and total nitrogen loads at the treatment site. These improvements have come via mechanical intervention on the hillslope which has starved the active gully of runoff (albeit in a below average rainfall year). It will be interesting to track the integrity of the interventions and how they perform over a longer period of time, including through average to above average rainfall seasons. Other sites with this type of treatment intervention have required on-going maintenance.

The condition of the landscape in terms of cover and biomass has not changed and has remained in C and D condition. Although both sites underwent the same grazing regime, the

treatment hillslope and gully had less cover and biomass than the control gully at the end of the 2019/20 wet season. Future improvements in land condition are likely to help support the improved changes in water quality that have been achieved using the hillslope diversion banks at the Strathbogie site. Future years of higher rainfall will help to assess the relative magnitude of reductions which have been achieved in runoff and loads.

Using the data presented in Figure 41 and Figure 42 and the sediment load reductions from before and after treatment, the relative effectiveness of the Strathbogie rehabilitation works is ~1.0. Given it was a very dry year, and the vegetation and land condition are fragile, a conservative estimate of the effectiveness of this treatment is set at ~0.95.

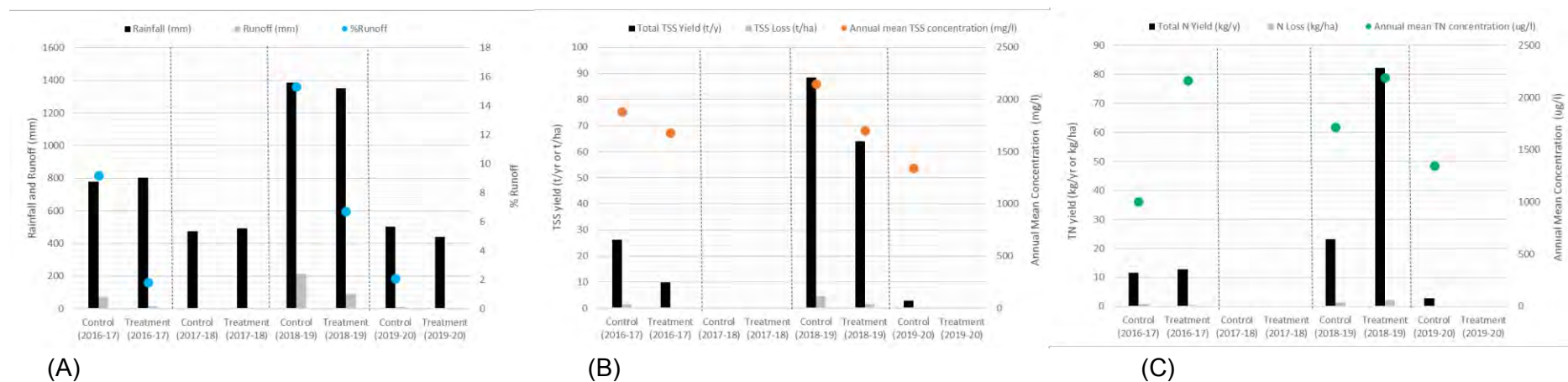


Figure 42: Strathbogie Control and Treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y and t/ha) and annual average TSS concentration (mg/L) and (C) Total Nitrogen (TN) loads (kg/y and kg/ha) and annual average TN concentration (ug/L). No loads data is presented in 2017/18 due to instrument issues. See data quality caveats in Appendix B).



(A) Control site peak event in 2018/19



(B) Treatment site peak event in 2018/19



(C) Control site peak event in 2019/20



(D) Treatment site peak event in 2019/20

Figure 43: The site web cam captured peak flow events at both the control and treatment sites during the 2018/19 wet season prior to the rehabilitation, and during the peak event in the 2019/20 wet season, which is the first year after rehabilitation.

5.4 Minnievale

5.4.1 Treatment progress

The Minnievale site is a Reef Trust 2 gully rehabilitation site that was managed by Greening Australia. The main treatment gully has been fenced off (~4 km of fencing). A total of 135 within gully structures were installed in 2016. There were two types of structures (coir logs and stick traps or PCDs). They were installed in the main gully and the side arms of the main gully (Figure 44). Many of the coir logs failed during the 2016/17 wet season (95% failure rate), and subsequently they were replaced with ~147 stick trap dams in 2017 (Figure 44 and Figure 45).

Ripping and seeding on portions of the catchment directly upslope of the treatment gully was undertaken using exotic pasture species in 2016/17. A pasture restoration site was also implemented in association with the Don River Trust and Department of Agriculture and Fisheries (DAF), however, this is just outside of the drainage boundary of the treatment gully. The landholder has also undertaken a Grazing Management Plan (GMP) and adapts his grazing numbers and rotations in the treatment paddock.



Figure 44: (A) Example of the stick traps installed at Minnievale station and (B) measurements of the vegetation cover and biomass behind the stick traps at this site in April 2019.

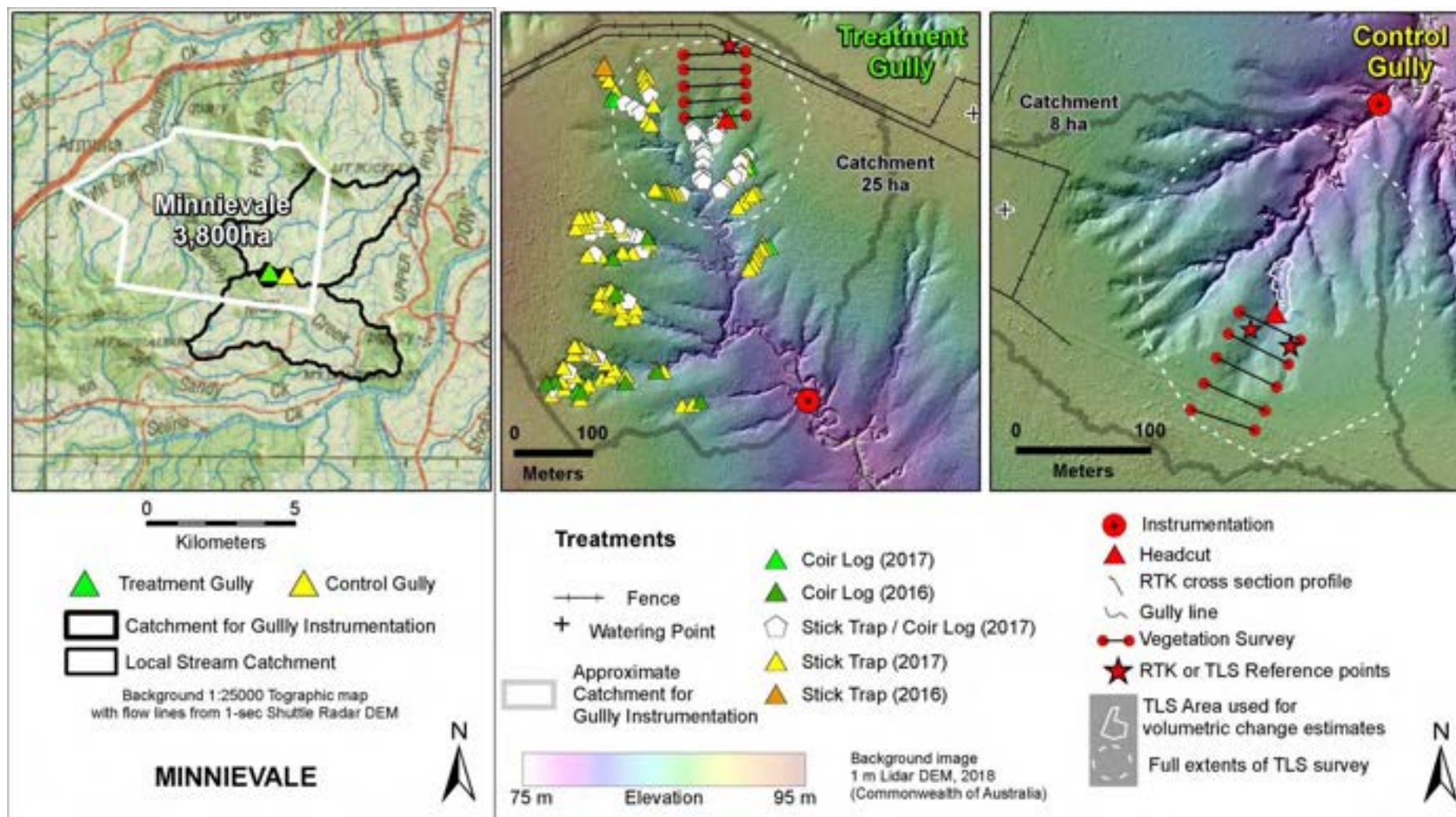


Figure 45: Location of Minnievale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)



(D)



(E)



(F)

Figure 46: Treatment gully at MinnieVale in (A) 2016 (B) during an event in 2017 (C) in April 2017 and (D) at the end of reporting period in April 2018 (E) during an event in Dec 2018 and (F) after the event in 2019.

5.4.2 Vegetation response

Figure 48 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully at Minnievale, as well as for the gully walls and gully floor. The results following the 2019/20 wet season show that there is higher cover on the treatment hillslope, compared with the control gully hillslope; however, the difference is not significant ($p=0.121$). There was significantly greater biomass on the treatment hillslope compared to the control at the end of the wet season ($p<0.001$) (Figure 47).

In the gullies, there was no difference in % cover on the gully floor between control and treatment ($p=0.136$), but biomass had increased in the treatment gully ($p=0.004$). Both the % cover and biomass had increased on the treatment gully walls compared to the control gully following the 2019/20 wet season ($p<0.001$) (Figure 48).

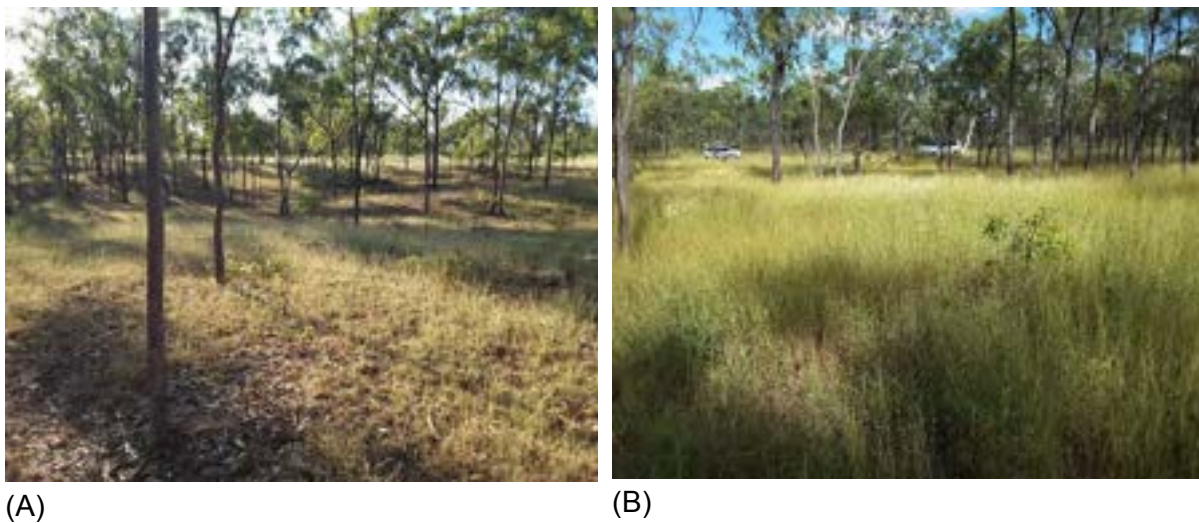


Figure 47: Minnievale hillslope above (A) control gully and (B) the treatment gully hillslope which has followed a grazing management plan.

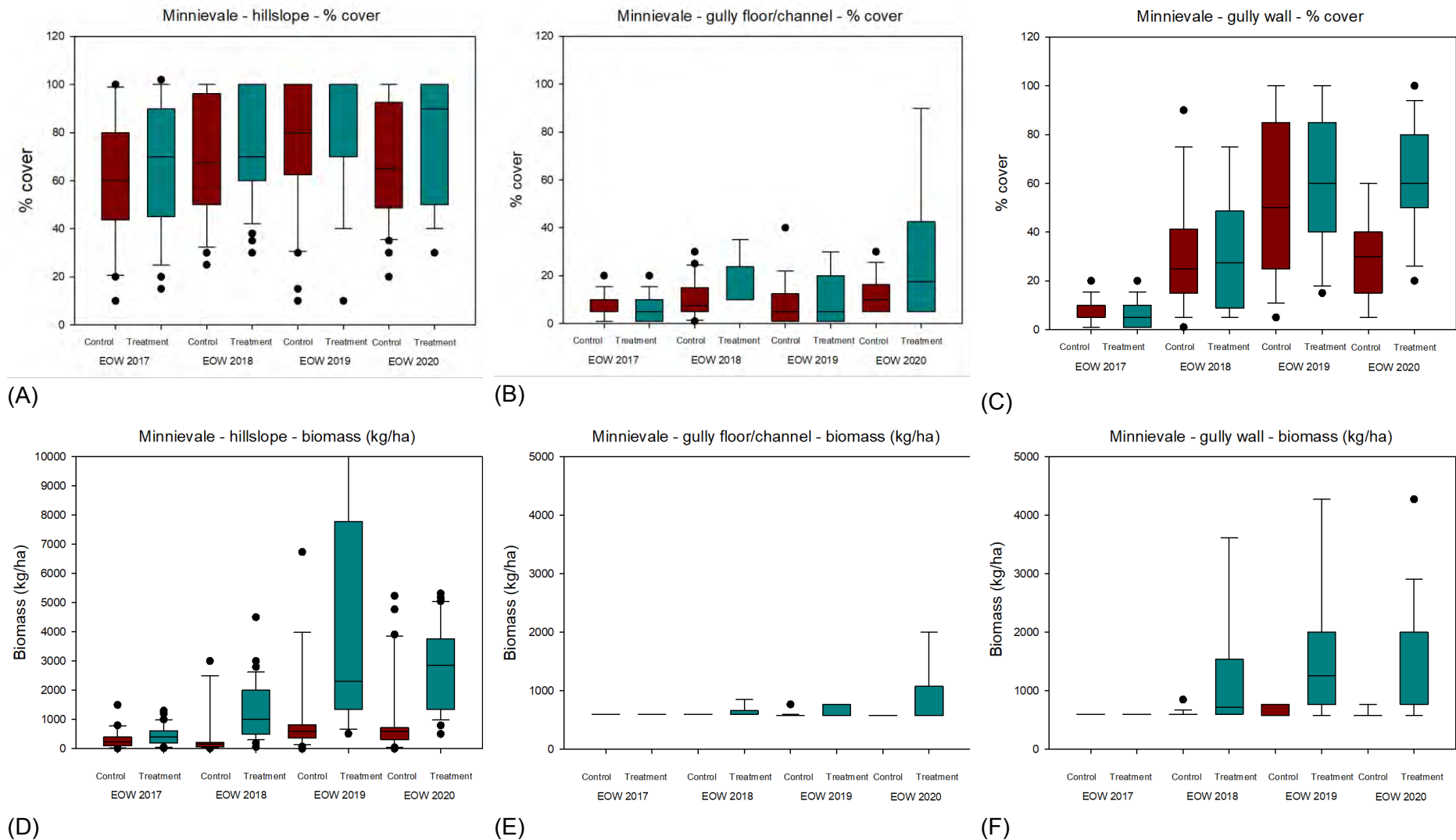


Figure 48: Minnievale control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the four year NESP study period. EOW = end of wet season. Note extreme outlier data were excluded at some sites for plotting purposes.

5.4.3 Terrain changes

The terrain analysis results obtained using the terrestrial laser scanner (TLS) were presented in Table 10 and Table 11. The volumetric change in sediment erosion and deposition between the treatment and control site is presented in Figure 49. Due to COVID-19, this section presents data only up to 2018/19.

The results demonstrate that the amount of sediment lost from the head-cut area of the treated gully (1.48 t/ha/y) is less than half that of the control gully (5.23 t/ha/y). At the control site, ~35% of the sediment is being trapped or stored in the gully. Interestingly, in the treatment gully more than 100% of that sediment is being trapped by the check dam structures. The fact that more sediment is being trapped than was eroded from the gully, suggests these structures are also trapping sediment that has come into the gully off the hillslope.

Figure 50 presents the TLS results including the DEMs of difference which show the dominant locations of the erosion (mainly the head-cuts) and the deposition areas. The 3-year linear head-cut growth of the treatment site is on average 0.24 m/y (Table 10) which is ~25% of the control site rate of 0.83 m/y. The treatment site has consistently had lower head-cut retreat rates over the study period, but in 2018/19 the retreat rate of the treatment gully (0.11 m/y) was ~10% of the control site (1.16 m/yr) (Table 10). The large amount of deposition behind the check dams can be observed in the left arm of the treatment site (Figure 50F).

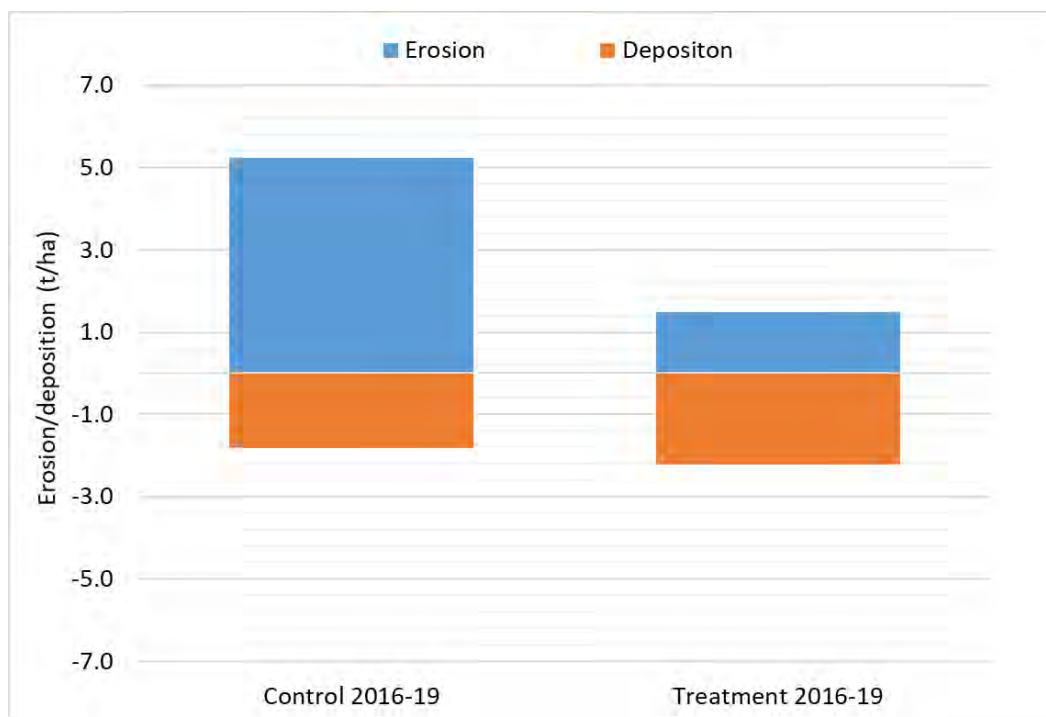
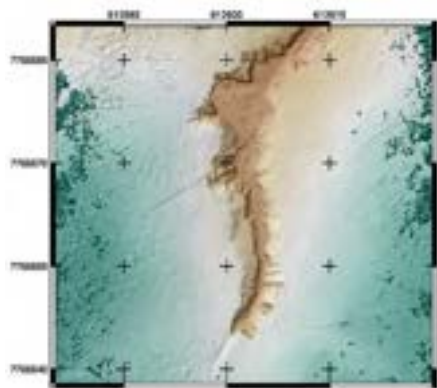
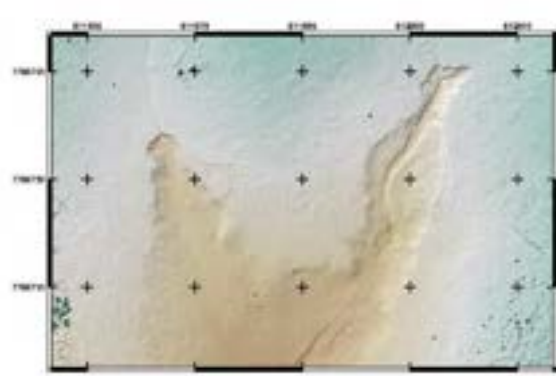


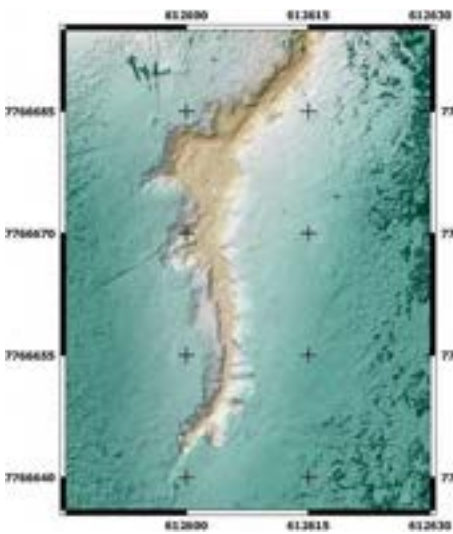
Figure 49: Net total (fine + coarse) sediment movement (t/ha/y) for Minnievale (using a measured soil bulk density of 1.5 t/m³) for the 2016-19 period. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The area (ha) is based on the upstream catchment area to the end of the TLS scan.



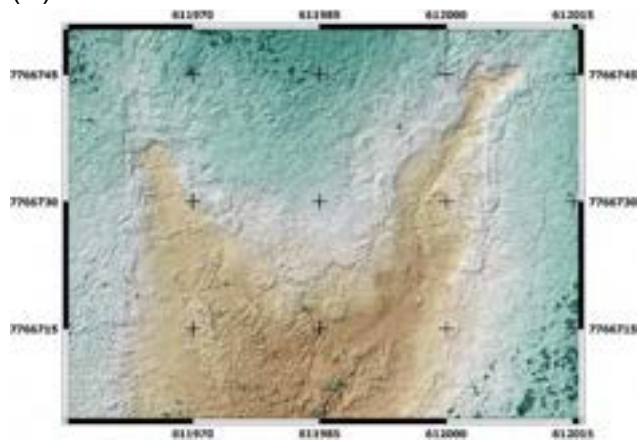
(A) Control 2016



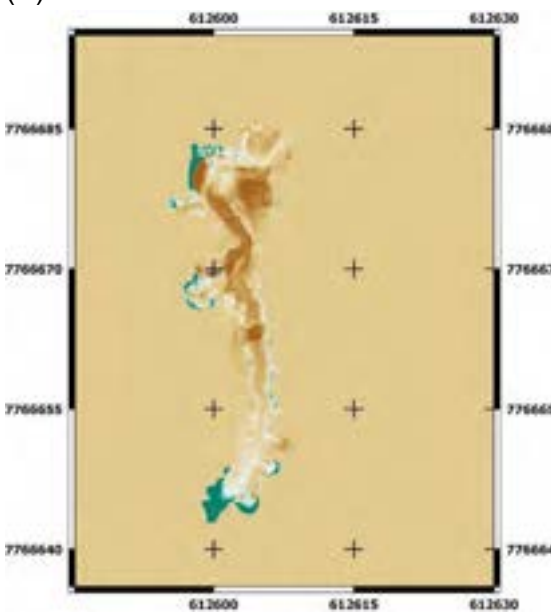
(D) Treatment 2016



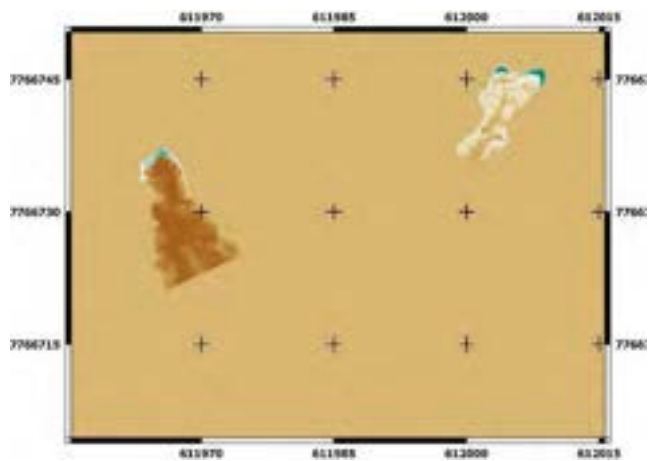
(B) Control 2019



(E) Treatment 2019



(C) Change 2016 - 2019



(F) Change 2016 - 2019

Figure 50: Minnievale (A) control gully in 2016 (B) control gully in 2019 and (C) DEM of Difference; (D) treatment gully in 2016, (E) treatment gully in 2019 and (C) DEM of Difference as measured by the RIEGL terrestrial laser scanner, where dark green is erosion and brown is deposition.

5.4.4 Water quality, runoff and loads

During the 2019/20 wet season, the control site received ~522 mm of rain and the treatment site ~506 mm. This was the lowest rainfall in the four years of monitoring (Figure 52A). The runoff was also low in 2019/20. The control site has one of the cheaper rising stage sampling (RSS) systems and no samples were collected at the control site this wet season due to debris blocking the RSS intake. However, we were able to derive a sediment and nutrient load for the control site using the depth-discharge relationships, and the Turbidity-TSS and TN curves generated in previous years.

The TSS and TN concentrations for the four wet seasons are shown in Figure 51. The TSS and TN concentrations were statistically lower at the Minnievale treatment site in 2016/17 and 2017/18 wet seasons. The treatment site continued to have lower (although not significant) concentrations in 2018/19. The TSS concentrations at the treatment site in 2019/20 are similar to 2018/19, but the TN concentrations are considerably lower.

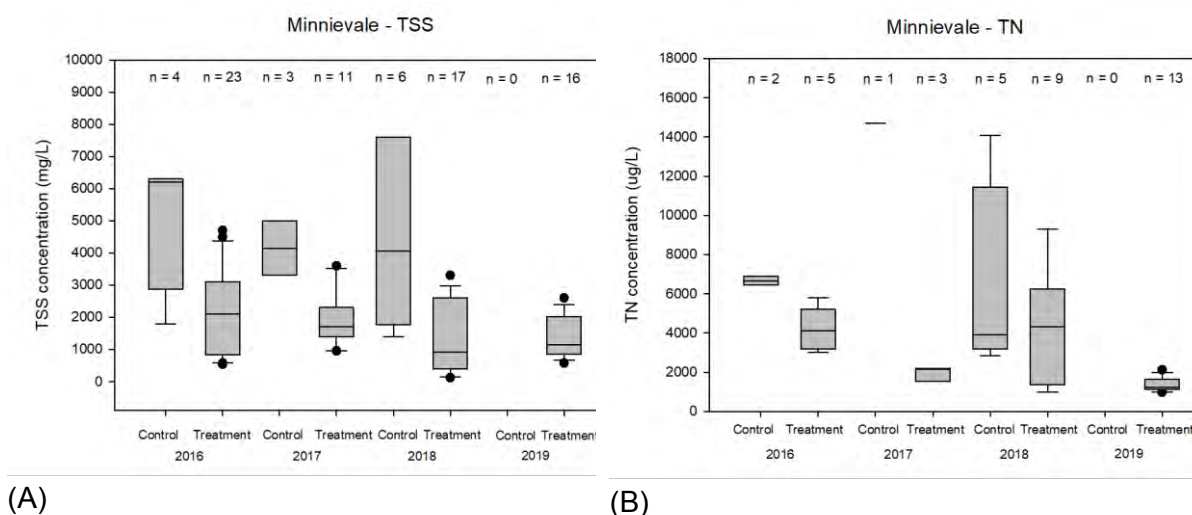


Figure 51: (A) TSS concentration and (B) TN concentrations at Minnievale for three wet seasons

5.4.5 Summary: Minnievale

Overall, despite not having pre-treatment data at the Minnievale site, most of the indicators suggest that the rehabilitation is having a positive effect on the treatment gully. The % of ground cover has improved at both the control and treatment sites over the study period, and the increase in biomass (on the hillslope and within the gully channel and walls) at the treatment site is significantly greater than the control. The amount of head-cut erosion has declined at the treatment gully over time, whereas the control site had its highest retreat rate in 2018/19. The proportion of sediment being trapped or stored in the treatment gully was >95% in 2018/19 compared to ~35% at the control site. The increase in biomass, in conjunction with the stick trap structures, has significantly improved the TSS and TN concentrations at the treatment site compared to the control.

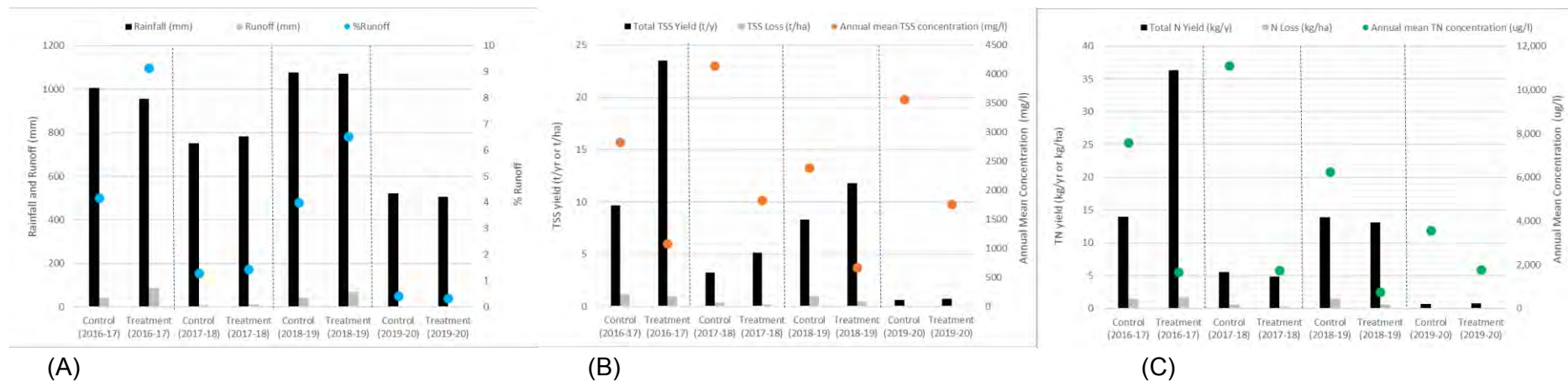


Figure 52: Minnievale Control and Treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y and t/ha) and annual average TSS concentration (mg/L) and (C) Total Nitrogen (TN) loads (kg/y and kg/ha) and annual average TN concentration (ug/L). Data quality caveats are in Appendix B.

5.5 Mt Wickham

5.5.1 Treatment progress

Mt Wickham was added to the study site in 2018. This site is a combination of linear and alluvial gully formations on highly sodic soils that drain into Sandalwood Creek and then into the Bowen River (Figure 53).

The water quality monitoring equipment was installed on 21st February 2018, and the pre-treatment pasture and biomass surveys were initiated in August 2018. The rehabilitation of the treatment site commenced on the 22nd of October 2018 following the site plan completed by Verterra and Alluvium consulting services (Figure 54). The rehabilitation plan involved a combination of grade control rock chutes, re-contouring of the extensively eroded gully surface (Figure 53B; Figure 56), soil amelioration using a range of chemical treatments and revegetation using a range of pasture and legume species (see Appendix C). Phase II of the on-ground works were undertaken at the beginning of the dry season in 2019, but they are not part of this evaluation. Images of the control and treatment water quality monitoring equipment before, during and after events in the 2019/20 wet season are shown in Figure 58.



(A)



(B)

Figure 53: (A) Single channel gully at the Mt Wickham site and (B) highly sodic soil resulting in Badlands or alluvial gully formation on the upper surfaces of the Mt Wickham site.

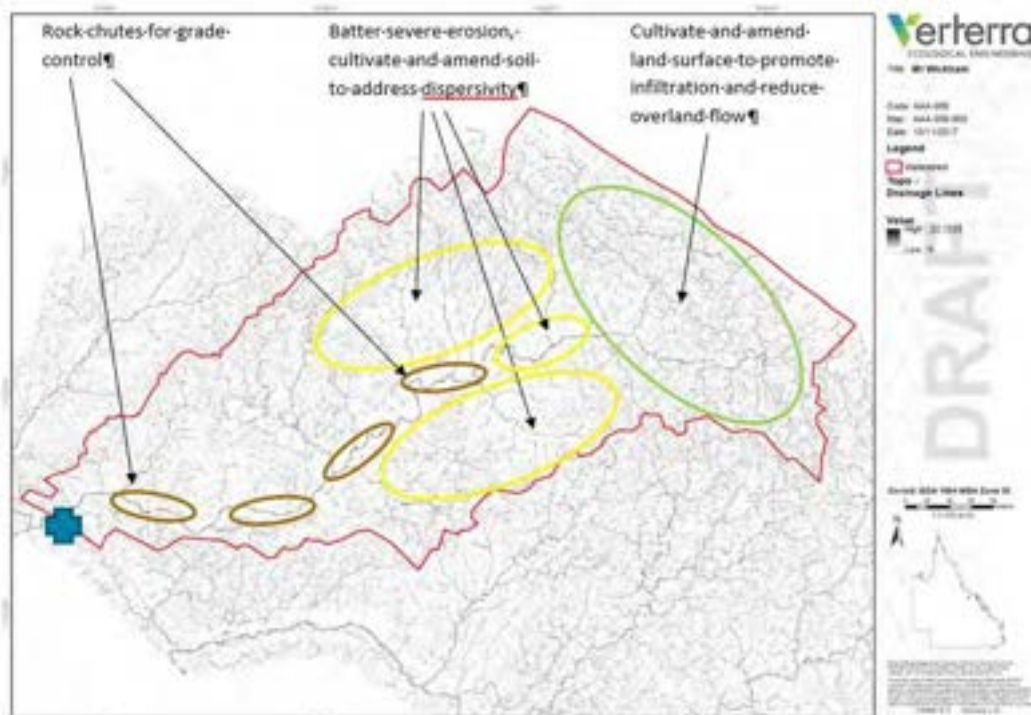


Figure 54: Mt Wickham planned erosion control activity (Source: Verterra, 2018)



Figure 55: Image taken during sample collection for the January/February rainfall event (Photo credit: Damon Telfer). Note the area under the gully 1A text with little vegetation as a result of works to repair holes and tunnel erosion following the heavy rainfall in July (Source: NQ Dry Tropics)



(A)



(B)



(C)

Figure 56: (A) Gully 1A during excavation, looking across the gully towards Blue Valley Road (B) Rock chute 5 looking upstream in the main gully; (C) Gully 1A being ripped with harrows. Looking towards the outlet (Source: NQ Dry Tropics).

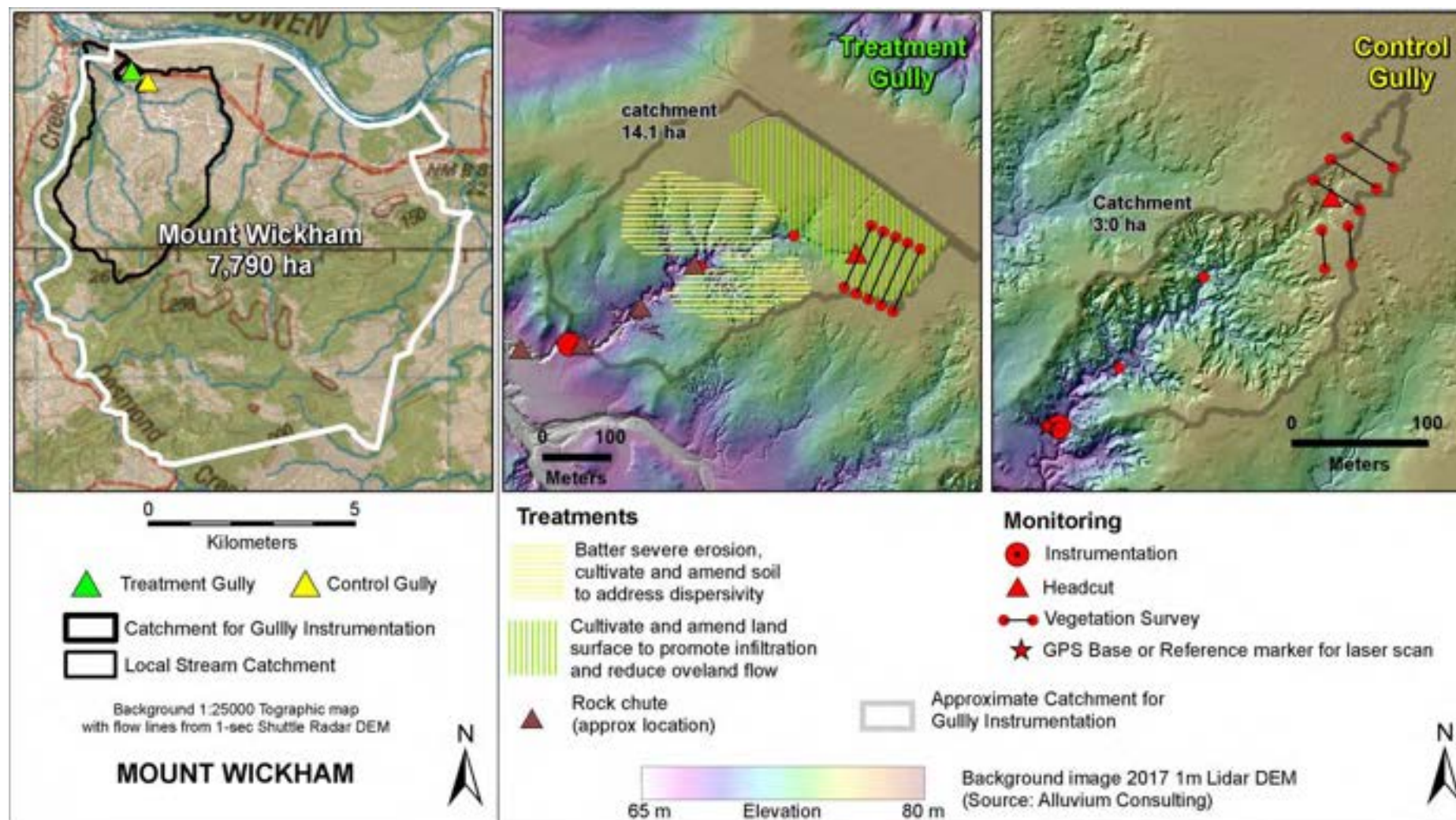


Figure 57: Location of Mt Wickham (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)



(D)



(E)



(F)

Figure 58: Mt Wickham Control gully (A) before (B) during an event in Jan 2020 and (C) April 2020. Mt Wickham Treatment gully (A) before (B) during and event in Jan 2020 and (C) April 2020.

5.5.2 Vegetation response

The change in vegetation on the hillslope or greater gully surface at Wickham treatment site has been quite dramatic over the last two wet seasons (Figure 59). Figure 60 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully at Mt Wickham as well as the gully floor/channel and gully walls.

Statistical t-tests showed that following the 2019/20 wet season, there was a statistically significant improvement in all vegetation attributes (cover and biomass) for the hillslopes, gully channel and gully walls at the Mt Wickham treatment site, compared with the control ($p < 0.001$).

A Two-way ANOVA was performed on the cover and biomass data to compare the treatments across the years. These data were not normally distributed, and transformation did not normalise the data; this slightly reduces the accuracy of the ANOVA. However, the results show that hillslope % cover and biomass was much improved after the first wet season and persisted after the second wet season ($p < 0.001$). There was also a significant improvement in gully wall cover ($p = 0.006$) and biomass ($p = 0.028$) that accounted for differences in both time and treatment. There were not yet statistical differences in gully channel cover or biomass over the three year time period as the control site had comparable cover and biomass in the gully channel at the beginning of the study (2018), that was not significantly different to the treatment site in 2020.

Despite the significant improvements in vegetation at the treatment site relative to the control, the low rainfall in 2019/20 meant that much of the vegetation (at both treatment and control sites) was drought affected by April 2020. Much of the Rhodes grass had disappeared, and there was an increase in legumes (*Desmanthus*) which had grown and started shading out other grasses. Although the vegetation recovery has been significant at Mt Wickham, it is still a fragile response that is vulnerable to low rainfall conditions and grazing.

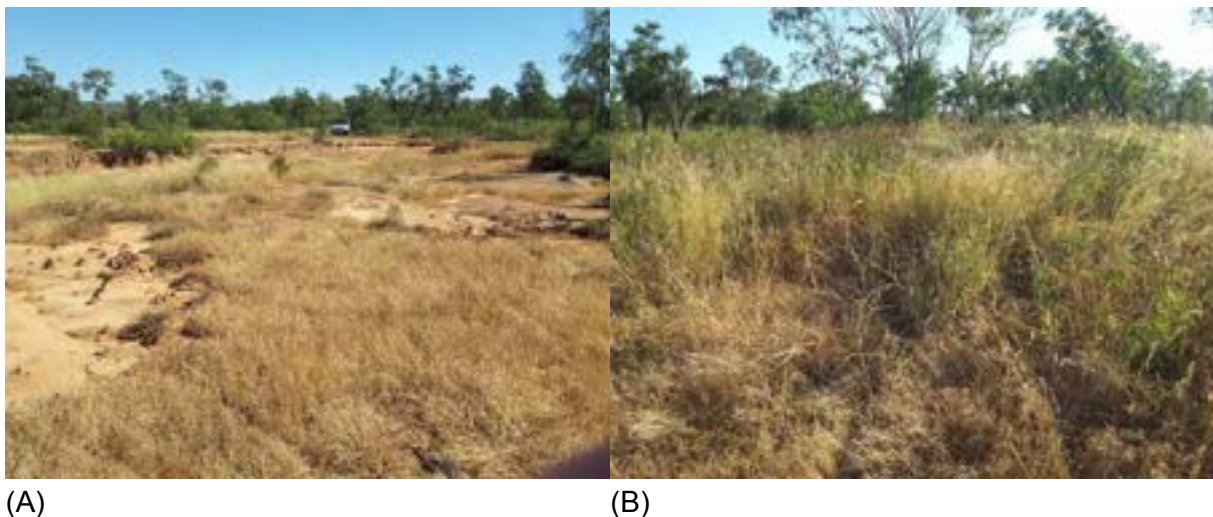


Figure 59: Mt Wickham hillslope above (A) control gully and (B) the treatment gully.

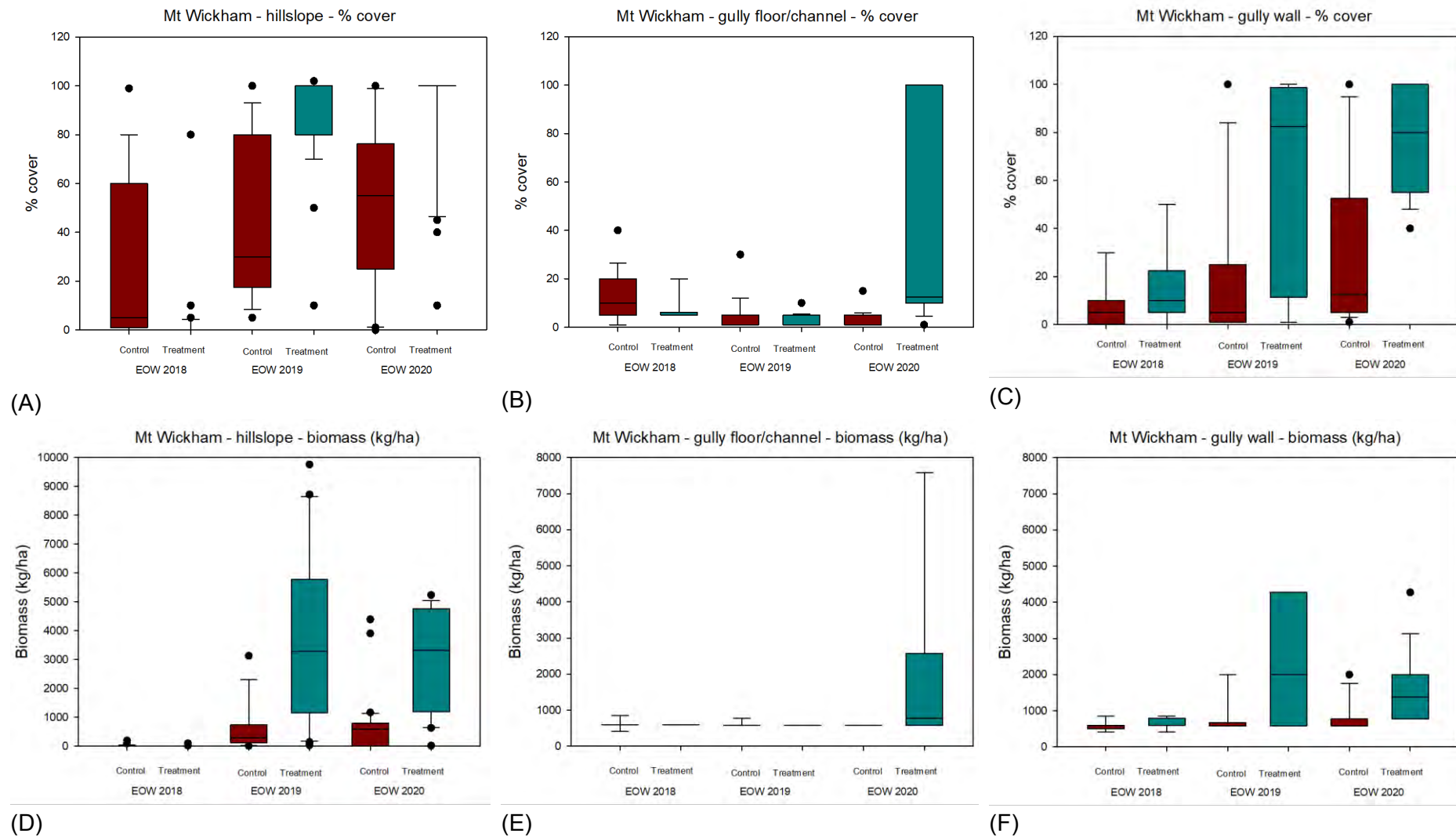


Figure 60: Mt Wickham control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the three year NESP study period. EOW = end of wet season. Note extreme outlier data were excluded at some sites for plotting purposes.

5.5.3 Terrain changes

CSIRO and the NESP project have not been responsible for the terrain analysis comparisons at this site, so there are no terrain data to report for the Mt Wickham site. It is understood that repeat lidar imagery may be collected in the future which could be used to assess the changes in erosion, deposition and net sediment loss from this site.

5.5.4 Water quality, runoff and loads

Over the 2019/20 wet season, ~370 mm of rain fell on the treatment site and ~390 mm on the control site at Mt Wickham. This is considerably less rainfall than the ~1100 mm that fell during the 2018/19 wet season. As a result of the low rainfall over the 2019/20 wet season, there were only a few small events at both the control and treatment sites, and runoff was generally very low (Figure 63).

Figure 61 shows the range of TSS and TN samples measured at Mt Wickham over the last 3 wet seasons, and Figure 62 separates the samples into the periods before and after rehabilitation treatment. There was at least one event at both the treatment and control site prior to rehabilitation works on the 22nd of October 2018. In the single pre-treatment event, there were 4 water quality samples collected at the control site and 16 samples at the treatment site (Figure 62A). These pre-treatment samples allowed for a BACI two-way ANOVA to be conducted on the data. The results show that for the first wet season after the treatment, there was not a significant difference between the control and treatment TSS concentrations ($p=0.09$). This is because there had also been a reduction in TSS concentration at the control site between 2017/18 and 2019/20 which did not undergo rehabilitation treatment.

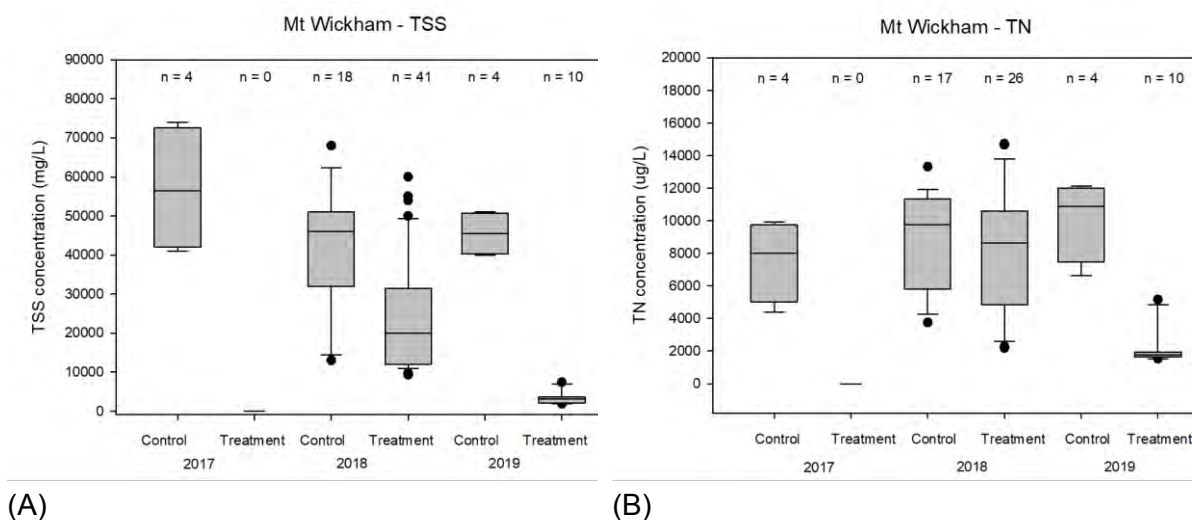


Figure 61: (A) TSS concentration and (B) TN concentrations at Mt Wickham for two wet seasons (noting 2017/18 was for single late wet season event). No samples were collected in 2016/17 or at the treatment site in 2017/18.

The data from 2019/20, two years after treatment, does show a statistically significant reduction on both the TSS concentrations and the event-based flow weighted TSS concentrations (mg/L) ($p<0.001$) (Figure 62B). Using flow weighted event mean concentration (EMC) data for each event is the more robust method for comparing between treatments as it balances out differences in rainfall and runoff between the sites.

The sediment and nutrient loads measured in the 2019/20 wet season were very low at just 0.56 t/ha for the control site and 0.09 t/ha for the treatment site. This is considerably lower than the unit area sediment yields measured for the control (~53 t/ha/y) and treatment (~12 t/ha/y) site during the 2018/19 wet season. The TN loads also demonstrated a similar pattern to the TSS loads in 2019/20 (Figure 63C).

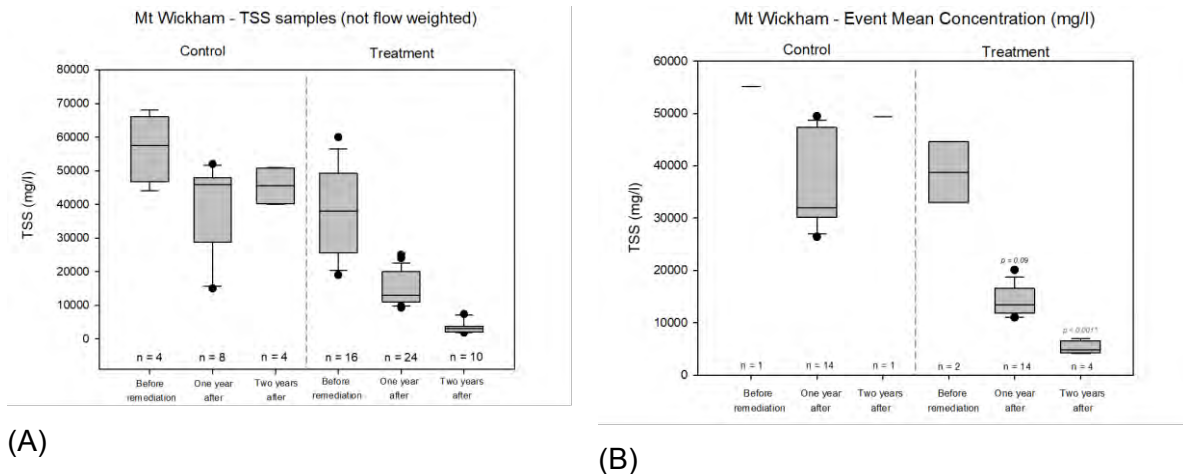


Figure 62: Mt Wickham TSS data from the 2019/20 wet season before and after rehabilitation works (treatment). Graph (A) is the TSS concentration lab data for all events before and after treatment was implemented on the 22nd of October 2018, and Graph (B) is the flow weighted Event Mean Concentration (EMC) for the events before and after treatment.

5.5.5 Summary: Mt Wickham

Two years after the treatment works were undertaken at Mt Wickham, there are several statistically significant outcomes that demonstrate that the treatment has had an effect that is independent of any natural climate variability at the site. The amount of cover and biomass on the hillslope and gully walls has significantly improved using the most robust statistical indicators. The water quality data, particularly TSS concentrations, have also shown statistical improvement, including for the flow weighted event mean concentrations (EMCs). Using the data presented in Figure 62 and Figure 63, and the load reductions from before and after treatment, the relative effectiveness of the Mt Wickham rehabilitation works is calculated as 0.85.

The main watch point for Mt Wickham is that despite significant improvements in cover and biomass, the land condition remains fragile. It will take several more years for additional perennial native plant species to take hold at this site. Until then, grazing should be carefully managed.

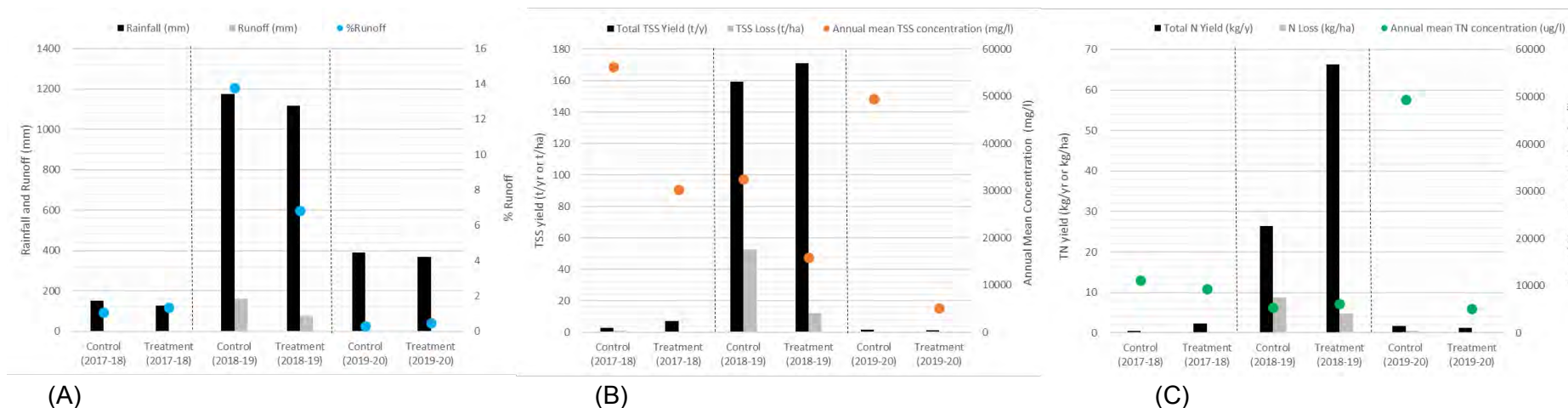


Figure 63: Mt Wickham Control and Treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y and t/ha) and annual average TSS concentration (mg/L) and (C) Total Nitrogen (TN) loads (kg/y and kg/ha) and annual average TN concentration (ug/L). The 2017/18 data was for a single event only and not the entire wet season as instruments were installed in February 2018. See the data quality caveats in Appendix B.

5.6 Glen Bowen

5.6.1 Treatment progress

Glen Bowen was a new Landholders Driving Change (LDC) site added in 2019. Glen Bowen Station has a large area of river frontage country adjacent to the Bowen River upstream of the Bowen River crossing (Figure 64). There were four gully sites initially evaluated as potential rehabilitation sites (Stout et al., 2019). Glen Bowen Gully 1 (GB1) was chosen as the treatment site, and Glen Bowen Gully 3 (GB3) was chosen as the control site (Figure 66). The treatment gully had an existing bund wall around the site which is evidence of previous attempts to reduce runoff and erosion at this site (Figure 65). The soils, geomorphology and history of gully evolution has been described in detail in Stout (2019). A summary of the key factors relevant to this site are given in Table 16.

The erosion control works commenced at the treatment site in October 2019 following the site plan by Neilly Group Engineering (2019) (Figure 65). The rehabilitation plan involved using cut-and-fill techniques and compaction earthworks. Three smaller gullies and six scalded areas were reshaped and compacted to protect the works. Two rock cut-off walls were also constructed downstream of the reshaping as well as rock check dams along the contours at one metre intervals in the basins. The existing earth bund wall was reinforced and gypsum was added to the soil to aid soil stabilisation. An average of 20 t/ha of gypsum was applied to condition the soil used in all works. Hay, bagasse and coir mesh was spread between the rock contours to protect the soil before vegetation was established. The area was then revegetated by contractors using drill-seeding and hydro-seeding (see Appendix C for species mix). Cattle grazing was also excluded from this site over the 2019/20 wet season.

Table 16: The key attributes of Treatment (GB1) and control (GB3) gullies (Stout et al., 2019)

Gully	Gully area (ha)	Contributing catchment area captured by water quality monitoring (ha)	Soil type	Fine sediment erosion rate over last 20 years
Treatment Gully (GB1)	4.3 ha	2.7 ha	Sites are located on alluvium with generally sodic/magnesian Brown or yellow sodosols.	650 t/y
Control Gully (GB3)	2.2. ha	2.9 ha	Sites are located on alluvium with generally sodic/magnesian Brown or yellow sodosols.	280 t/y

The location of the water quality monitoring sites, land condition and terrain analysis surveys are shown on Figure 66. The water quality monitoring equipment was installed in early November 2019, and the terrain, pasture and biomass surveys were conducted in early Dec for the pre-wet analysis and April 2020 for the post-wet analysis. Noting that there was no pre-wet vegetation survey conducted on the treatment gully as rehabilitation had already been initiated before the field data could be collected. However, it is safe to assume that the land condition and cover metrics at the treatment gully were equivalent or similar to the control gully prior to rehabilitation (see Figure 64 and Figure 66).

The location of the instrumentation was based on the pre-purchased cable length of 10 m for all instruments, the ability to safely install the instrumentation during earthworks, and to locate it in an area that would not undergo considerable backwater flow from the Bowen River in large events. The stream monitoring instrumentation at the treatment site captures about 2/3rds of the treated gully area. The bed of the treatment gully at the location of the monitoring station has reached bedrock or an older coarse sub-stratum (see Figure 68E). The bed of the control gully is predominantly clay and sand (Figure 68F).

Unlike the Mt Wickham site, no 'before' treatment water quality samples were collected prior to the rehabilitation treatment at Glen Bowen. Due to the relatively low rainfall over the 2019/20 wet season, and the impact of the rehabilitation works, no water quality samples were collected at the treatment gully in 2019/20. There were ~17 samples collected at the Glen Bowen control gully during 2019/20 wet season, however, there was insufficient rainfall and runoff to completely submerge the velocity sensors enough for measurement (Figure 68C) and therefore no discharge or loads calculations were possible at this site in 2019/20.



Figure 64: Glen Bowen control (above) and treatment (below) sites prior to rehabilitation

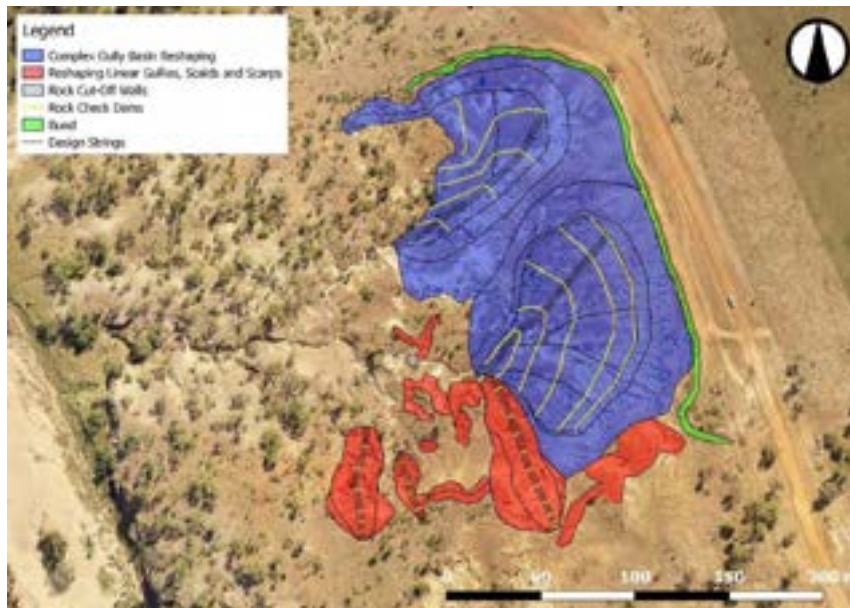


Figure 65: Glen Bowen erosion control activity implemented at the treatment site (Source: Neilly Group Engineering, 2019)

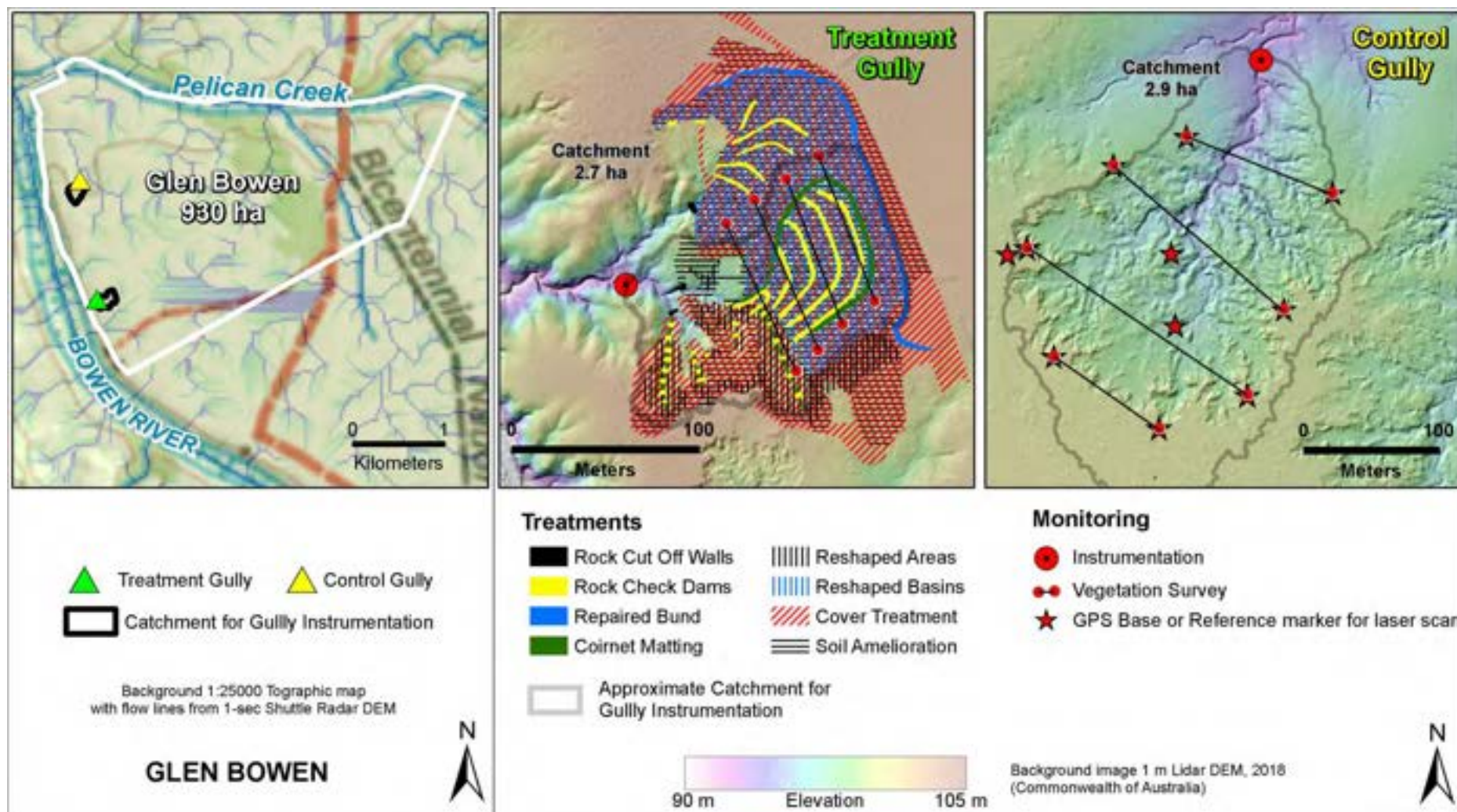


Figure 66: Location of the Glen Bowen site (left) and the Treatment and Control gullies, including the location of the treatment structures and monitoring equipment/locations.



Figure 67: Before and after images of the Glen Bowen Treatment gully (Image source: NQ Dry Tropics)



(A)



(B)



(C)



(D)



(E)



(F)

Figure 68: Glen Bowen water quality monitoring station set up (A, D). The instrumentation setup is the same at both treatment and control sites (B) the control site sensor cluster on the bed of the gully and (C) the control site sensors during an event that was just above the event threshold for sample collection. (E) The treatment gully sensor and (F) is following a small runoff event at the treatment gully site. Note the difference in the colour of water between the control (C) and treatment sites (F).

5.6.2 Vegetation response

The data have been presented in the same format as the other NESP sites, although the vegetation data collection did not commence at this site until Dec 2019. Given the actual alluvial gully surface was the area being treated (i.e. the hillslope/catchment is the gully), and no rehabilitation was occurring on the gully channel, the vegetation and land condition data was focused on the gully site only. Figure 70 presents the end of wet season % cover and biomass data for the control and treatment gully at Glen Bowen.

At the end of the 2019/20 wet season, there was a significant difference in the vegetation % cover ($p < 0.001$) and biomass ($p < 0.001$) between the control and treatment sites on Glen Bowen. The cover and biomass were both significantly higher on the treatment than the control site (Figure 70).

Interestingly, despite the significant increase in the % cover and biomass at the treatment site, the land condition is still considered to be relatively poor, and is still in D condition following treatment (Table 9). A large proportion of the treatment gully is in D1 condition, which is one sub-class below C condition (Figure 71) whereas the control site is dominated by the more degraded patchkey sub-classes (D3, D7 and D11). The treatment site is classed as D condition this year due to the predominance of annual grasses that have grown from the seed mix used at the treatment site, as well as naturally occurring button grass. These species will disappear going into the dry season (become litter, blow away etc). While there has been an increase in some short-term function from mechanical soil disturbance and annual plant growth, it is expected that much of this vegetation will be gone coming into the next wet season. Most of these annuals will not reappear next year, and this will leave bare earth and litter. More perennial grasses need to grow to further improve land condition. The newly re-shaped gully surface rock contours have reduced run-off and will trap some larger sediment particles and seeds. We will need to wait until next wet season to see how the contours perform, and how this affects land condition.

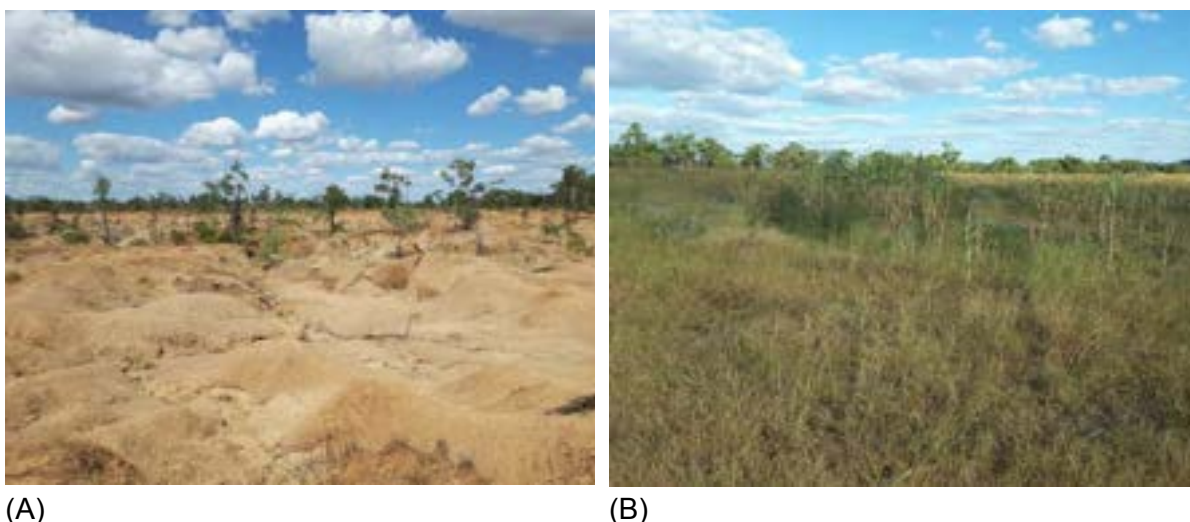


Figure 69: Glen Bowen hillslope above (A) control gully and (B) the treatment gully at the end of the first wet season after rehabilitation at the treatment site.

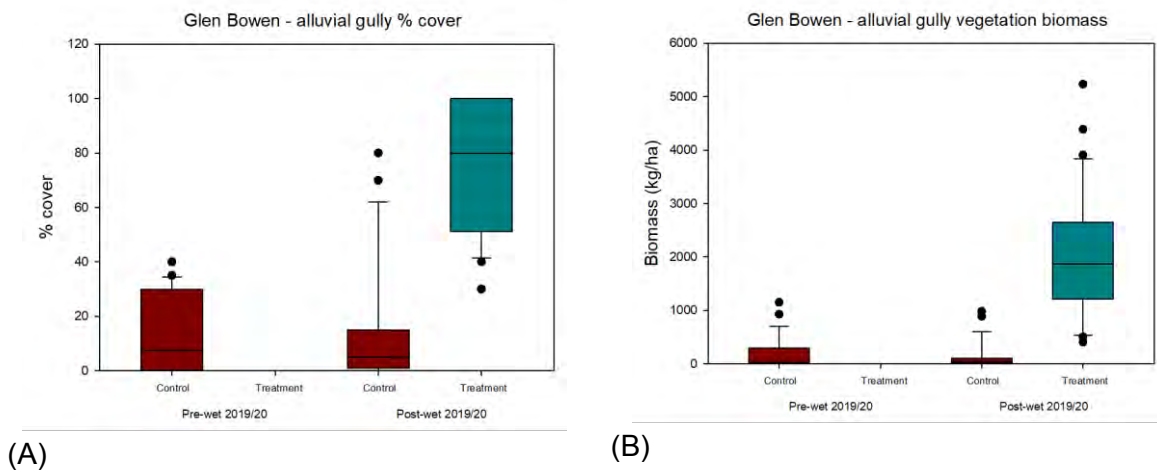


Figure 70: Glen Bowen control and treatment sites showing the changes in (A) % cover on the gully surface and (B) the vegetation biomass (kg/ha) from before the wet season and prior to treatment, to after the wet season and after treatment. Note extreme outlier data were excluded at some sites for plotting purposes.

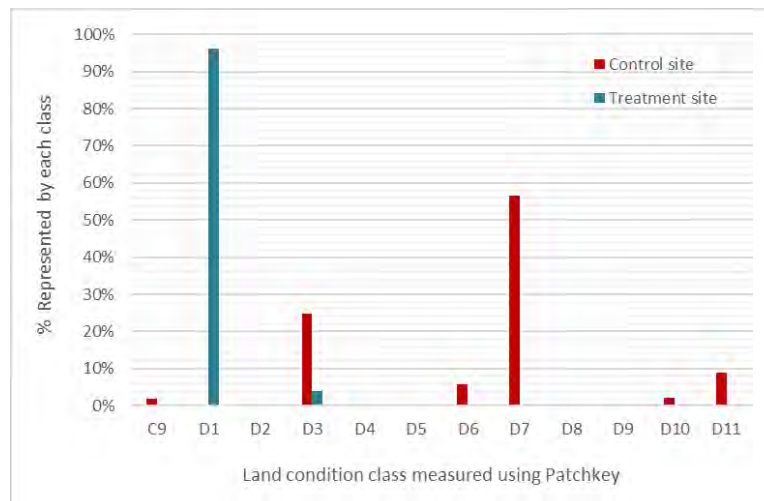


Figure 71: Comparison of the Glen Bowen treatment and control site represented by the different land condition classes measured using the Patchkey method (April 2020).

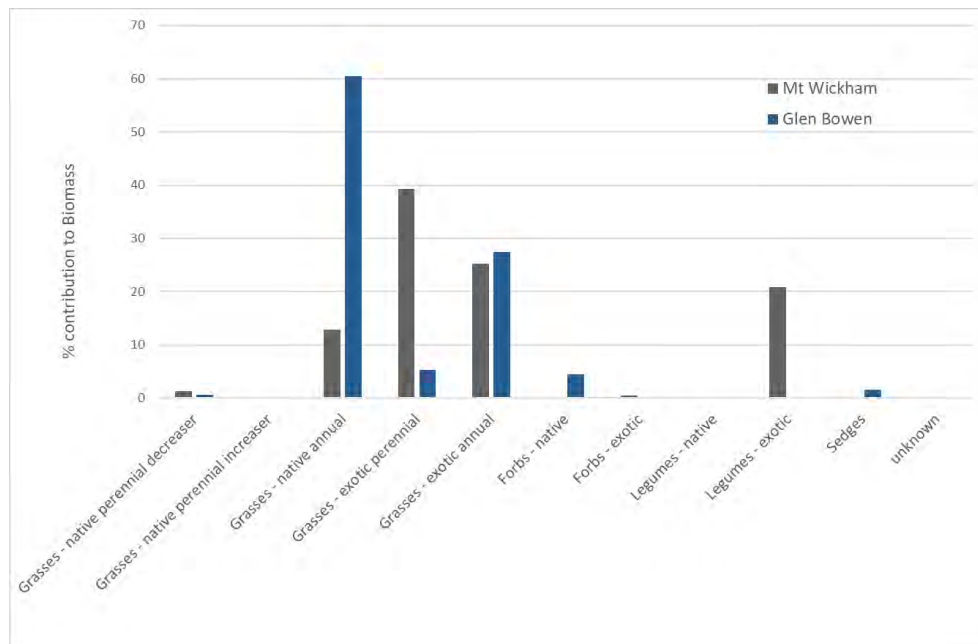


Figure 72: Comparison of the proportion of perennial and annual grasses between the two large alluvial gully rehabilitation treatments (Mt Wickham and Glen Bowen).

5.6.3 Terrain changes

CSIRO collected terrain scans using the Zebedee instrument on the Glen Bowen control site before and after the 2019/20 wet season. It was not possible to collect Zebedee scans on the treatment site as rehabilitation had already started at the time of surveying. A DEM of difference was calculated for some sections of the control gully which highlights that there were areas of erosion and deposition in different parts of the gully (Figure 73). The changes are relatively small, which is not surprising given the below average rainfall over the 2019/20 wet season. It also highlights that several sections of the gully appear to be stable, with no significant erosion or deposition occurring in many areas.

Baseline LiDAR data was collected at Glen Bowen prior to treatment. It is expected that post-treatment LiDAR and/or drone imagery would provide useful insights into the overall changes in erosion, deposition and net sediment loss from the treatment site in the future.

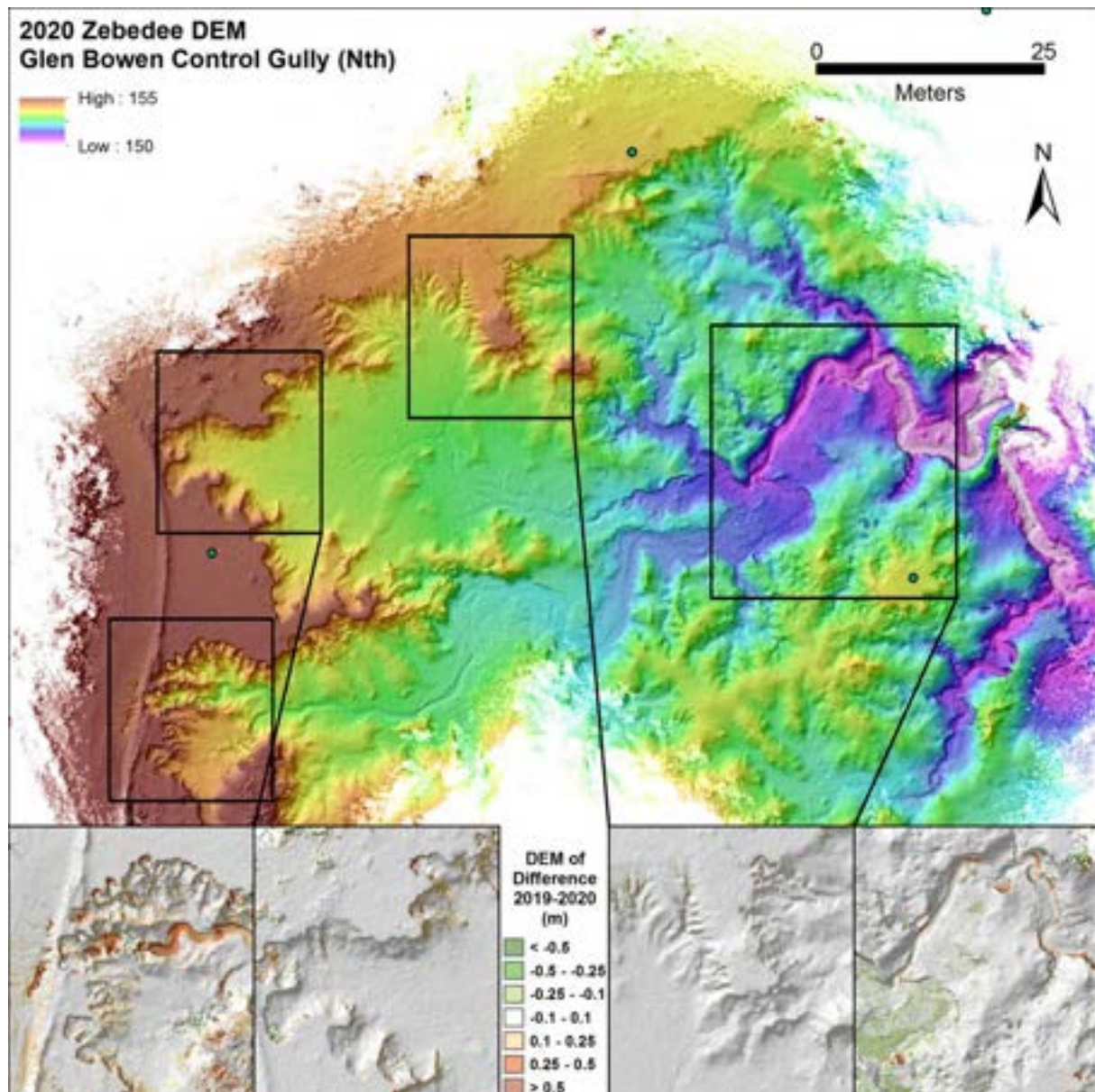


Figure 73: Zebedee scan image of the Glen Bowen control site over the 2019/20 wet season. On the DEM of Difference, brown represents erosion and green sediment deposition.

5.6.4 Water quality, runoff and loads

In the 2019/20 wet season there was ~370 mm of rainfall at the treatment site and ~340 mm at the control site, which is considerably lower than the long-term average for this area (Table 13). At the Glen Bowen control site, there were 17 water quality samples collected during two events over the 2019/20 wet season (Figure 74). The median TSS value at the Glen Bowen control site was ~53,000 mg/L. This is highest median sediment concentration of any of the study sites (Figure 11A). The median Total Nitrogen (TN) concentration is ~8,064 ug/L which is slightly lower than the median TN value measured at Mt Wickham and not that different to the other gully sites included in this study (Figure 11A). This suggests that these sites are highly degraded and naturally low in nutrients.

There was some flow recorded at the control site (see Figure 68C), and although some depth data was collected (Figure 62), this was not sufficient to submerge the velocity sensors

appropriately and no velocity data were collected at this site. Therefore, it was not appropriate to calculate discharge and loads for the 2019/20 wet season. The treatment site, which has a large catchment area, should have had the same amount or more runoff than the control site. However, other than very small flow (see Figure 68F), no runoff data or samples were collected from the treatment site.

Importantly, there is an obvious difference in the colour of water between the control (Figure 68C) and treatment sites (Figure 68F) during the only runoff event of the season. This suggests that the rehabilitation works have considerably reduced the runoff at this site, and subsequently they have also reduced the amount of soil being transported from the treatment gully into the Bowen River.

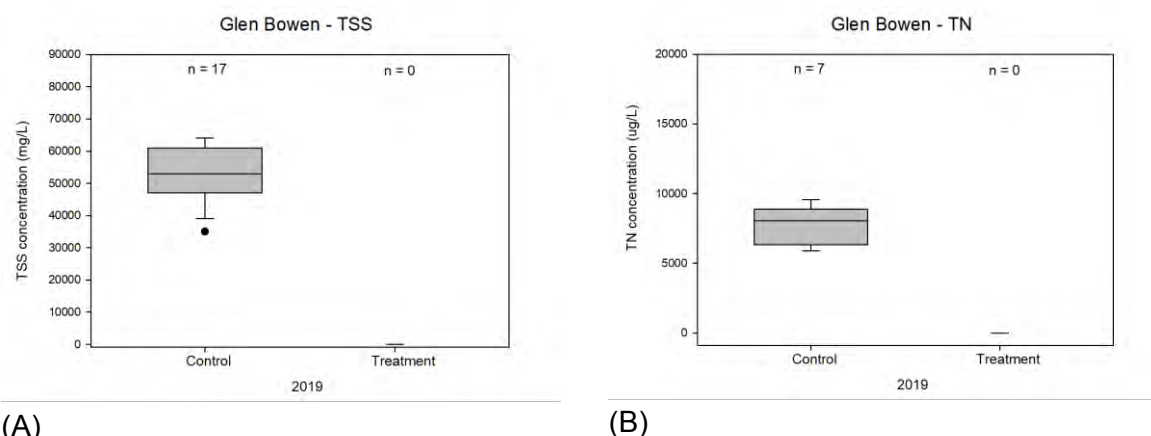


Figure 74: (A) TSS concentration and (B) TN concentrations at Glen Bowen for the 2019/20 wet season. No samples were collected the treatment site in 2019/20.

5.6.5 Summary: Glen Bowen

Only one wet season has passed since the treatment works were undertaken at Glen Bowen, however, there are some early positive response indicators that the rehabilitation on the treatment gully has been effective. The amount of vegetation cover and biomass on the treatment gully has significantly improved. The absence of any runoff data at the treatment site is a good sign that the treatments have managed to capture all the rain that fell on the treatment area, and virtually no water or soil left the treatment gully during the 2019/20 wet season. However, there was also very little runoff at the control gully, therefore additional years of data under (hopefully) average rainfall conditions, will further test the effectiveness of the treatment at this site.

5.7 Mt Pleasant

5.7.1 Treatment progress

Mt Pleasant Station is a 14,000 ha grazing property located within the Bogie sub-catchment. The property straddles the Bowen to Collinsville road and train line (Figure 76). This site was a new Landholders Driving Change (LDC) project initiated in 2019, however, the property has undergone considerable land management changes and property improvements using the principles of regenerative grazing (RCS method) over the last 10-15 years.

The gullies on this property are generally the smaller, linear style gullies, that act as extensions of the channel network. Many of the gullies on this property were likely initiated under a previous management regime, several decades ago. Therefore, the focus of the rehabilitation works at this site was on reinstating the hydrological function that was present in the landscape prior to channelization. This involved slowing the flow of water and spreading the water within the landscape. This was expected to improve the biodiversity, habitat and landscape function of the site.

Two gullies on this property were selected; one was not treated and represented a control site, and the other had extensive landscape rehabilitation, and this was the treatment site (Figure 76). Detailed soil descriptions are presented in Hardy (2019), and a summary of the treatment and control sites is given Table 3 and Table 14.

The rehabilitation works on Mt Pleasant were designed by the Mulloon Institute and included a series of log and rock weirs to slow down the water and create a backwater or ponding environment within the treatment gully (Mulloon Consulting, 2019). The specific location of the rehabilitation structures are shown in Figure 76, and a series of before and after photos from site #1 and #2 are shown in Figure 77 and Figure 78.

The location of the water quality monitoring sites, land condition and terrain analysis surveys are shown on Figure 76. The water quality monitoring equipment was installed in early November 2019, and the terrain, pasture and biomass surveys were conducted in early December for the pre-wet analysis and in April 2020 for the post-wet analysis. To our knowledge, no assessment of pre-treatment gully erosion rates had been undertaken at this site.

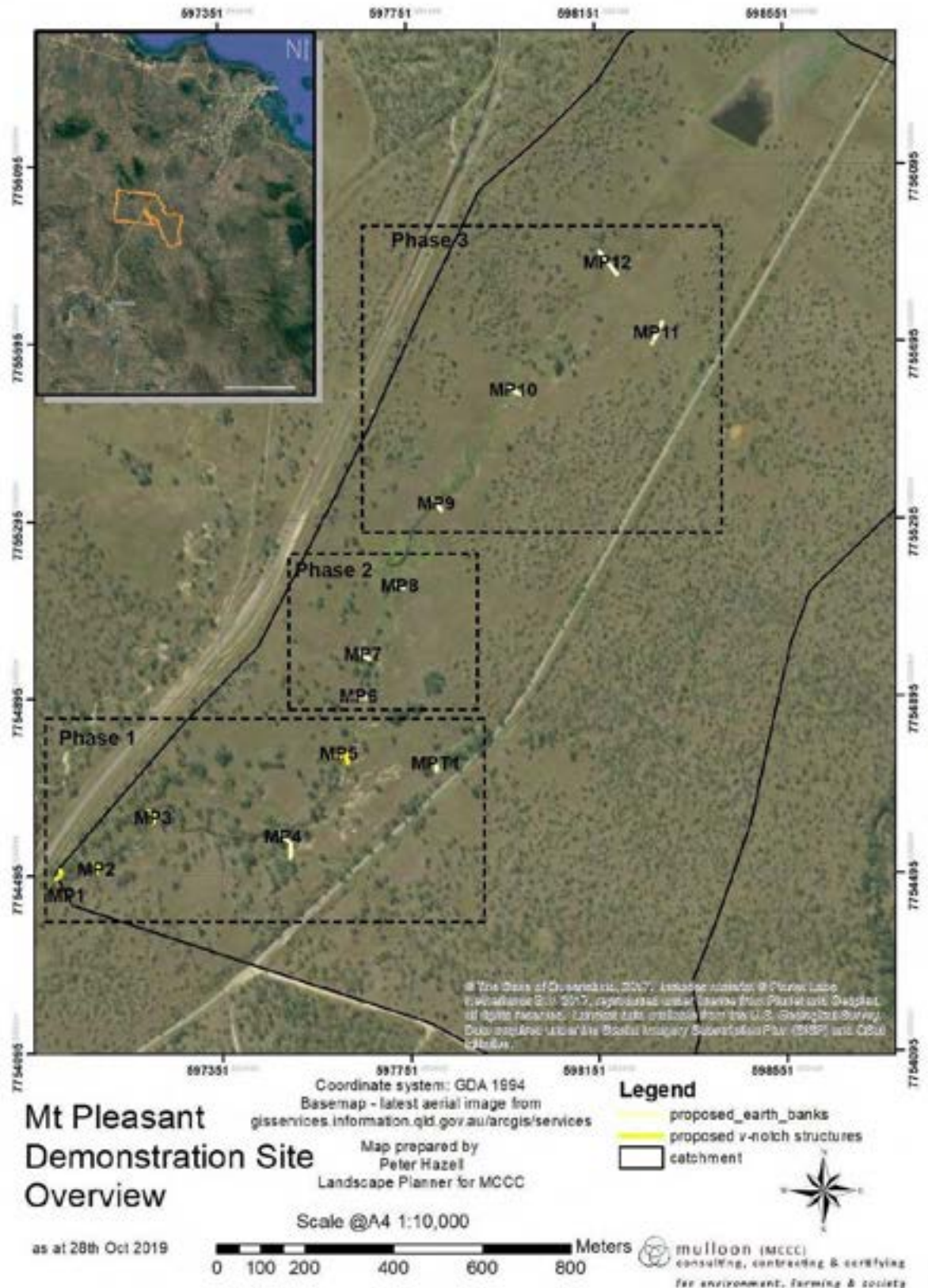


Figure 75: The Mt Pleasant design plan for all three Phases of rehabilitation. Only Phase 1 was completed in 2019 (Mulloon Consulting, 2019).

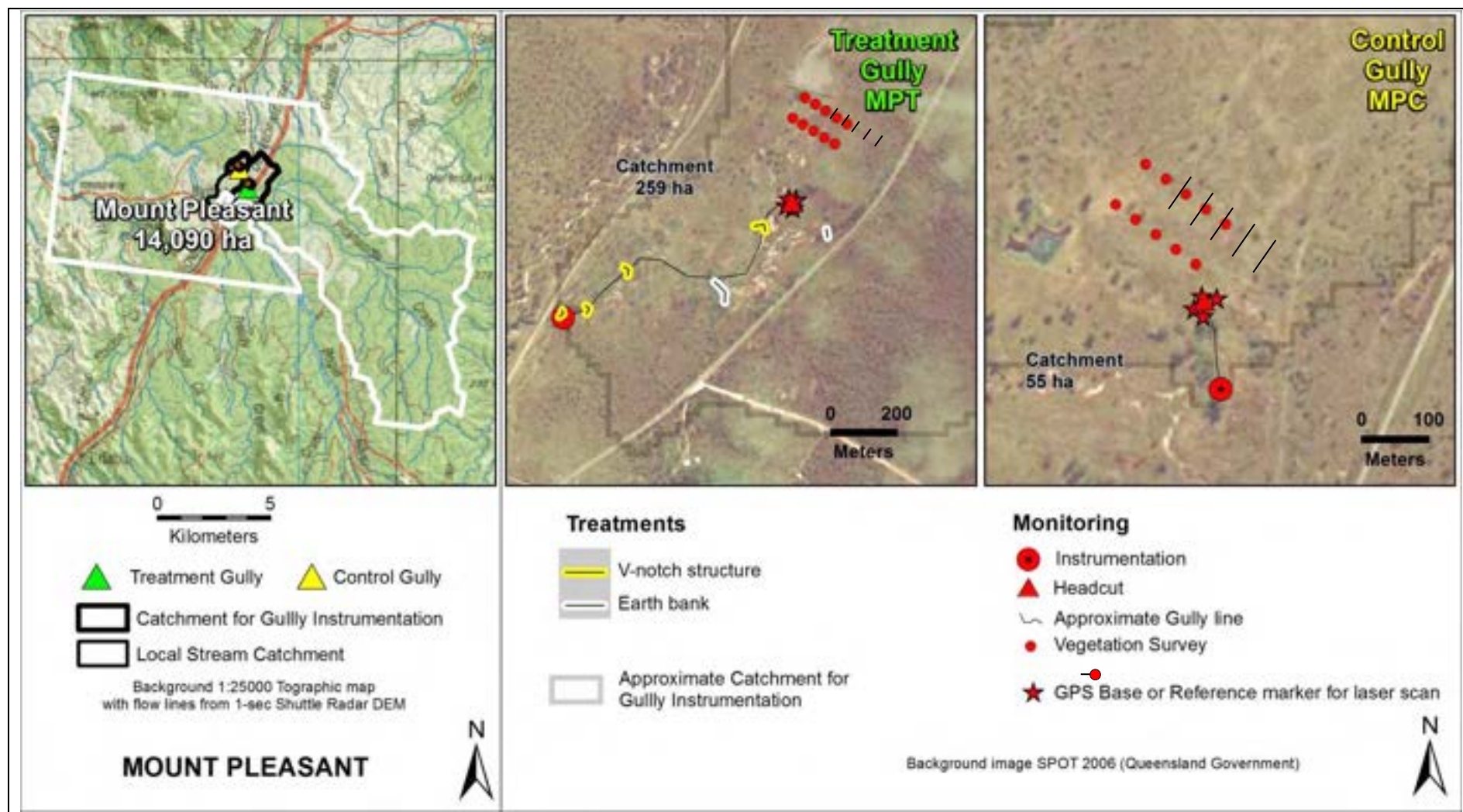


Figure 76: Location of the Mt Pleasant (left) and the Treatment and Control gullies. The location of the installed treatment structures and monitoring equipment/locations are shown.



(A)



(B)



(C)

Figure 77: Mt Pleasant (A) During (B) before and (C) after rehabilitation at the treatment site (MP1). Photo (C) is after ~100 mm of rain in late February 2020. The CSIRO water quality monitoring station can be seen in the background of photo (C). (Image Source: NQ Dry Tropics)



(A)



(B)

Figure 78: Mt Pleasant treatment site (MP2) (A) immediately after remediation but prior to rainfall and (B) after ~100 mm of rain in late February 2020 (Image Source: NQ Dry Tropics).



(A)

Figure 79: (A) aerial photo from helicopter of the control gully (left) and the treatment gully on the right of the image; (B) the treatment gully backing up behind the rehabilitation structures (Photo credit: Fruition Environmental). Red dots show the approximate location of the water quality monitoring equipment at Mt Pleasant (Image Source: Fruition Environmental).



(A)



(B)



(C)



(D)



(E)



(F)

Figure 80: Mt Pleasant Treatment gully site setup (A and D). The same system was set up at the control site. The treatment site (B) at the beginning of an event; and (C) during an event. The Control site (E) before an event and (F) during an event.

5.7.2 Vegetation response

The vegetation data collection commenced at this site in December 2019 for the hillslopes and gullies. It is important to note that the hillslope vegetation surveys are in the upper part of the catchments of both gullies (Figure 81). This is the area we want to monitor to see if there is any future change in the proportion of vegetation that may influence the rainfall and runoff entering the gully site. It is acknowledged that the pasture species and biomass diversity is much greater on the areas adjacent to the treatment instrument site on the alluvial flats; however, no transects were measured in this area. Figure 82 presents the end of wet season % cover and biomass data for the hillslope above the control and treatment gully as well as the gully walls and gully floor.

Overall, the cover and biomass levels on the hillslopes are very high compared to other grazed sites with % cover measured as $>80\%$ for both control and treatment sites and biomass reaching nearly 3000 kg/ha at the control site prior to the wet season. As with other properties in 2019/20, the lower than average rainfall generally resulted in a decline in biomass over the wet season. At Mt Pleasant the cover and biomass declined at the control site, but it did not change significantly at the treatment site (Figure 82).

At the end of the 2019/20 wet season, there wasn't a significant difference in the hillslope % cover, between the treatment and control sites ($p=0.252$). Nor was there any difference between the % cover on the gully walls ($p=0.953$). There was, however, a significant difference in the % cover between the control and treatment sites on the gully floor/channel ($p<0.001$).

The vegetation biomass data followed the same pattern as the % cover data with no significant difference between the control and treatment hillslopes ($p=0.110$) or gully walls ($p=0.223$), but there was a difference for gully floor/channel ($p<0.001$).

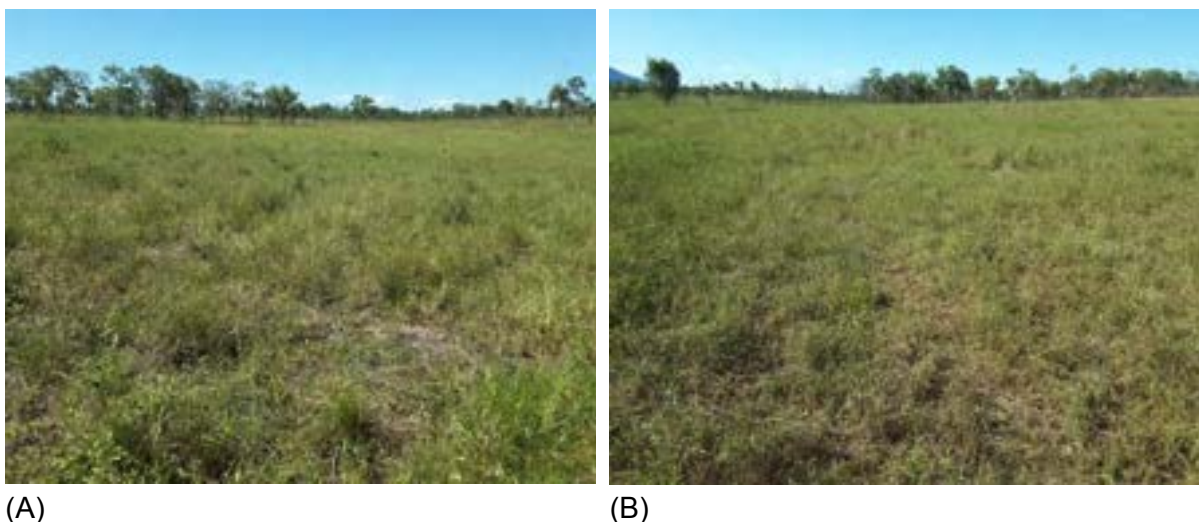
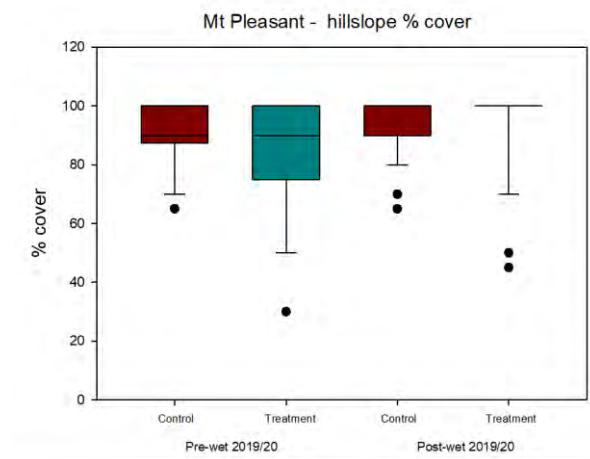
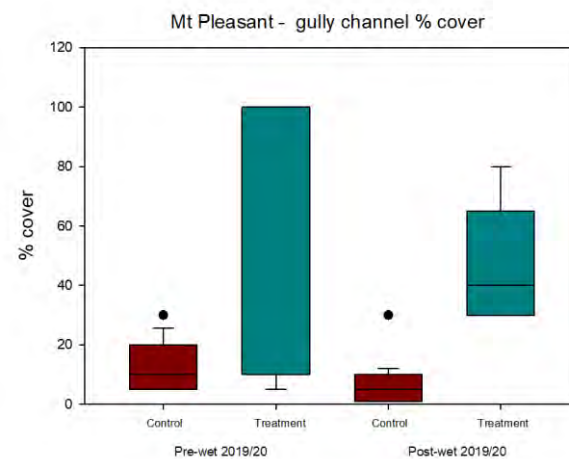


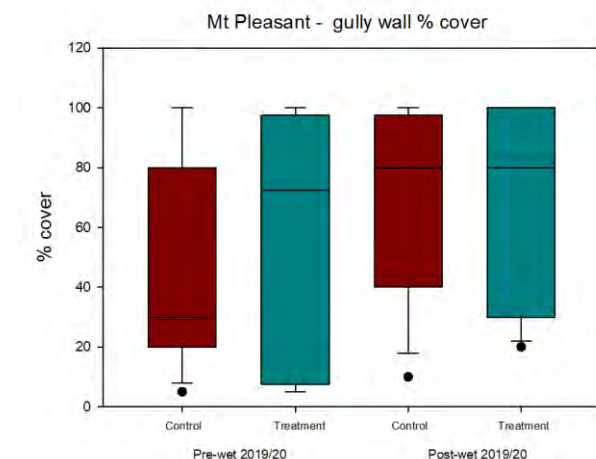
Figure 81: Mt Pleasant hillslope above (A) control gully and (B) the treatment gully.



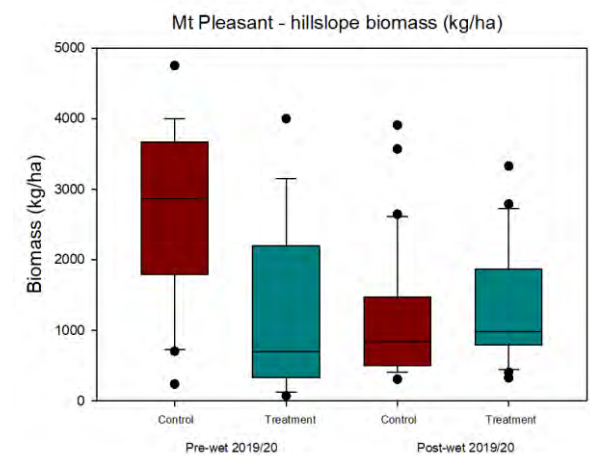
(A)



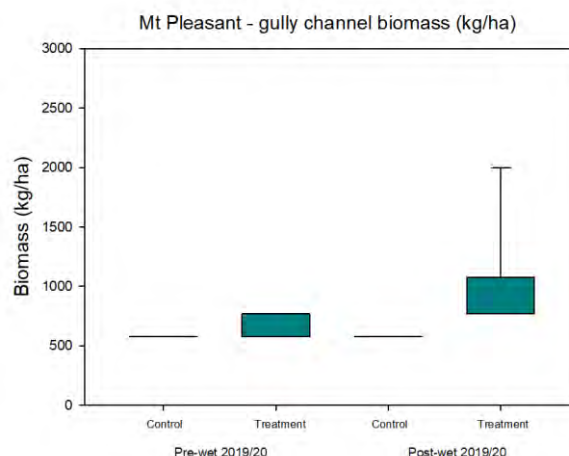
(B)



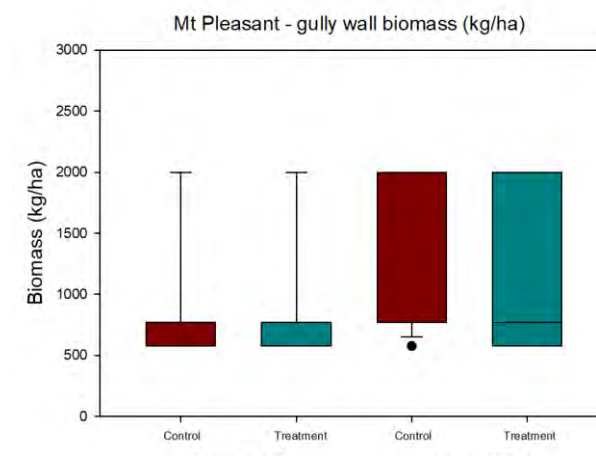
(C)



(D)



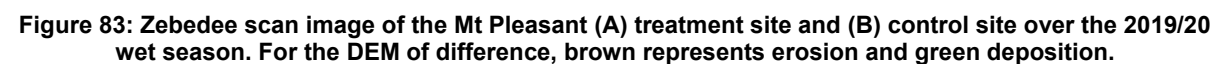
(E)



(F)

Figure 82: Mt Pleasant control and treatment sites showing the changes in % cover on the (A) hillslope, (B) gully floor/channel and (C) gully walls, and change in pasture biomass (kg/ha) on the (D) hillslope, (E) gully floor/channel and (F) gully walls over the 2019/20 wet season. Note extreme outlier data were excluded at some sites for plotting purposes.

CSIRO collected preliminary Zebedee scans on the Mt Pleasant treatment and control site head-cuts which are provided in Figure 83. Given the relatively high levels of cover at this site, it was pleasing that the Zebedee scanner was able to capture terrain images. The results suggest that the gully heads are relatively stable, particularly at the treatment site which would have received more runoff after treatment. There was little erosion or deposition occurring at the head cuts of either gully over the 2019/20 season.



In the 2019/20 wet season there was ~440 mm of rainfall at the treatment site, and ~449 mm at the control site, which is considerably lower than the long-term average for this area (Table 12). Due to the backwatering that occurred at the sites, numerous water quality samples were collected at this site through the wet season. In total 33 samples were processed for TSS, and 14 for nutrients, at the treatment site. At the control site, 32 samples were processed for TSS, and 16 for nutrients.

These are extremely low median TSS values for gully sites, and interestingly there is not significant difference between the control and treatment sites for either TSS ($p=0.470$) or TN data ($p=0.835$), despite the large initial ponding and backwatering that was created by the treatment structures. The most surprising result was how low the TSS concentrations were at

the control site that had not been treated. This lack of difference in the TSS and TN data may be due to the relatively good condition that the catchment is in relative to other sites, as the ground cover is near 100% at both control and treatment sites at the end of the 2019/20 wet season.

For all other sites, we rely on the Turbidity-TSS and Turbidity-TN relationships to derive sediment and nutrients loads for the entire wet season. The Turbidity-TSS curves were strong at Mt Pleasant, however, the ponding and backwatering processes appeared to influence the TN data and a sensible relationship between Turbidity and TN could not be derived at either the control or treatment site.

The total sediment loads (t/y) measured at the treatment site were higher than at the control site due to the larger catchment area and increased discharge at the treatment site. However, the unit area sediment loads (t/ha/y) and flow weighted annual mean TSS concentrations, were lower at the treatment site than the control.

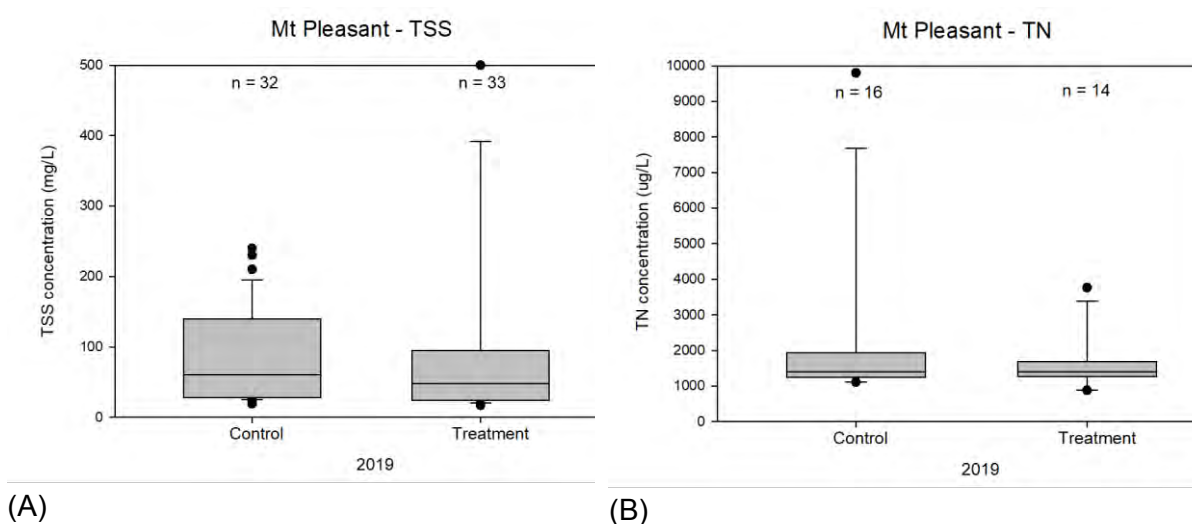


Figure 84: (A) TSS concentration and (B) TN concentrations at Mt Pleasant for the 2019/20 wet season.

5.7.5 Summary: Mt Pleasant

Only one wet season has passed since the treatment works were undertaken at Mt Pleasant. Interestingly, there has been very little improvement between the control and treatment sites as this property was in relatively good condition prior to the rehabilitation works, and the baseline conditions were already quite high. The annual median and mean TSS concentrations measured at the Mt Pleasant site are some of the lowest concentrations measured on any of the gully sites, even for the control site which has not undergone any active treatment. This suggests that the land management at this site has contributed to low sediment concentrations and loads. Additional years of average or above average rainfall will test if these findings hold.

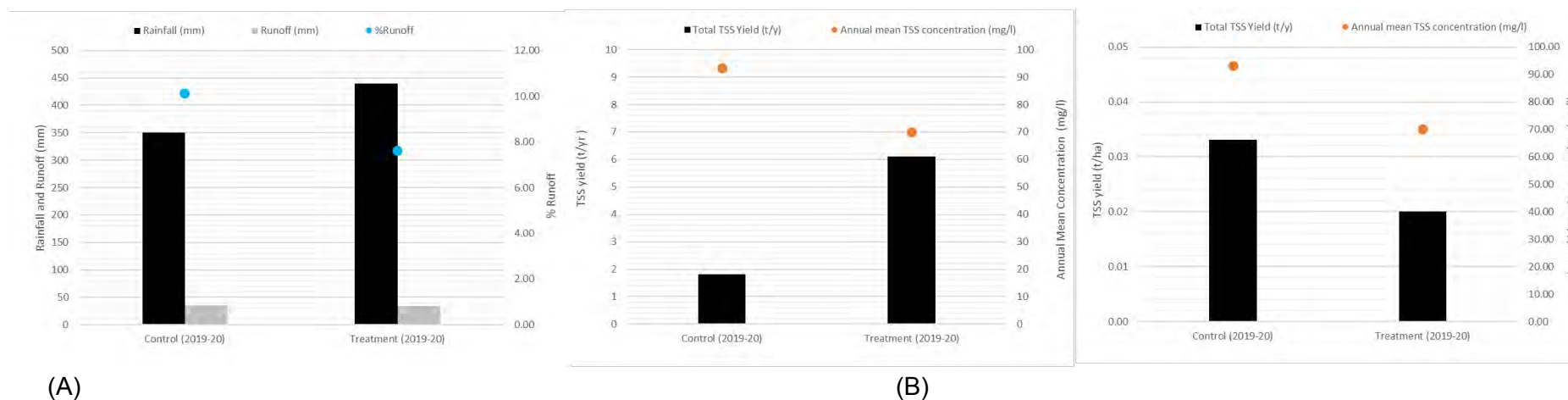


Figure 85: Mt Pleasant control and treatment results for (A) Rainfall, runoff and % runoff (B) Total Suspended Sediment (TSS) loads (t/y) and t/ha. Data quality caveats are in Appendix B.

6.0 DISCUSSION AND RECOMMENDATIONS

This study was designed to evaluate the effectiveness of a diversity of rehabilitation options for a range of gully types within the rangeland systems of the Burdekin catchment. Table 17 presents a synthesis of the treatments used at each site, and the measured improvement at each treatment site compared to the control. The sections below document some of the other findings from the study and the implications of these findings for management, policy, further gully rehabilitation and additional areas of research.

6.1 Summary of monitoring results in 2019/20

Spatial variation of erosion and water quality in gullies

- Across the sites, annual average soil loss from gullies is strongly dependent on the drainage area above the gully head-cuts. Catchment area is a surrogate for runoff volume or energy and is the strongest predictor of sediment yield found in this study; however, other studies have also found soil properties and vegetation condition to be important. Therefore, the catchments above gullies should be a focus of grazing management or remediation interventions.
- The total suspended sediment (TSS) concentrations varied considerably between control sites with the highest median concentrations measured at Glen Bowen (53,000 mg/L) and Mt Wickham (~47,000 mg/L), and the lowest concentrations at Mt Pleasant (60 mg/L). The other sites had median concentrations between ~1,300 and ~6,300 mg/L. Mt Wickham and Glen Bowen gullies have both formed on sodosol dominated landscapes.
- Total nitrogen (TN) concentration values are highly variable between sites, and between events within sites, and not as responsive as sediment to rehabilitation treatment. TN concentrations show a similar pattern of variation between sites although the differences are of smaller magnitude than for TSS.
- There are differences in the sediment yields (t/ha/yr) estimated using different measurement approaches (loads monitoring vs terrain analysis). A multiple lines of evidence approach is encouraged until further data is collected to resolve these differences.

Calculating rehabilitation effectiveness

- When sites have water quality and runoff data collected from periods both before and after treatment, from control and treatment sites, statistical analysis can be used to calculate the effectiveness of the rehabilitation on erosion control (as described in Section 3.7 and 3.8). This approach takes in account variations in response due to inter-annual rainfall variability between wet seasons.
- If water quality samples have been adequately sampled across the flow event hydrograph for the main events in all seasons at both control and treatment sites (including first flush and peak events) then it is suitable to use concentration data to evaluate rehabilitation effectiveness.

- However, comparison of changes in the sediment loads between sites is the most appropriate metric to use to evaluate treatment effectiveness, as this represents the total tonnes of fine sediment delivered or saved due to the rehabilitation. It is acknowledged that runoff and load data are notoriously challenging to obtain and highly uncertain in these flashy systems, however, loads are considered important for gold standard monitoring.
- When using control and treatment data, without coincident before data at each site, or using before and after data at a treatment site, without a control site to compare to, it is possible to detect changes, but it is difficult to attribute these to the treatment effects alone. The changes could be influenced by variations in rainfall, runoff or individual gully dynamics. For sites without before data, indicative trends can be identified, but longer time frames (e.g. >5 years) will likely be required to detect statistically significant changes that are independent of rainfall/runoff variability.

Livestock management and revegetation

- Most sites have shown some improvement in % cover or biomass following treatment; however, gully catchment land condition remains in C or D class for most sites. This is because the pasture species are primarily dominated by the exotic perennial grass Indian couch, forbs, and/or exotic legumes. Indian couch produces less biomass and is more sensitive to seasonal climate variations than native perennials, resulting in relatively poor infiltration.
- The 'fencing off only' rehabilitation site (Meadowvale) has shown improved gully floor/channel vegetation biomass, which is increasing the sediment trapping potential of the site.
- Grazing management during and following rehabilitation needs to be carefully monitored to ensure treatments are not compromised. In most cases it is important to give treated areas a spell from grazing to allow vegetation to recover from the initial disturbance associated with rehabilitation. Grazing can then be reintroduced using an adaptive management approach.

Porous Check Dams

- The sites that have had fencing and porous check dams installed (Virginia Park and Minnievale) are showing improvements in the vegetation metrics in the gully floor/channel and gully walls. This increased cover, in conjunction with the sediment check dam structures, has resulted in high (>90%) sediment trapping. However, the material that is being trapped is predominantly coarse (>63 µm) sediment (Koci et al., Accepted).

Hillslope runoff diversions above the gully

- The treatment at Strathbogie focused on hillslope runoff diversion banks which have effectively 'starved' the active gully and statistically improved the runoff and water quality metrics for this site. Given the site has statistically improved water quality and sediment yields following treatment, an effectiveness value of ~0.95 was calculated for this treatment. However, this first year was relatively dry, and the test will be whether the

diversion banks concentrate surface runoff and cause gully initiation elsewhere. Subsequent wetter years will be an important test for this site. The land condition is still relatively poor and should be the focus for the long-term resilience of this site. Hence, this effectiveness value needs to be used with caution, and can be considered preliminary.

- Hillslope diversions always require careful design, placement and maintenance of the structures to prevent the breaching of the structures or the initiation of new gullies where diverted water accumulates.

Runoff management within a gully

- The Mt Pleasant site implemented a landscape rehydration project that aimed to reduce the erosive force of runoff within the treatment gully. This project appears to have had some success; however, the changes between the treatment and control site are small, as the property was already in relatively good condition compared to other sites. When properties have good vegetation metrics, and relatively mature and in-active gully systems, gully rehabilitation is not worth doing for water quality benefits alone. There is negligible improvement in terms of water quality and sediment savings relative to other more active gully sites, however, there may be other benefits including increased ecological habitat.
- Hillslope diversions always require careful design, placement and maintenance of the structures to prevent the breaching of the structures or the initiation of new gullies where diverted water accumulates (see Nichols et al., 2018). Ripping and seeding is also known to have a relatively short lived influence on pasture and runoff, and should not be considered a replacement for improved grazing land management (Mead and Chan, 1992; Alexander et al., 2001).

Gully reshaping and structural control

- The larger scale rehabilitation works at Mt Wickham have resulted in statistically improved vegetation metrics on the hillslope and within the gully after just two wet seasons. There are also statistically significant improvements in total suspended sediment (TSS) concentrations following the major earth works at the treatment site. Sediment loads have also declined following treatment, relative to the un-treated control. Given the site has statistically improved water quality and sediment yields following treatment, the effectiveness value was calculated as ~0.85 for this treatment. Additional years of data will determine how variable this effectiveness value is for a broader range of rainfall seasons.
- The larger scale rehabilitation works at Glen Bowen have shown early signs of success with significantly improved cover and biomass on the treatment site. Visually, the water leaving the treatment site is relatively clear and considerably less turbid than the control site which reached sediment concentrations as high as 64,000 mg/L. The vegetation will need to be carefully managed at the treatment site due to the low rainfall during the establishment phase.

6.2 Key findings for management

- It is possible to improve gully floor vegetation biomass (and in some cases % vegetation cover) if a series of porous check dams (PCDs) are installed, and livestock is managed (but largely excluded) for >3 years.
- High gully head-cut erosion rates can be rapidly 'switched off' using hillslope diversion banks that effectively starve the gully of runoff and reduce soil loss.
- Alluvial gullies can be rehabilitated using re-shaping and re-vegetation in relatively short time frames (~12-24 month) given sufficient rainfall. Engineering treatments (e.g. earth works and rock chutes etc) are likely to be important for stabilising the vegetation at these sites in the long term. These alluvial gullies have high sediment concentrations, and also very high rehabilitation costs. Ongoing maintenance costs for these engineering works may also be significant.
- Grazing management following rehabilitation needs to be carefully considered and monitored to ensure treatments are not compromised in the future.
- Due to the variability in erosion rates within and between gully types, cost-effectiveness values will vary between sites, even when the same treatment is used. The key to ensuring remediation resources are allocated cost-effectively is (i) to match the treatment value (\$) proportionally to sediment loss, and (ii) prioritising sites with high baseline erosion rates, and high delivery to coastal systems.

6.3 Key findings for management

- This type of research will continue to deliver improvements in understanding for many years as an increasing range of climates are experienced and as the composition of revegetation continues to develop. These studies require a high level of expertise, and a lot of luck with respect to rainfall and instrumentation behaviour, to produce reliable results.
- While the quantitative data on sediment reductions will continue to emerge, the qualitative information such as terrain monitoring of gully erosion, photographs of event runoff, vegetation responses and treatment intactness provides early information to support gully rehabilitation.
- The P2R program has been modelling possible/potential water quality improvement following land management rehabilitation for more than a decade; however, there is very little measured data available to constrain model predictions. This study presents some of the first control/treatment field experiments that are measuring changes in water quality on the ground. The data from these projects will be critical for scenario analysis using the P2R modelling.
- Due to the variability in erosion rates within and between gully types, cost-effectiveness values will vary between sites, even when the same treatment is used. The key to ensuring remediation resources are allocated cost-effectively is (i) to match the treatment \$ value proportionally to sediment loss, and (ii) prioritise sites with high current erosion rates, and high delivery to coastal systems.

6.4 Recommendations for other rehabilitation projects

- Due to the high variability in rainfall and site characteristics in these landscapes, whenever possible, measurements should be collected from both control and treatment sites for at least one, preferably two, wet seasons prior to rehabilitation works being undertaken. This provides much greater statistical power to detect and quantify changes in shorter time frames. It also allows for instrumentation breakdowns, which do occur in these challenging and remote conditions.
- Some sites are more suited to quantitative evaluation of rehabilitation effectiveness than others. It is important to have comparable treated and untreated control gullies (e.g. the same soil, vegetation, rainfall, terrain, morphology, instrumentation) otherwise monitoring design and site selection may introduce additional bias into the statistical analysis that reduces the ability to detect a change.
- Where funding permits, the same instrumentation should be used at both control and treatment sites. Using cheaper cut-down monitoring equipment reduces the number of samples collected, and subsequently reduces the statistical power to detect changes between control and treatment sites.

6.5 Areas of further work

- There is a need to resolve the difference in sediment yields being generated using the different techniques at each site (flow monitoring vs terrain approaches). This will likely occur as more data is collected from a range of rainfall and runoff events.
- Additional work is needed to consolidate the link between grazing management, land condition, cover and biomass, and the runoff and water quality responses that have been measured at these sites. This information is in high demand for some of the new investment models (e.g. Land Restoration Fund and Reef Credits) but is currently beyond the scope of this study.
- Further work is needed to increase the proportion of native vegetation species included in gully rehabilitation projects.
- Contemporary erosion rates (t/ha) can differ considerably from longer-term historical erosion rates, such as those measured from aerial photos. For example it appears that recent erosion at Strathbogie is more rapid than in past decades, while other sites appear to be more stable. It would be useful to have spatial assessments of contemporary gully activity to inform the targeting of gully rehabilitation and maximise the downstream water quality benefits.
- This study has focused on determining the proportion of sites with detectable and significant rehabilitation responses. As the post-treatment monitoring period becomes more representative of average climate, and as rehabilitation outcomes stabilise, the results of evaluations such as this can improve quantitative estimation of the proportional reductions in gully sediment yield which may be expected more broadly.
- There is a need to link some of the water quality data collected from these gully sites to coincident data collected in the adjacent streams, rivers and marine system. This may help identify additional hot-spot areas within the Burdekin regions and understand the consequences of sediment transfer between gullies and downstream receiving waters.

Table 17: Description of treatment history and monitoring results for all sites to 2020. * represents early indicator, pending further data. Improved condition is defined when the difference between treatment was statistically better than the control gully.

		Virginia Park	Meadowvale	Strathbogrie	Minnievale	Mt Wickham	Glen Bowen	Mt Pleasant
	Burdekin basin	Upper Burdekin	Upper Burdekin	Bogie	Don	Bowen	Bowen	Bogie
	Managing organisation	CSIRO	CSIRO	NQDT	Greening Aust.	NQDT (Verterra)	NQDT (Neilly Group)	NQDT (Mulloon Institute)
	Gully type	Linear hillslope gullies and scalds	Linear hillslope gullies and scalds	Linear hillslope gullies	Linear hillslope gullies and scalds	Linear hillslope gullies, scalds and major alluvial gullies	Scalds and major alluvial gullies	Linear hillslope gullies
	Average annual long-term rainfall (mm) derived from nearest BOM site	~ 660 mm	~ 680 mm	~ 750 mm	~ 880 mm	~600 mm	~ 725 mm	~ 690 mm
	Soil type	Red Chromosol	Red Chromosol	Black Vertosol	Sodic Hypocalcic Red Dermosol	Hypernatric Brown Sodosol	Brown or Yellow Sodosols	Black and Brown Chromosols and Brown Sodosols .
	Catchment area (ha) above monitoring station at treatment site	1.3 ha	5.0 ha	41 ha	25 ha	14 ha	2.7 ha	259 ha
	Primary treatment	- Disc plough above the treatment gully - Fenced off gully (electric fence) - Porous check dams installed in the gully (n=6)	- Four strand cattle exclusion fence around the gully - ~30% of the gully catchment has long term cattle exclusion	- Five hillslope flow diversion banks with two drains - Fencing - Small rock revetment -	- Hillslope ripped, and seeded (creeping blue grass, V8 stylo, R.Rhodes etc) - Fencing - Total of 200 timber porous check dams installed	- Major earth works, soil treatment, rock chute structures - Fencing - Significant re-veg using mixed exotic species	- Major earth works, soil treatment, rock chute structures + earth bund, water points - Fencing pending - Significant re-veg using mixed exotic species	- Landscape rehydration - Four v-notch log rock sill structures and an earth bank to divert flows - Fencing (pending) and trough
	Grazing management in treatment paddock	Historically this site has undertaken wet season spelling and forage budgeting.	No grazing management outside of enclosure areas.	No grazing management.	Grazing Mgt Plan. Reduced stock numbers in treatment paddock.	Cattle have been excluded since works began, but future grazing proposed.	Cattle excluded during rehab. Low stock numbers and short duration graze proposed.	Exclusion for limited periods and then rotational grazing.
	No. years treatment in place	10	3	1	4	2.5	1	1
	No. years of control/treatment monitoring	3-4	3-4	4	4	3	1	1
	Total cost (\$) of on-ground works	\$3.5k	\$3.8k	~\$44k	~\$27k	\$595k	~\$840k	\$95k
Measured improvement at treatment site compared to control.	Land condition	Improved	Improved	Declined	Improved	Improved	No significant effect	No significant effect
	Vegetation (hillslope + gully)	Improved	Improved	No significant effect	Improved	Improved	Improved	Improved
	Erosion rate (headcut)	Improved	Improved	Improved*	Improved	NA	NA	NA
	Sediment concentrations	Improved	No significant effect	Improved	Improved	Improved	Improved*	No significant effect
	Sediment loads	No significant effect	No significant effect	Improved	No significant effect	Improved	NA	No significant effect
	Effectiveness value			0.95*		0.85*		

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APPENDIX A: WATER DEPTH, TURBIDITY AND SAMPLE COLLECTION FOR 2019/20 AT EACH SITE

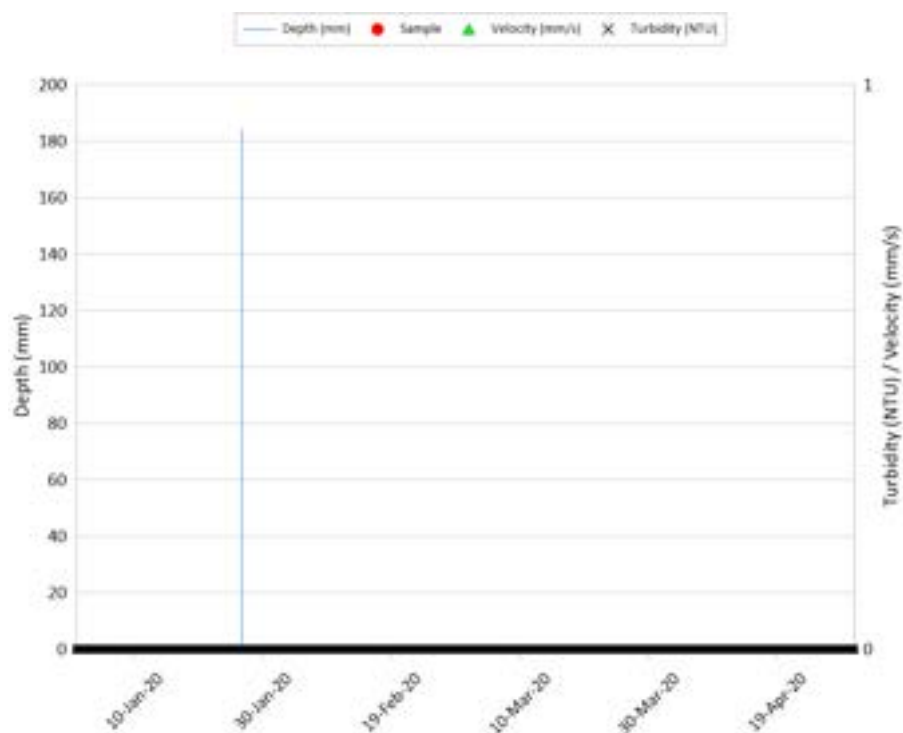


Figure 86: Virginia Park Treatment gully runoff, turbidity, velocity and sample points on the hydrograph.
Event threshold = 210 mm.



Figure 87: Virginia Park Control gully runoff, turbidity, velocity and sample points on the hydrograph.
Event threshold = 300 mm.

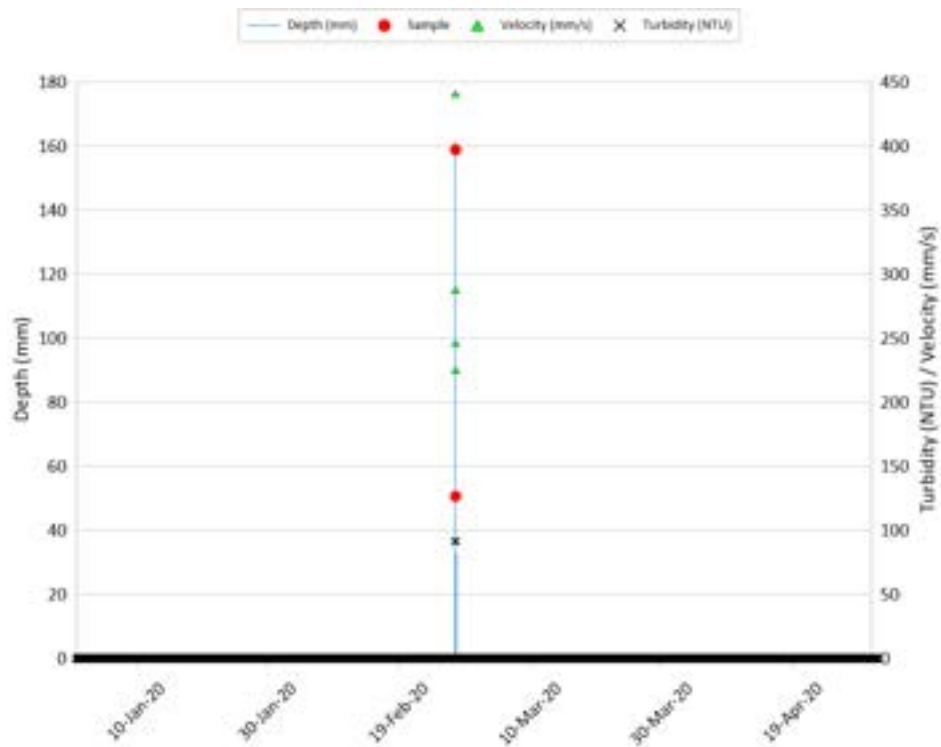


Figure 88: Meadowvale Treatment gully runoff, turbidity, velocity and sample points on the hydrograph. Event threshold = 120 mm.

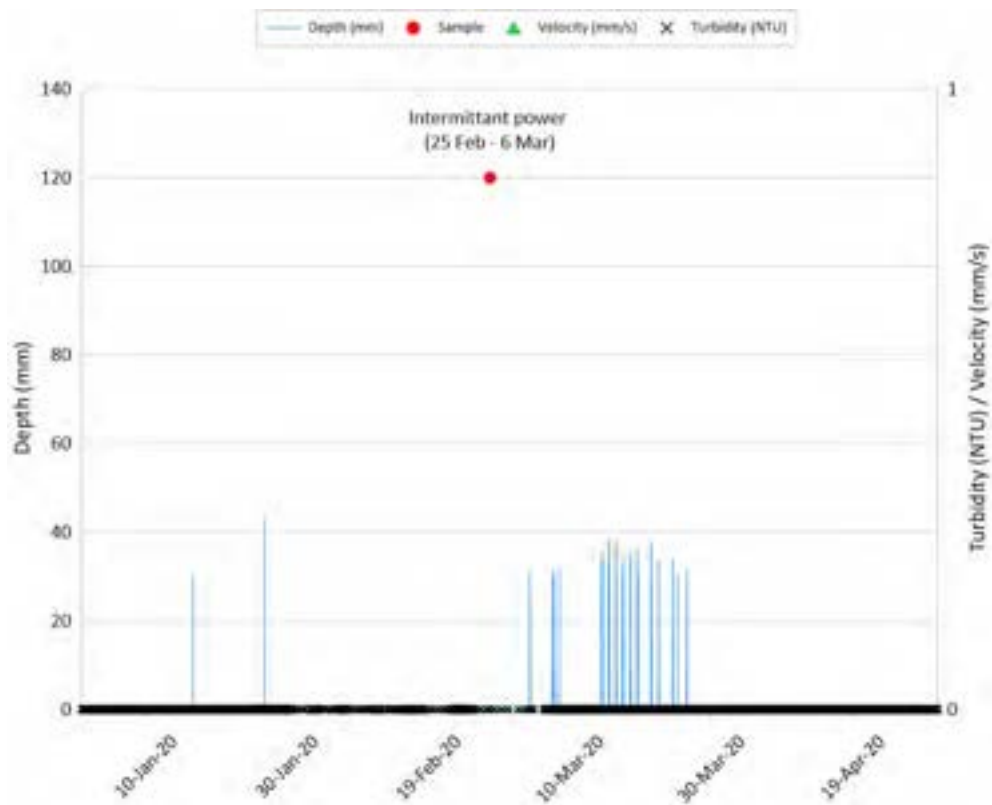


Figure 89: Meadowvale Control gully runoff, turbidity, velocity and sample points on the hydrograph. Event threshold = 120 mm.



Figure 90: Strathbogie Treatment (SBT2) gully runoff, turbidity and sample points on the hydrograph. Event threshold = 120 mm.

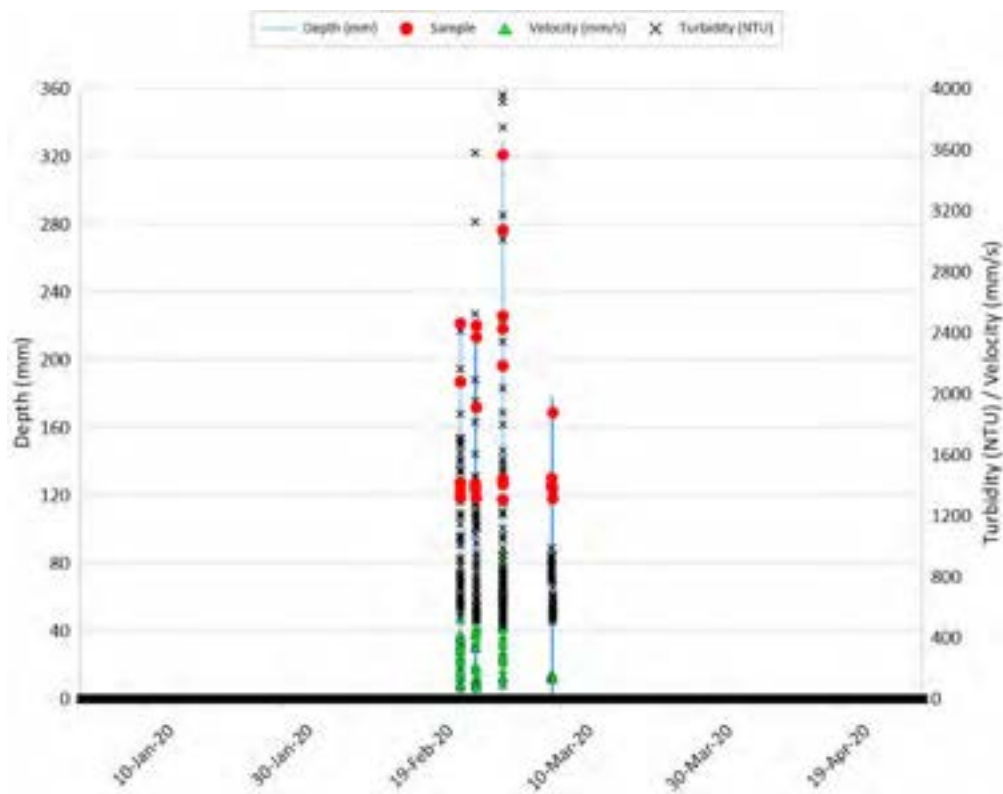


Figure 91: Strathbogie Control (SBT) gully runoff, turbidity and sample points on the hydrograph. Event threshold = 120 mm.

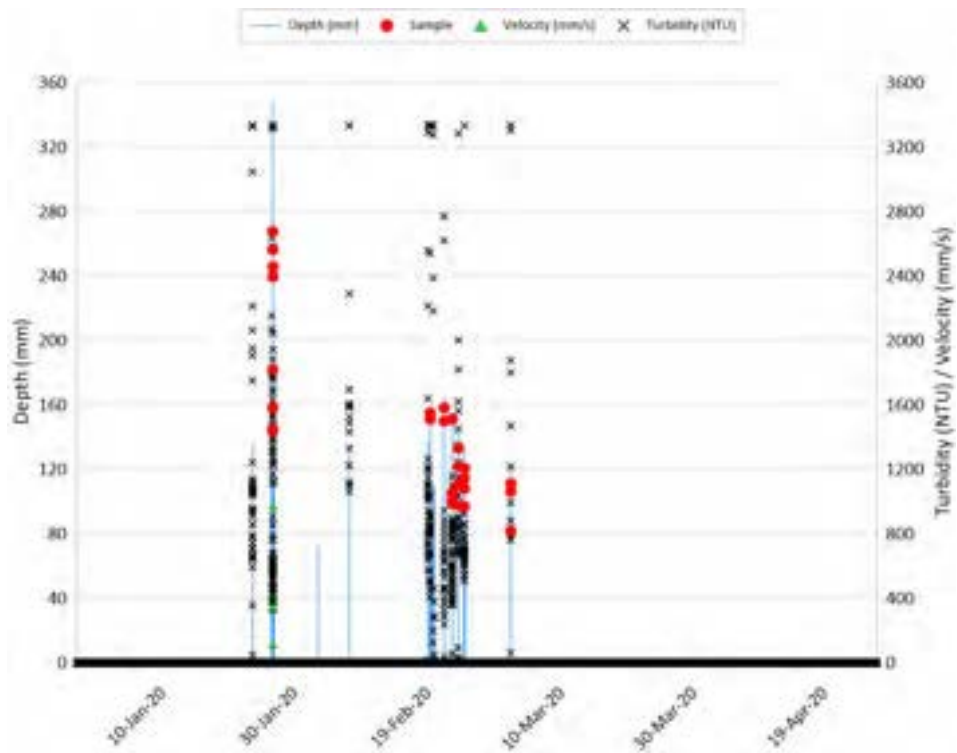


Figure 92: Minnievale Treatment gully runoff, turbidity and sample points on the hydrograph. Event threshold = 150 mm.

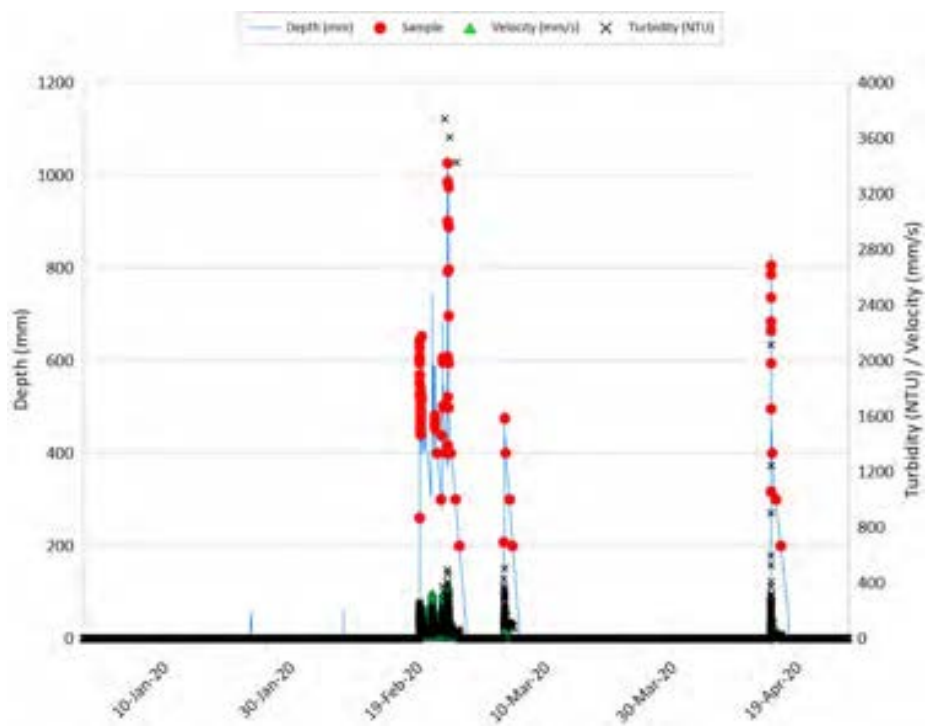


Figure 93: Minnievale Control gully runoff, turbidity, velocity and sample points on the hydrograph. Event threshold = 100 mm.

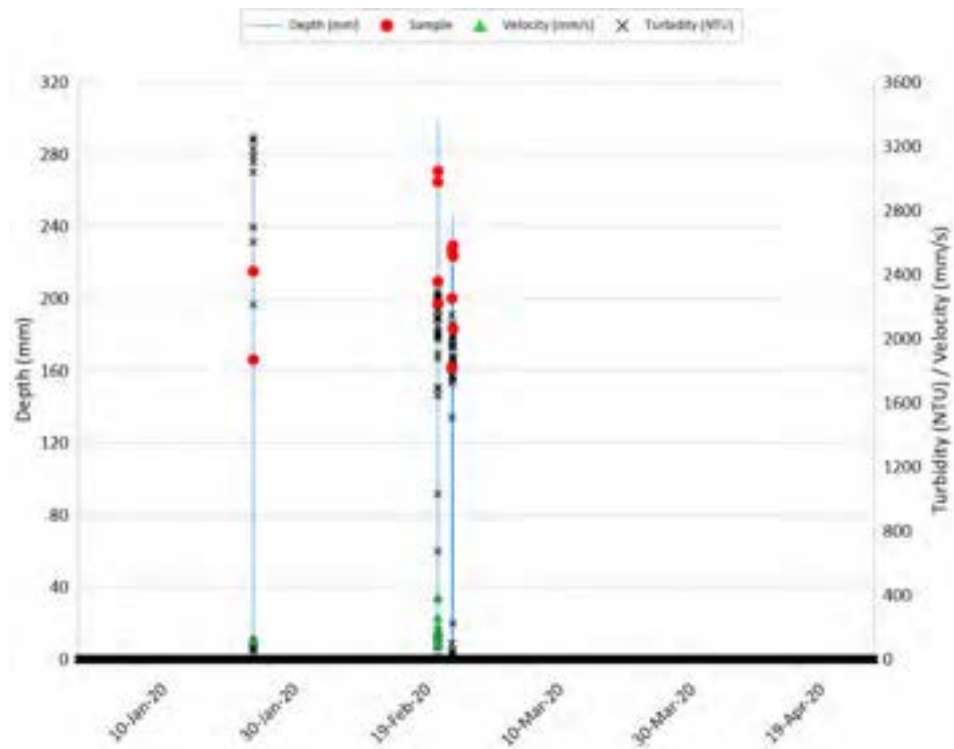


Figure 94: Mt Wickham Treatment gully runoff, turbidity and sample points on the hydrograph. Event threshold = 200 mm.

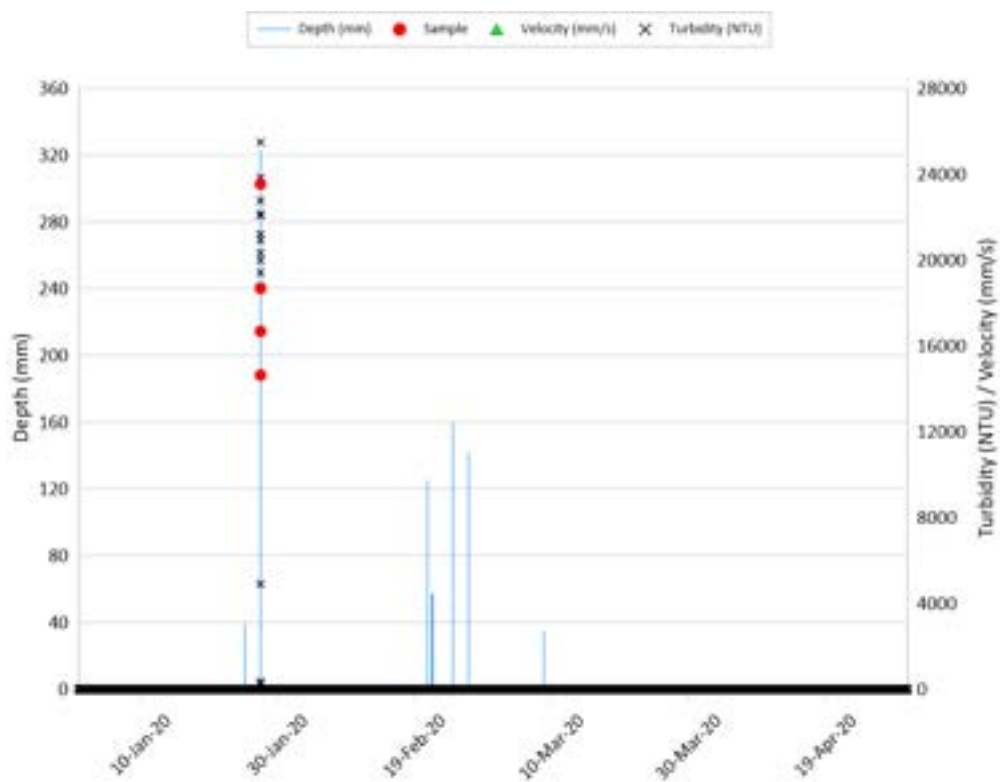


Figure 95: Mt Wickham control gully runoff, turbidity and sample points on the hydrograph. Event threshold = 200 mm.

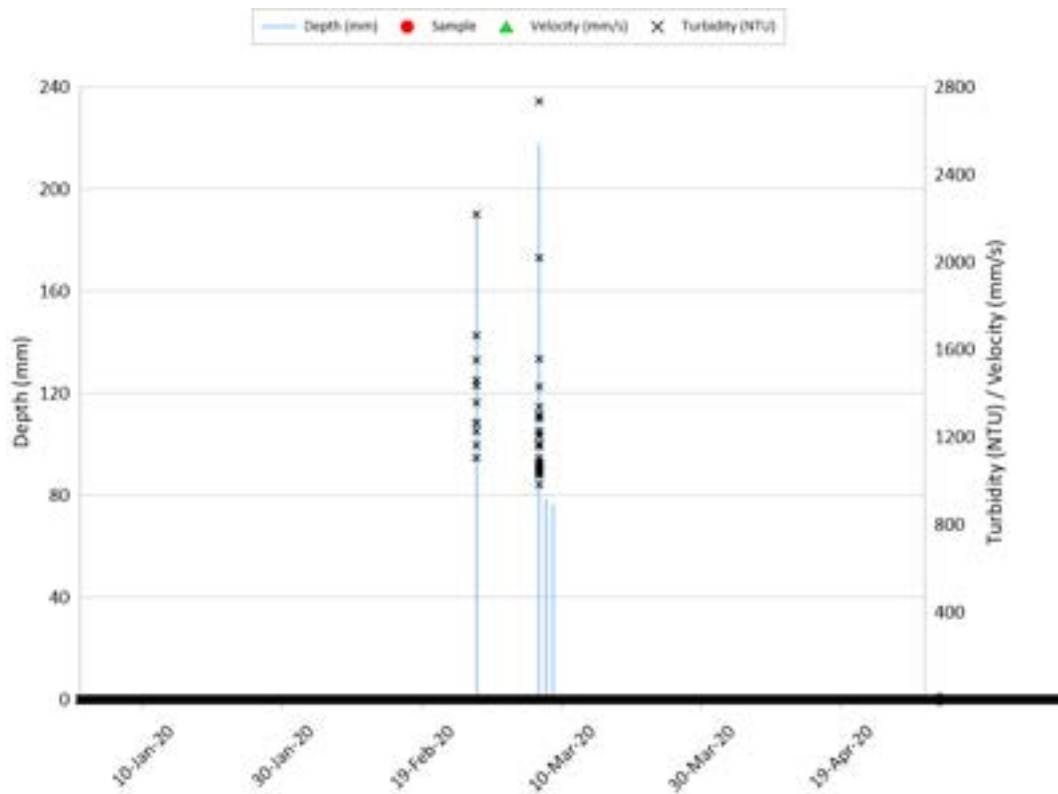


Figure 96: Glen Bowen treatment gully runoff, turbidity and sample points on the hydrograph. Event threshold = 250 mm.

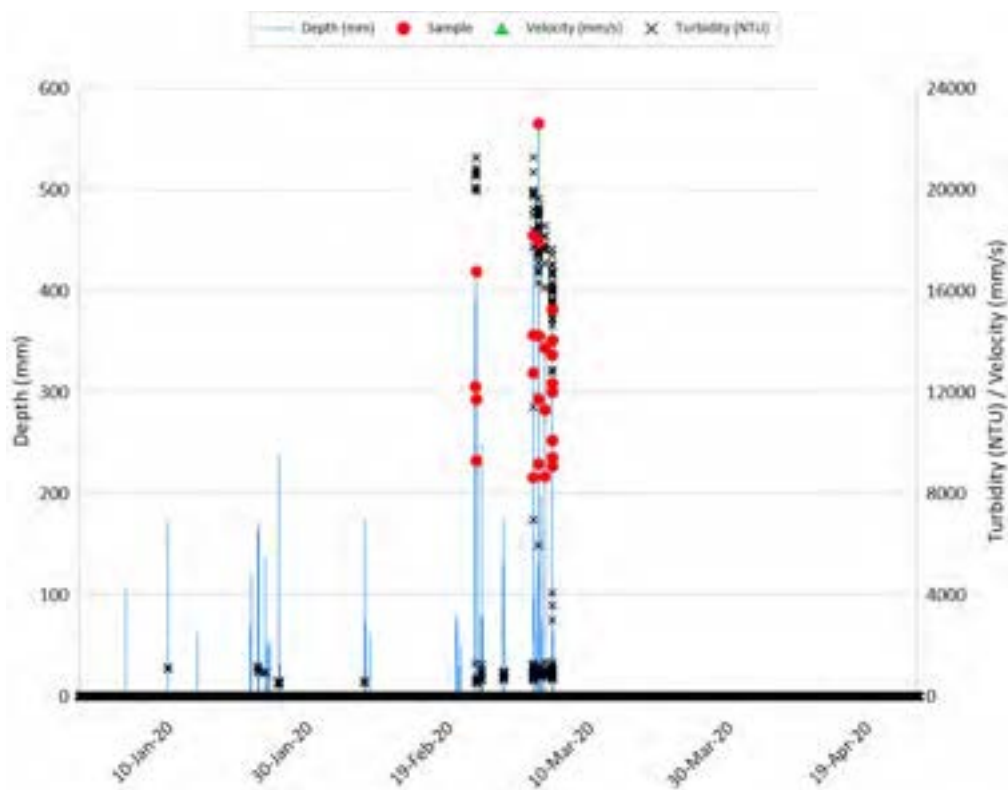


Figure 97: Glen Bowen control gully runoff, turbidity and sample points on the hydrograph. Event threshold = 200 mm.

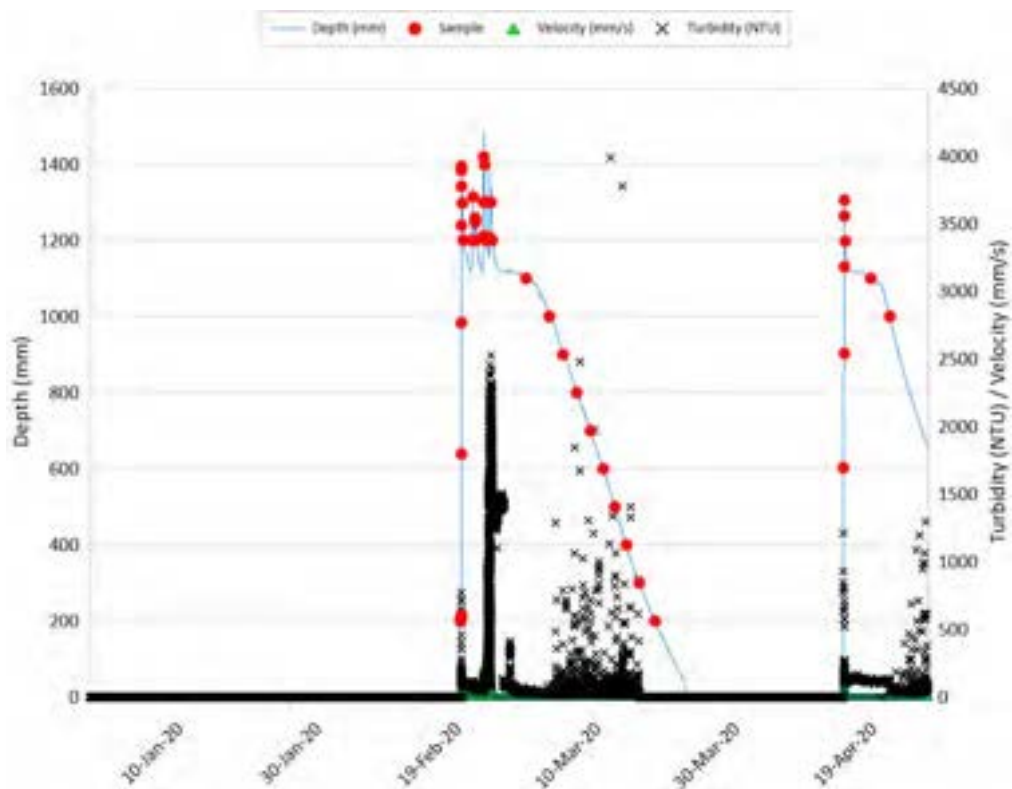


Figure 98: Mt Pleasant treatment gully runoff, turbidity and sample points on the hydrograph. Event threshold = 200 mm.

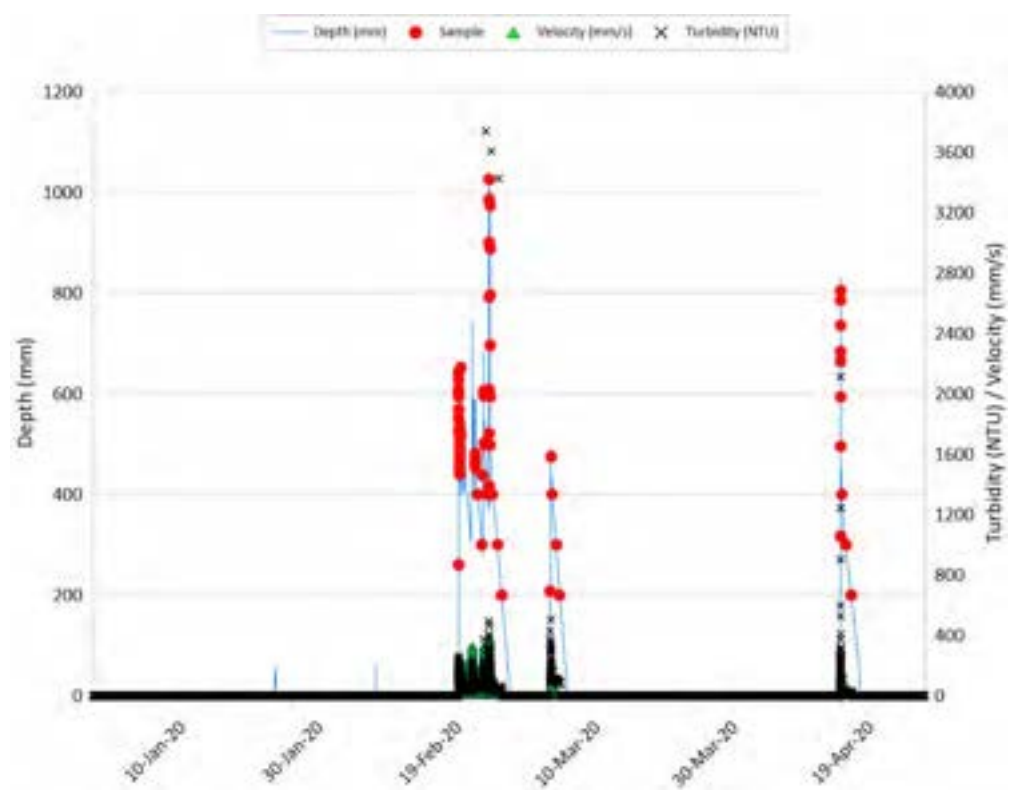


Figure 99: Mt Pleasant control gully runoff, turbidity and sample points on the hydrograph. Event threshold = 200 mm.

APPENDIX B: RAINFALL, RUNOFF AND LOADS DATA AT ALL SITES FOR ALL YEARS

Table 18: Rainfall, runoff and TSS loads for all sites for the years of measurement

Confidence colour	Discharge Issues	Loads Issues
Excellent	a - few or no velocity data	a - Very few samples
Good	b - Incomplete or noisy vel data	b - Turbidity data missing or wrong
Fair	c - Depth data for year has issues	c - Marginal to Poor turbidity relationship
Poor	d - backwatering	d - Species of constituent not well predicted by turbidity

Water Year (ending June)	Site	Catchment area (sq km)	Rainfall (mm)	Runoff (mm)	%Runoff	Total TSS Yield (t/y)	TSS Loss (t/ha)	Average TSS from timeseries (mg/L)	Discharge confidence	Loads Confidence	% of discharge with loads estimated from Turbidity
2020	Virginia Park Control	0.031	305	3.5	1.1	0.7	0.22	6439	a		
2019	Virginia Park Control	0.031	858	29.4	3.4	1.0	0.32	1087	a		88%
2018	Virginia Park Control	0.031	590	7.3	1.2	0.9	0.30	4124	a		100%
2017	Virginia Park Control	0.031	320	9.5	3.0	0.8	0.25	2628	a	b	15%
2020	Virginia Park Treatment	0.013	259	50.3	19.4	0.24	0.19	375			#N/A
2019	Virginia Park Treatment	0.013	791	254.7	32.2	2.5	1.89	743		b	100%
2018	Virginia Park Treatment	0.013	543	92.3	17.0	0.4	0.29	318			100%
2017	Virginia Park Treatment	0.013	496	138.0	27.8	1.6	1.22	885			100%
2020	Meadowvale Control	0.042	248						a,c	a,b	0%
2019	Meadowvale Control	0.042	1135	334.5	29.5	7.0	1.66	496	b	b,c	33%
2018	Meadowvale Control	0.042	749	218.6	29.2	10.8	2.57	1174	b	b,c	69%
2017	Meadowvale Control	0.042	342	29.1	8.5	1.384	0.33	1131	b	c	100%
2020	Meadowvale Treatment	0.050	350	0.3	0.1	0.0	0.01	1899			100%
2019	Meadowvale Treatment	0.050	1403	120.6	8.6	1.8	0.35	291	b		90%

2018	Meadowvale Treatment	0.050	784	73.1	9.3	4.8	0.97	1324	1335		100%
2017	Meadowvale Treatment	0.050	402	1.4	0.4	0.1	0.02	1539	1551		100%
2020	Minnie Vale Control	0.081	522	2.2	0.4	0.6	0.08	3568			95%
2019	Minnie Vale Control	0.081	1077	43.0	4.0	8.3	1.03	2392	b	b	74%
2018	Minnie Vale Control	0.081	301	9.7	3.2	3.2	0.40	4143	4556		96%
2017	Minnie Vale Control	0.081	1006	42.1	4.2	9.7	1.19	2831	b		81%
2020	Minnie Vale Treatment	0.249	506	1.7	0.3	0.7	0.03	1764			
2019	Minnie Vale Treatment	0.249	1072	70.1	6.5	11.8	0.47	676	b		100%
2018	Minnie Vale Treatment	0.249	784	11.3	1.4	5.1	0.21	1826	b		15%
2017	Minnie Vale Treatment	0.249	956	87.4	9.1	23.5	0.95	1082	b,c	b	92%
2020	SBT (Control)	0.194	504	10.7	2.1	2.8	0.14	1343			100%
2019	SBT (Control)	0.194	1384	212.0	15.3	88.3	4.55	2148	b	b	100%
2018	SBT (Control)	0.194	474	0.9	0.2	0.3	0.02	1911	b	b	0%
2017	SBT (Control)	0.194	777	71.5	9.2	26.2	1.35	1884	b	b	100%
2020	SBC-SBT2 (Treatment)	0.414	439	0.0	0.0	0.0	0.00	#N/A	b		
2019	SBC-SBT2 (Treatment)	0.414	1352	90.6	7	63.9	1.5	1704	b		100%
2018	SBC-SBT2 (Treatment)	0.414	493	0.0	0			1232	b		100%
2017	SBC-SBT2 (Treatment)	0.414	804	14.3	2	9.9	0.2	1679	b		100%
2020	Mount Wickham Control	0.030	390	1.1	0	1.7	0.56	49356			
2019	Mount Wickham Control	0.030	1175	161.7	14	159.2	52.5	32491	d	b	19%
2018	Mount Wickham Control	0.030	152	1.6	1	2.8	0.9	56163		d	100%
2020	Mount Wickham Treatment	0.141	370	1.8	0.5	1.2	0.09	5118			
2019	Mount Wickham Treatment	0.141	1117	76.1	6.8	170.8	12.08	15868			100%
2018	Mount Wickham Treatment	0.141	127	1.7	1.4	7.3	0.52	30243			100%
2020	Mount Pleasant Control	0.548	350	35.5	10.1	1.8	0.03	93	d		
2020	Mount Pleasant Treatment	2.587	440	33.6	7.7	6.1	0.02	70	d		

Table 19: Rainfall, runoff and TN loads for all sites for the years of measurement

Confidence colour	Discharge Issues	Loads Issues
Excellent	a - few or no velocity data	a - Very few samples
Good	b - Incomplete or noisy vel data	b - Turbidity data missing or wrong
Fair	c - Depth data for year has issues	c - Marginal to Poor turbidity relationship
Poor	d - backwatering	d - Species of constituent not well predicted by turbidity

Water Year (ending June)	Site	Catchment area (sq km)	Rainfall (mm)	Runoff (mm)	%Runoff	Total N Yield (kg/y)	N Loss (kg/ha)	Average N from timeseries (ug/l)	Discharge confidence	Loads Confidence	% of discharge with loads estimated from Turbidity
2020	Virginia Park Control	0.031	305	3.5	1.1	0.5	0.17	5026	a		100%
2019	Virginia Park Control	0.031	858	29.4	3	1.6	0.52	1759	a		100%
2018	Virginia Park Control	0.031	590	7.3	1	0.9	0.28	3809	a		100%
2017	Virginia Park Control	0.031	320	9.5	3	0.9	0.28	3001	a	b	100%
2020	Virginia Park Treatment	0.013	259.2	50.3	19	0.9	0.66	1322			100%
2019	Virginia Park Treatment	0.013	790.6	254.7	32	2.7	2.07	813		b	100%
2018	Virginia Park Treatment	0.013	543.0	92.3	17	1.6	1.19	1294			100%
2017	Virginia Park Treatment	0.013	496.0	138.0	28	2.9	2.19	1589			100%
2020	Meadowvale Control	0.042	248						a,c	a,b	0%
2019	Meadowvale Control	0.042	1135	334.5	29.5	18.4	3.7	1313	b	b,c	33%
2018	Meadowvale Control	0.042	749	218.6	29.2	27.6	5.5	3004	b	b,c	69%
2017	Meadowvale Control	0.042	342	29.1	8.5	5.8	1.2	4702	b	c	100%
2020	Meadowvale Treatment	0.050	350	0.3	0.1	0.0	0.01	1899			100%
2019	Meadowvale Treatment	0.050	1403	120.6	8.6	6.3	1.5	1042	b		90%
2018	Meadowvale Treatment	0.050	784	73.1	9.3	6.3	1.5	1730	1335		100%
2017	Meadowvale Treatment	0.050	402	1.4	0.4	0.1	0.0	1873	1551		100%

2020	Minnie Vale Control	0.081	522	2.2	0.4	0.6	0.08	3568			95%
2019	Minnie Vale Control	0.081	1077	43.0	4.0	13.9	1.4	6250	b	b	74%
2018	Minnie Vale Control	0.081	301	9.7	3.2	5.5	0.6	11118	4556		96%
2017	Minnie Vale Control	0.081	1006	42.1	4.2	14.0	1.4	7583	b		81%
2020	Minnie Vale Treatment	0.249	506	1.7	0.3	0.7	0.03	1764			
2019	Minnie Vale Treatment	0.249	1072	70.1	6.5	13.1	0.6	751	b		100%
2018	Minnie Vale Treatment	0.249	784	11.3	1.4	4.9	0.2	1729	b		15%
2017	Minnie Vale Treatment	0.249	956	87.4	9.1	36.3	1.7	1669	b,c	b	92%
2020	SBT (Control)	0.194	504	10.7	2.1	2.8	0.14	1343			100%
2019	SBT (Control)	0.194	1384	212.0	15.3	23.2	1.3	1715	b	b	100%
2018	SBT (Control)	0.194	474	0.9	0.2				b	b	0%
2017	SBT (Control)	0.194	777	71.5	9.2	11.5	0.7	1001	b	b	100%
2020	SBC-SBT2 (Treatment)	0.414	439	0.0	0.0	0.0	0.00	#N/A	b		
2019	SBC-SBT2 (Treatment)	0.414	1352	90.6	7	82.2	2.2	2193	b		100%
2018	SBC-SBT2 (Treatment)	0.414	493	0.0	0	0.0	0.0	1592	b		100%
2017	SBC-SBT2 (Treatment)	0.414	804	14.3	2	12.8	0.3	2162	b		100%
2020	Mount Wickham Control	0.030	390	1.1	0	1.7	0.56	49356			
2019	Mount Wickham Control	0.030	1175	161.7	14	26.4	8.7	5384	d	b	19%
2018	Mount Wickham Control	0.030	152	1.6	1	0.5	0.2	11156		d	100%
2020	Mount Wickham Treatment	0.141	370	1.8	0.5	1.2	0.09	5118			
2019	Mount Wickham Treatment	0.141	1117	76.1	6.8	66.3	4.7	6162			100%
2018	Mount Wickham Treatment	0.141	127	1.7	1.4	2.3	0.2	9303			100%
2020	Mount Pleasant Control	0.548	350	35.5	10.1	#N/A	#N/A	#N/A	d		
2020	Mount Pleasant Treatment	2.587	440	33.6	7.7	#N/A	#N/A	#N/A	d		

APPENDIX C: SPECIES MIX USED AT ALLUVIAL SITES

Table 20: Re-vegetation species mix used at Mt Wickham (Alluvium and Verterra, 2018)

Scientific name	Common name	Treatment	Application rate (kg / ha) ¹	Area (ha)	Total seed weight
Canopy species					
<i>Eucalyptus platyphylla</i>	Poplar Gum	Nil	20g	2.2	50g
<i>Eucalyptus tereticornis</i>	Forest red gum	Nil	20g	2.2	50g
<i>Eucalyptus crebra</i>	Narrowleaf ironbark	Nil	20g	2.2	50g
<i>Corymbia clarksoniana</i>	Clarkson's Bloodwood	Nil	100g	2.2	200g
<i>Corymbia intermedia</i>	Pink bloodwood	Nil	100g	2.2	200g
Pasture grasses					
<i>Cenchrus ciliaris</i>	Gayndah Buffel Grass	Coated	4kg	13.2	52.8kg
<i>Urochloa mosambicensis</i>	Sabi Grass	Coated	4kg	13.2	52.8kg
<i>Bothriochloa pertusa</i>	Indian blue couch	Coated	4kg	13.2	52.8kg
<i>Bothriochloa insculpta</i>	Creeping blue grass	Coated	4kg	13.2	52.8kg
<i>Chloris gayana</i>	Katambora Rhodes	Coated	4kg	13.2	52.8kg
Legumes					
<i>Stylosanthes scabra</i>	Seca Stylo	Coated	4kg	13.2	52.8kg
<i>Desmanthus propargis</i>	Propargis	Coated	4kg	13.2	52.8kg
Cover crops					
<i>Panicum miliaceum</i>	White French Millet	Bare	10kg	13.2	132kg
Total			38.14	13.2	

Table 21: Re-vegetation species mix used at Glen Bowen (Neilly Group Engineering, 2020)

Treatments carried out included:
• Gypsum – 34t/ha
• Mill mud – 70m ³
• Drill seeding – 70kg/ha
• Hay cover – 4,000m ²
• Bagasse cover – 6,600m ²
• Matting – 2,000m ²
• Hydromulching of the remaining reshaped and disturbed footprint (including seeding where drill seeding was not possible)
The seed used for revegetation works was the following:
Primary Species (Cover Crop)
• Japanese Millet
Secondary Species
• Callide Rhodes
• Gatton Panic
• Milgarra Butterfly
• Garnet Burgundy Bean
• Presto Burgundy Bean
• Mega stylo
• Ray Desmanthus
• Thiram Filmcoat
• Red Caloona Cowpeas
• Chicory
• Summer Green Forage Maize Opticote
• USA Buffle
• Bird Seed

APPENDIX D: JOURNAL PUBLICATIONS ASSOCIATED WITH THIS PROJECT

Publications attributed to the NESP TWQ Hub listed below. **Blue** = large NESP funding contribution, **Green** = minor NESP funding contribution. NESP TWQ Hub Project 2.1.4 and 5.9 team members noted in **bold**. Papers available as open access in italics.

1. Jarihani, B., Sidle, R.C., **Bartley, R.**, Roth, C.H. and **Wilkinson, S.N.**, 2017. Characterisation of Hydrological Response to Rainfall at Multi Spatio-Temporal Scales in Savannas of Semi-Arid Australia. *Water*, 9(7), 10.3390/w9070540.
2. Koci, J., Leon, J., Jarihani, B., Sidle, R., **Wilkinson, S.** and **Bartley, R.**, 2017. Assessment of UAV and ground-based Structure from Motion with Multi-View Stereo photogrammetry in a gullied savanna catchment. *International Journal of Geo-Information.*, 6(328), doi:10.3390/ijgi6110328.
3. Kuhnert, P.M., Pagendam, D.E., **Bartley, R.**, Gladish, D.W., Lewis, S.E. and Bainbridge, Z.T., 2018. Making management decisions in the face of uncertainty: a case study using the Burdekin catchment in the Great Barrier Reef. *Marine and Freshwater Research*, <https://doi.org/10.1071/MF17237>.
4. **Wilkinson, S.N.**, **Kinsey-Henderson, A.E.**, **Hawdon, A.A.**, Hairsine, P.B., **Bartley, R.** and **Baker, B.**, 2018. Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. *Earth Surface Processes and Landforms*, 10.1002/esp.4339.
5. Bainbridge, Z., Lewis, S., **Bartley, R.**, Fabricius, K., Collier, C., Waterhouse, J., Garzon-Garcia, A., Robson, B., Burton, J., Wenger, A. and Brodie, J., 2018. Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. *Marine Pollution Bulletin*, 135: p1205-1220, 10.1016/j.marpolbul.2018.08.002.
6. Judy, J.D., Kirby, J.K., Farrell, M., McLaughlin, M.J., **Wilkinson, S.N.**, **Bartley, R.** and Bertsch, P.M., 2018. Colloidal nitrogen is an important and highly-mobile form of nitrogen discharging into the Great Barrier Reef lagoon. *Scientific Reports*, 8 (Article number 12854), 10.1038/s41598-018-31115-z.
7. Koci, J., Sidle, R.C., **Kinsey-Henderson, A.E.**, **Bartley, R.**, **Wilkinson, S.N.**, **Hawdon, A.A.**, Jarihani, B., Roth, C.H. and Hogarth, L., 2020. Effect of reduced grazing pressure on sediment and nutrient yields in savanna rangeland streams draining to the Great Barrier Reef. *Journal of Hydrology*, 582: 124520, <https://doi.org/10.1016/j.jhydrol.2019.124520>.
8. Walker, S.J., **Wilkinson, S.N.**, van Dijk, A.I.J.M. and Hairsine, P.B., 2020. A multi-resolution method to map and identify locations of future gully and channel incision. *Geomorphology*, 358: 107115, <https://doi.org/10.1016/j.geomorph.2020.107115>.
9. **Bartley, R.**, Poesen, J., **Wilkinson, S.** and Vanmaercke, M., 2020. A review of the magnitude and response times for sediment yield reductions following the rehabilitation of gullied landscapes. *Earth Surface Processes and Landforms*, 10.1002/esp.4963.
10. Koci, J., **Wilkinson, S.**, **Henderson, A.**, **Hawdon, A.**, **Bartley, R.** and **Goodwin, N.**, In Press. Rehabilitation effects on gully sediment yields and vegetation in a savanna rangeland. *Earth Surface Processes and Landforms (Special Issue on Gully Erosion)*.
11. Vanmaercke, M., Panagos, P., Vanwalleggem, T., Hayas, A., Foerster, S., Borrelli, P., Rossi, M., Torri, D., Casali, J., Borselli, L., Vigiak, O., Maerker, M., Haregeweyn, N., De Geeter, S., Zgłobicki, W., Bielders, C., Cerdà, A., Conoscenti, C., de Figueiredo, T., Evans, B., Golosov, V., Ionita, I., Karydas, C., Kertész, A., Krása, J., Le Bouteiller, C., Radoane, M., Ristić, R., Rousseva, S., Stankoviansky, M., Stolte, J., Stolz, C., **Bartley, R.**, **Wilkinson, S.**, Jarihani, B. and Poesen, P., In Review. Measuring, modelling and managing gully erosion at regional to continental scales: a state of the art. *Earth-Science Reviews* (invited).

