

Quantifying the effectiveness of gully remediation on off-site water quality: preliminary results from demonstration sites in the Burdekin catchment

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Supported by the Australian Government's
National Environmental Science Programme
Project 2.1.4 Demonstration and evaluation of gully remediation on downstream water quality
and agricultural production in GBR rangelands

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This report should be cited as:

Bartley, R., Hawdon, A., Henderson, A., Wilkinson, S., Goodwin, N., Abbott, B., Baker, B., Matthews, M., Boadle, D., Telfer, D., Smith, B., Jarihani, B. and Burkin, G., 2017. *Quantifying the effectiveness of gully remediation on off-site water quality: preliminary results from demonstration sites in the Burdekin catchment*. Project 2.1.4. Report to the National Environmental Science Programme. Reef and Rainforest Research Centre Limited, Cairns (76pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Programme (NESP) Tropical Water Quality (TWQ) Hub.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Programme and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESPTWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

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Dan Tindall has provided input and support for the terrain analysis component of the report.

CONTENTS

FIGURES	II
TABLES.....	IV
ACKNOWLEDGMENTS.....	V
EXECUTIVE SUMMARY	VI
1 INTRODUCTION	8
2 EXPERIMENTAL DESIGN.....	10
2.1 GENERAL APPROACH.....	10
2.2 GULLY REMEDIATION OPTIONS	11
3 STUDY LOCATION	15
3.1 THE BURDEKIN CATCHMENT	15
3.2 TRIAL SITES	15
3.3 TREATMENTS APPLIED AT EACH SITE	19
4 METHODS.....	20
4.1 VEGETATION AND PASTURE METRICS	20
4.2 GULLY EROSION	20
4.2.1 <i>Historical rates of gully erosion: historical air photo interpretation</i>	20
4.2.1 <i>Current rates of gully erosion: terrain analysis</i>	21
4.3 RUNOFF	22
4.4 WATER QUALITY AND PARTICLE SIZE	23
5 RESULTS	25
5.1 TREATMENT LOCATION AND SURVIVAL	25
5.1.1 <i>Virginia Park</i>	25
5.1.2 <i>Meadowvale</i>	28
5.1.3 <i>Strathbogie</i>	30
5.1.4 <i>Minnievale</i>	32
5.2 LANDSCAPE CONDITION	35
5.3 VEGETATION AND PASTURE METRICS	36
5.3.1 <i>Hillslope</i>	36
5.3.2 <i>Gullies</i>	36
5.4 GULLY EROSION RATE	38
5.4.1 <i>Historical rates of gully erosion: historical air photo results</i>	38
5.4.2 <i>Current rates of gully erosion: terrain analysis</i>	41
5.5 RAINFALL, RUNOFF, WATER QUALITY AND PARTICLE SIZE.....	50
6 DISCUSSION	59
7 CONCLUSION AND AREAS OF FURTHER WORK.....	61
8 REFERENCES	62
9 APPENDIX A: FREQUENCY AND BIOMASS FUNCTIONAL GROUP DATA	67
10 APPENDIX A: WATER DEPTH, TURBIDITY AND SAMPLE HISTORY FOR EACH SITE.....	68

Figures

Figure 1: The adaptive monitoring framework implemented in this study (Lindenmayer and Likens, 2009).....	10
Figure 2: Conceptual model of the outcome of various treatment options within a gully (Wilkinson et al., 2015a). The green triangles represent within gully trapping structures such as porous check dams (PCD's).	11
Figure 3: Underlying geology at each of the trial properties (Source: GeoScience Australia)	17
Figure 4: Underlying soil type at each of the properties (Source: Atlas of Australian Soils).....	17
Figure 5: Rainfall distribution for each of the properties (Source: SILO 5 km grid)	18
Figure 6: Total ground cover (2015) for each of the properties (Source: Queensland Government fractional ground cover product)	18
Figure 7: (A) Example of a treatment gully set up and (B) and example of a control gully set up including two rising stage samplers.....	23
Figure 8: The treatment (left) and control (right) instrumented gullies at each property. (A) Virginia Park (B) Meadowvale (C) Strathbogie and (D) Minnie Vale	24
Figure 9: 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.	26
Figure 10: Changes in the vegetation adjacent to a check-dam structure (#1) in the Treatment gully (upstream is to the right) (adapted from Wilkinson et al., 2015b).	27
Figure 11: Location of Meadowvale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.....	29
Figure 12: Location of Strathbogie site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.....	31
Figure 13: Location of Minnievale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.....	33
Figure 14: The Minnievale site showing (A) in-tact stick trap in a side gully; (B) partial failure of a stick trap that has had been outflanked on one side (C) complete failure of a coir log and (D) and partial failure of a coir log in the main gully (Photos: Greening Australia).	34
Figure 15: Relationship between % cover and biomass (kg/ha) between the gully wall, gully floor and hillslopes for the post-wet season data. Minnievale not included due to site access.....	38
Figure 16: The cumulative rates of gully length for the control and treatment gullies at each site for the available historical photo record.....	40
Figure 17: Relationship between upslope catchment area (ha) and TLS measured erosion rate (t/m). Note that Minnievale Treatment gully was not included on the graph as it was net deposition and Meadowvale data are not available	42
Figure 18: Net sediment movement (tonnes per metre surveyed, t/m) for each of the gully sites. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The Virginia Park data is for 2015- 2017. The other sites represent 2016/17 only.....	42
Figure 19: The change in deposition and erosion (m ³) for the Virginia Park Control gully in 2016-17 and the treatment gully over 2 consecutive wet seasons (2015-16 and 2016-17).....	43
Figure 20: Virginia Park treatment: (a) 2015 DEM, (b) 2016 DEM, (c) 2017 DEM, (d) 2015 and 2016 DoD, (e) 2016 and 2017 DoD, (f) 2015 and 2017 DoD.	45
Figure 21: Virginia Park control: (a) 2016 DEM, (b) 2017 DEM and (c) DoD.	46

Figure 22: Meadowvale: (a) treatment and (b) control.	46
Figure 23: Strathbogie treatment: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.....	47
Figure 24: Strathbogie control: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.....	48
Figure 25: Minnievale treatment: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.....	49
Figure 26: Minnievale control: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.	49
Figure 27: Treatment gully at Virginia Park before (left) and during (middle) an event and at the end of reporting period (April 2017)	52
Figure 28: Treatment gully at Meadowvale before (left) and during (middle) an event and at the end of reporting period (April 2017)	52
Figure 29: Treatment gully at Strathbogie before (left) and during (middle) an event and at the end of reporting period (April 2017)	53
Figure 30: Treatment gully at Minnievale before (left) and during (middle) an event and at the end of reporting period (April 2017)	53
Figure 31: TSS concentration at each site for the Control and Treatment gullies. Note that only Virginia Park and Minnievale have active treatments in place by Nov 2016.	54
Figure 32: TN concentration at each site for the Control and Treatment gullies. Note that only Virginia Park and Minnievale have active treatments in place by Nov 2016.	55
Figure 33: Particle size of suspended sediment collected the Treatment Gully at each of the four sites over the 2016/17 wet season.....	56
Figure 34: The relationship between TSS (mg/l) and particle size (μm) from samples collected during flow events in the treatment gullies	56
Figure 35: The relationship between TSS (mg/l) and TN (mg/l) for all samples collected during flow events across all eight gullies. Note two extreme outlier values were removed.	57
Figure 36: Relationship between upslope catchment area (km^2) and the maximum measured TSS value (mg/l).	57
Figure 37: Virginia Park Treatment gully (top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	68
Figure 38: Virginia Park Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	69
Figure 39: Meadowvale Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	70
Figure 40: Meadowvale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	71
Figure 41: Strathbogie Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	72
Figure 42: Strathbogie Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	73
Figure 43: Minnievale Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	74
Figure 44: Minnievale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	75
Figure 45: Minnievale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.	76

Tables

Table 1: Global gully erosion remediation studies with measured sediment yield responses, building on the table presented in Wilkinson et al., (2015a)	12
Table 2: The range of gully remediation treatment options, expected outcomes and measurement metrics. The number of v's represents the relative magnitude of expected response. The text in blue highlights legacy or ancillary data not currently covered within the NESP project and green is not reported this year	14
Table 3: Description of the four study sites (Virginia Park, Meadowvale, Strathbogie and Minnievale). Note that the gully density data was based on Tindall et al., (2014) except Minnievale (**) which was based on the NLWRA (2001) data.	16
Table 4: Description of treatment history at each site.....	19
Table 5: Response of within gully structures at the Minnievale site following the first event of the wet season (prior to Cyclone Debbie).	34
Table 6: A, B, C, D Land condition classification for each of the properties in this study	35
Table 7: Amount of cover on the hillslope at the end of the wet season. Standard deviation shown in parentheses. Where the text is highlighted in blue/bold, there is a significant difference between the Treatment and Control gullies.....	37
Table 8: Amount of cover on the gully walls and floor at the end of the wet season (April 2017). Standard deviation shown in parentheses. Where the text is highlighted in blue/bold, there is a significant difference between the Treatment and Control gullies.....	37
Table 9: Rates of recent gully extension estimated by air photo interpretation.	39
Table 10: Gully volumetric change results using the RIEGL Terrestrial laser scanner. The negative values represent net deposition and positive values represent net erosion. The U_{crit} threshold for defining erosion/deposition was set as 0.1 m at all sites. Bulk density of sediment is assumed to be 1.5 t/m ³	44
Table 11: Summary of rainfall, runoff, water quality concentration and loads for each of the sites for the 2016/17 wet season. The Minnievale access road was out of action after the cyclone and the post wet vegetation sampling will be done in June.	58
Table 12: Frequency % and biomass represented by vegetation functional groups	67

Acknowledgments

We would like to thank NESP, CSIRO and Queensland State Government (DEHP and DSITI) for funding this research. We would also like to thank the Property owners for allowing access to their properties and involvement in the projects. Thankyou to Rob, Sue and Matt Bennetto at Virginia Park, John Ramsay and Family at Meadowvale, Darren Watts and Family at Strathbogie, and Barney and Juanita Gordon at Minnievale. Thankyou to Max Magee, a University of Queensland intern student for undertaking the historical aerial photo interpretation. Thankyou also to Dr Christian Roth for reviewing an earlier version of this report.

EXECUTIVE SUMMARY

Gully erosion contributes ~40% of the excess soil erosion 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 understood. Gully erosion is a complex process influenced by soil properties, terrain, surface and sub-surface runoff 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.

This study was designed to evaluate the effectiveness of a range of remediation options for the smaller more ubiquitous hillslope gullies found within rangeland systems of the Burdekin basin. Sediment source tracing based on geochemistry and clay mineralogy indicates that these features make a large contribution to river sediment loads. A total of four properties are being used for this project, with two properties located in the Upper Burdekin, one in the Bogie, and one in the Don River catchment. Paired gully sites (treatment and control) were identified at each property. Due to the risk associated with gully remediation, this study is focused on relatively low cost remediation approaches. The remediation options implemented on the treatment gullies include fencing, stock exclusion, sediment trapping structures (within the gullies) and hillslope vegetation management. Of the four properties being monitored, only two had active treatments installed prior to the 2016/17 wet season. Of the two sites with active remediation one site had seven years of treatment data.

To quantify the effectiveness of the various treatment options a suite of monitoring equipment and sites have been set up on both the treatment and control gully at each location. These 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 3D laser scanning of terrain to estimate changes in erosion and deposition, and (iii) water quality and quantity monitoring equipment that allows the measurement of water stage, runoff, turbidity, sediment and nutrient concentration and particle size.

This report presents the results of the first 18 months of the project which includes the initial site setup and monitoring results from the first wet season. This report focuses on quantifying the baseline condition so that the 'effectiveness' can be quantified following remediation. This report does not focus on the costs associated with the remediation; that information will be included in next year's report. It is important to note that two sites had well below average rainfall, and at the other two sites ~30 - 52% of the rainfall received was associated during the Cyclone Debbie event. The hydrological reporting period presented is November 1st 2016 until April 30th, 2017. The May 2017 event was not included in this reporting period. The key results so far suggest that:

- All of the properties are in C or D class land condition and the pasture species are dominated by the exotic perennial grass Indian couch, forbs, and/or exotic legumes. Indian couch is known to have relatively poor infiltration properties compared to native perennial species.
- As a treatment option, stick traps constructed from small logs, have a greater survival success than coir logs, particularly in gullies with larger catchment areas (area > 10 ha).
- Porous check dams (or PCD's), in combination with stock exclusion fencing, appear to have a statistically significant impact on the amount of vegetation (% cover and biomass) that stabilises gullies floors. This, in turn, appears to have improved the water quality within the treated gullies, although several more years of average to above average rainfall is required to validate this finding.
- The gully headcut extension during this wet season, as measured using the RIEGL Terrestrial Laser Scanner (TLS), ranged from 0.46 m at Virginia Park, to 18.1 m at Strathbogie. The amount of sediment eroded from the gullies ranges from 0.02 tonnes per metres (t/m) to 0.77 t/m, and the Minnievale site experienced net deposition over the 2016/17 wet season. This is possibly related to hillslope remediation works on the hillslope above the gully.

- There is a strong relationship between the catchment area above the gully and erosion rate (t/m) for all erosional sites ($r^2 = 0.92$). Catchment area is a surrogate for runoff or energy. This relationship is not as strong between gully catchment area and TSS concentration ($r^2 = 0.36$).
- The total suspended sediment (TSS) concentrations vary considerably between sites with the highest mean and absolute concentrations being measured at Strathbogie at $\sim 4570 \text{ mg L}^{-1}$ and $10,000 \text{ mg L}^{-1}$, respectively. This gully intersects vertosol and chromosol soil units.
- The total nitrogen (TN) concentrations follow a similar pattern to TSS when comparing the control and treatment sites. However, there are some differences, as the TN concentrations seem to be sensitive to the process and handling times (including ant nests in the samplers!), and more data is required to confirm patterns at any one site.
- Across all of the gullies, there is a reasonably strong relationship between TSS and TN concentration ($r^2 = 0.76$), however, there is no relationship between TSS and sediment particle size. This is not that surprising given that soil type is a strong driver of particle size.
- Three out of four sites had a median sediment particle size $< \sim 10 \mu\text{m}$ which suggests that given the right flow conditions, sediments from these gullies may make it to the marine environment.
- **These preliminary findings suggest that gullies located on black (vertosol) soils warrant further investigation and attention. These soil types are also known to be a major sediment and particulate nutrient source based on sediment source tracing.**

As the treatments are not yet in place at all of the study sites, and to date, there has been only one wet season experiencing relatively low rainfall, we cannot definitely say which treatments are likely to be more cost-effective than any other at this stage of the project. A climate cycle in these tropical rangeland environments can be ~ 10 years, and therefore several more years of data will be required to provide statistically defensible estimates of the effectiveness of these treatments. The next year of this project will be focusing on:

- Installing velocity sensors to help improve our estimates of runoff volume at each of the gully sites;
- Deriving a full estimate of the costs associated with the implementation of the remediation at each of the sites and understanding how the gully remediation project fits with other aspects of farm management;
- Calculating the initial cost-effectiveness estimates at all of the sites. These estimates will be used to help inform the Reef Trust investments;
- Developing methods for scaling up the results from these four sites to additional gullied landscapes within the Burdekin (and Fitzroy) regions.

1 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 (Bartley et al., 2007; Wilkinson et al., In Review). Both gully forms are likely to be a major anthropogenic sediment source in GBR catchments. 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 remediation options, with the longer term goal of reducing sediment and particulate nutrient delivery to the GBR.

As part of the Reef Trust 2 and 4 programs, the Australian Government is investing in gully remediation projects in focused gully prone areas of the GBR catchments (Wilkinson et al., 2016). Gully erosion has been a problem across many parts of the world since 750 AD (Doolittle, 1985) and gully remediation, 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 remediation 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 remediation approaches in the tropical catchments draining to the GBR.

Hundreds of millions of dollars are spent each year on catchment and stream remediation 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 remediation 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.

The overarching aims of this project are to (i) provide new knowledge about the links between gully remediation, ground cover, erosion rates and water quality and (ii) to help quantify the cost-effectiveness of gully remediation strategies used in the Reef Trust 2 gully investments. The type of remediation approaches used in this program are outlined in Wilkinson et al., (2015c) and are primarily based on using vegetation and targeted low cost engineering structures. These structures are used to reduce flow velocities, facilitate sediment and seed trapping, and reduce sediment yield from gully systems. This program is focused on using a combination of vegetation management and structural control approaches 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).

To provide evidence of the relative effectiveness of these projects to stakeholders and the public, the specific aims of this project are to investigate the benefit of remediation on (i) physical processes including runoff generation, vegetation growth, sediment trapping, (ii) the concentration and loads of sediments and nutrients leaving the treated area compared to an untreated control site (iii) the cost-effectiveness of the treatment options and (iv) the influence of the treatment (including paddock subdivision and grazing management) on agricultural production at the paddock scale. This project will focus on linear or hillslope gullies only. A related NESP project (Project 2.1.10) will investigate the effectiveness of remediation on the larger alluvial gully types.

This report represents the primary deliverable for NESP Project 2.1.4 June 2017 milestone. This report will focus on our progress towards component (i) and (ii) outlined above, which are addressing the 'effectiveness' component of the cost-effectiveness metric. The main aim of this report is to present the results of the first year (or wet season) of the project. The results with focus on:

- (i) A presentation of the experimental design and remediation options;
- (ii) The baseline condition at all sites in terms of:
 - a. Vegetation and pasture metrics
 - b. Historical gully erosion rates
 - c. Pre-treatment terrain analysis
- (iii) Post wet season changes, with respect to:
 - a. The treatment survival
 - b. Vegetation and pasture changes
 - c. Long and short term gully erosion rates at each site
 - d. Rainfall, runoff, water quality and particle size

This study is located in the Upper Burdekin and Bogie and Don sub-catchments of the larger Burdekin catchment. These areas are known to be contributing higher anthropogenic sediment yields than other areas (Bainbridge et al., 2014; Bartley et al., 2015) and the Burdekin is the largest source of sediment to the GBR lagoon (Kroon et al., 2012). The Upper Burdekin sites (Virginia Park and Meadowvale) were chosen as they will capitalize on previous research investments looking at rangeland management and water quality response (Hawdon et al., 2008; Wilkinson et al., 2013; Bartley et al., 2014; Wilkinson et al., 2014). The Bogie (Strathbogie) and Don (Minnievale) sites are Reef Trust 2 partnership projects. The project includes partners from Queensland Government, NQ Dry Tropics Regional Body and Greening Australia.

2 EXPERIMENTAL DESIGN

2.1 General approach

In this study, we use an adaptive monitoring framework similar to that outlined in Figure 1. The key question that we are asking is, 'is there a measurable improvement in the erosion and water quality leaving remediated gully sites compared to sites left un-treated?' The monitoring approach used is a modified BACI (before, after, control, impact) design (Green, 1979). It is a modified design as we do not have the luxury of measuring before conditions at all of the sites within a three year funding period. Without the before condition data we will have less statistical power to measure the effect of a change that can be directly attributed to the 'treatment'. However, the use of a control site will provide an estimate of the variability that would likely occur at the site prior to remediation. In this case, the standard error or deviation (SE or SD) of the variability of the control site will need to be exceeded before we can attribute any of the change to the treatment. It is acknowledged that BACI designs with multiple control sites and temporal replication are more robust (Underwood, 1994), however, as with most monitoring studies, there is a need to balance the monitoring design, and the funding available for the project. In this study, each site had one treatment and one control site.

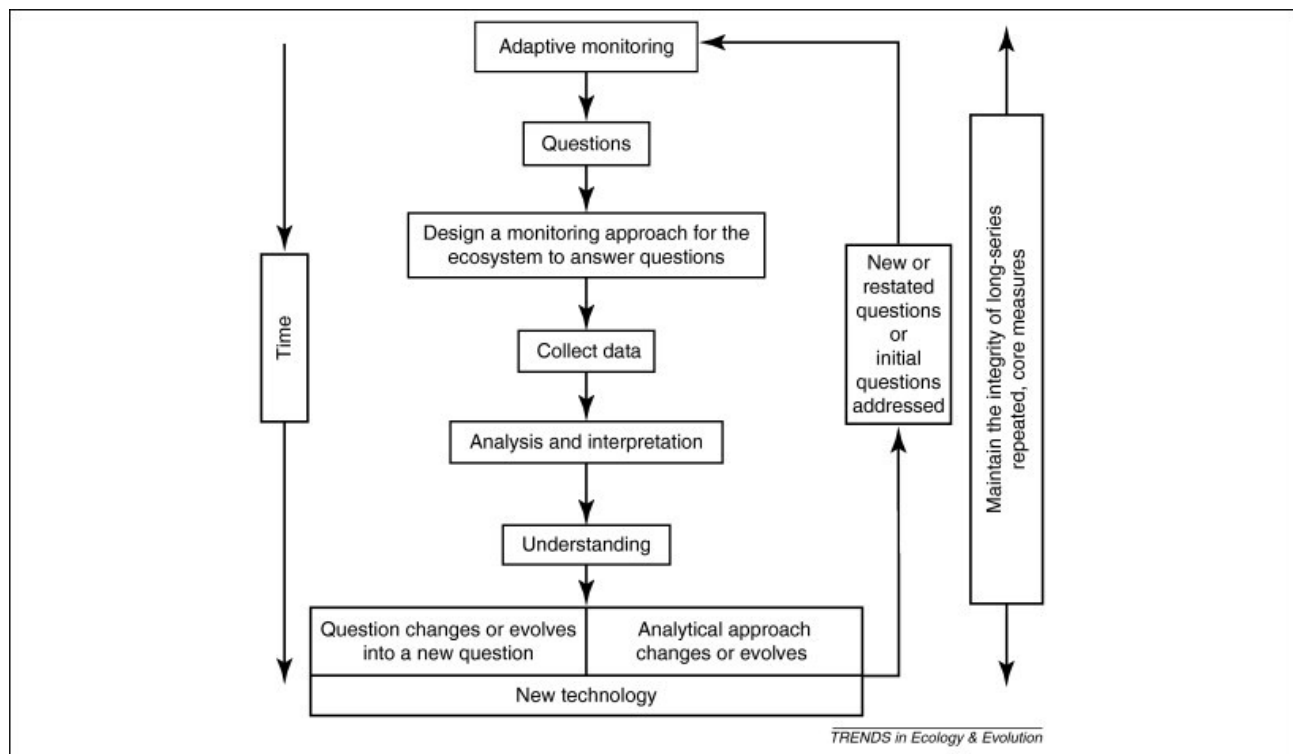


Figure 1: The adaptive monitoring framework implemented in this study (Lindenmayer and Likens, 2009)

2.2 Gully remediation options

The Gully Erosion Toolbox, a document prepared for the Reef Trust gully remediation program (Wilkinson et al., 2015c), outlines a range of treatment options suitable for gully remediation. The treatment options are based on evidence of the effectiveness of studies elsewhere in the world (Table 1). The evidence from these published studies highlight that although gully remediation can be effective, there is also significant risk associated with gully remediation, with many studies highlighting the high failure rate of within gully structures (e.g. Nyssen et al., 2004). Therefore, the treatment options in this study are primarily based on using vegetation, fencing and low cost engineering structures. The logic also being that if these options are effective, then it should be possible to treat a larger area for a given cost. A conceptual diagram of the relative role of these options on runoff and sediment/nutrient losses are described in Figure 2 and Table 2.

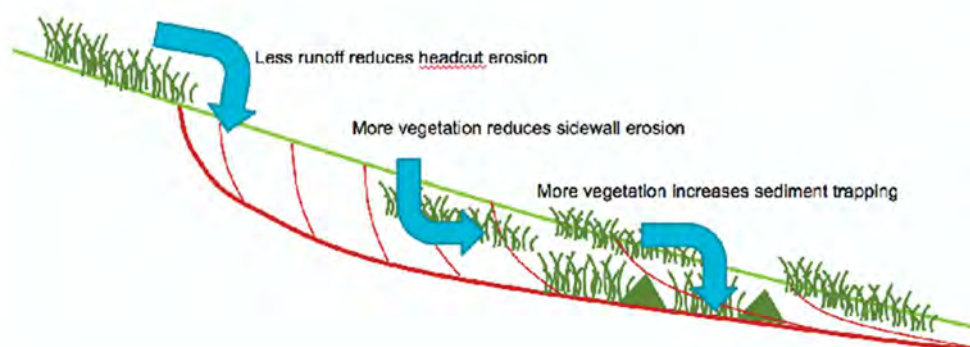


Figure 2: Conceptual model of the outcome of various treatment options within a gully (Wilkinson et al., 2015a). The green triangles represent within gully trapping structures such as porous check dams (PCD's).

Table 2 outlines the conceptual framework used to capture the various 'effectiveness' measures used in this study. As we are not sure exactly which variable will be the most suitable for quantifying the effectiveness of gully response following remediation, we are following a multiple lines of evidence approach. Table 2 describes the range of treatments being trialled along with our hypothesised response or outcome. We then outline the primary, secondary and tertiary response variables and the associated technique used to measure this response. Following gully remediation we anticipate that improvement in vegetation, both on the hillslope, and within the gully, will be a primary or initial response (Wilkinson et al., 2013). If the vegetation improves, then we expect to see an improvement in the rate of erosion and the concentration of the sediments (and particulate nutrients) leaving the site. Finally, in the longer term, we expect that we would see a change in runoff on both the treated hillslopes above the gully, but also within the gully. However, because of the long time frames associated with a reduction in runoff following improvements in ground cover (Bartley et al., 2014), and the high variability in rainfall within and between years, we don't expect to see a statistically significant difference in the runoff related variables within the time frame of this study.

Table 1. Global gully erosion remediation studies with measured sediment yield responses, building on the table presented in Wilkinson et al., (2015a)

Country	River/Region	Management action	Treated area (km ²)	Runoff and Sediment yield response	Time frame of study (years)	Reference
USA	Colorado	Stock exclusion, increased vegetation and check-dams	2.6 km ²	78% decline in net erosion rate for vegetation control only 90% reduction in sediment loads for sites with check dam	11 years	Heade (1979)
China	Loess Plateau	Stock exclusion and increased (forest) vegetation cover	NA	50–60% reduction in runoff 60–80% reduction in soil loss	NA	Gong and Jiang (1977) in Morgan and Davidson (1986)
Philippines	Reservoir of the Binge Hydroelectric Plant	Trenches filled with brushwood or brush/stick groins	Small plot scale (<1 km ²)	Reduced soil erosion by 99%	5 years	Costales and Costales (1985) in Lal (1992)
Ethiopia	May Zeg Zeg catchment	(non-porous) Check dams and vegetation restoration	2 km ²	81% reduction in runoff volume (which resulted in sediment deposition)	~30 years	Nyssen et al., (2010)
China	Loess Plateau	Conversion of farmland to forest and grassland	9-49 km ²	Reduced erosion by 75%	~30 years	Chen and Cai (2006)
New Zealand	Te Werorua	Changing from grass to forests	29 km ²	Reduced sediment from gullies by 62%	~40 years	Gomez et al., (2003)
New Zealand	Waipaoa River	Reforestation	140 km ²	51% reduction in denudation rates 12% reduction in sediment yield (due to remobilisation of stored sediments)	28 years	Marden et al., (2014)
Ecuador	Andean Valley	Re-forestation of barren land	0.1-20 km ²	10–45 fold decrease in sediment flux	>15 years	Vanacker et al., (2007)
Arizona	Santa Rita Mountains	Porous rock structures	0.03 – 0.04 km ²	Impacts of the check dams on runoff from major rainstorms were not detectable; however, the number of runoff events generated by small (less than one year recurrence interval) rainstorms decreased by 60%. During four years check dams retained 50% of sediment yield and were filled to more than 80% of their capacity.	35 year baseline + 7 years of treatment	Polykov et al., (2014) and Nichols et al., (2016)
China	Loess Plateau	Check dams	0.32 – 6.7 km ²	Large check dams trapped between 42 to 50% of the sediment yield in the treated catchments	6-35 years	Wei et al., (2016)
Ethiopia	Tigray Region of Northern Ethiopia	Stone check dams and vegetation	< 0.001 km ²	This study shows that the implementation of check dams combined with vegetation reduced peak flow discharge and runoff volume as large sections of runoff infiltrated in the sediments deposited behind the check dams.	7-14 years	Guyassa et al., (2017)
USA	South East Arizona	Thousands of check dams 30 years prior (1) Check dams at beginning of study (1)	2 reaches	Check dams are effective across vastly different timescales and both erosion and deposition is observed.	3 years	Norman et al., (2017)
China	Yangjuangou watershed, Loess Plateau	Check dam installed ~60 years prior + land use change	2.02 km ²	Check dam sediments used to indicate environmental change and its effect on soil erosion. Check dams and a slight reduction in rainfall and its erosivity led to a significant reduction in sediment supply over the past 50 years	11 years	Wang et al., (2014),
Spain	Saldaña region Carion River. Badlands existed since 1400s	Intense reforestation >100 check dams	3.17 km ²	In restored zones, runoff is negligible. Erosion has almost been stopped by the effects of vegetation cover. Check dams effectively work to reduce the sediment	~80 years since treatment	Hevia et al., (2014)

		Wattle fences		yield into the Carion River by almost three orders of magnitude compared to data from the 1930s and 1940s. Significant reduction in downstream turbidity.		
India	Chambal River Valley	Land use change Earthen dams	~109 km ²	Areas covered by badlands are reducing at a greater rate than badland encroachment. Badlands were reduced by 20 % in the last ca. 40 years	40 years	Ranga et al., (2016)
Ethiopia	Gullies, Tigray	490 loose rock check dams	n/a	39% of check dams failed/collapsed after 2 years. The frequent collapse of dams is strongly associated with drainage area (A) and slope gradient of the soil surface parallel to the gully (S), the product of these factors (S×A) being a measure of runoff energy.	2 years	Nyssen et al., (2004)

Table 2: The range of gully remediation treatment options, expected outcomes and measurement metrics. The number of v's represents the relative magnitude of expected response. The text in blue highlights legacy or ancillary data not currently covered within the NESP project and green is not reported this year

Treatment				Stock management, controlled grazing on hillslopes	Ripping, seeding and re-vegetation of hillslope	Fencing off gullies and stock removal	Porous within gully structures	Solid within gully structures
Expected Outcome or Objective				Improved vegetation (cover/biomass) on hillslopes above the gully	Improved vegetation (cover/biomass) + infiltration on hillslopes above the gully	Improved vegetation (cover/biomass) on gully walls and floor	Slows down runoff and facilitates deposition of sediment (and attached nutrients and seeds)	Slows down runoff and facilitates deposition of sediment (and attached nutrients and seeds). Creates backwater.
Indicator or response variable	Metric	Specific Attribute	Measurement technique					
Primary	Vegetation cover and biomass	Hillslope cover and biomass	Surveys of cover and biomass on the hillslopes above the gully	√√	√			
		Gully wall and floor cover and biomass	Surveys of cover and biomass within the gully	√		√√	√√	√√
	Within gully erosion (t)	- Headcut erosion - Wall erosion or deposition	DEM’s of Difference using the TLS (erosion) * bulk density	√	√	√		
Secondary		- Floor erosion or deposition				√√	√√√	√√√
	Improved water quality	- Sediment conc. (mg/l) - Nutrient conc. (mg/l) - Particle size	Samples collected during events across the hydrograph	√	√	√√	√√√	√√√
Tertiary	Reduced runoff (mm) or rainfall – runoff coefficient (%)	Hillslope runoff	Hillslope Flumes and runoff troughs at Virginia Park and Meadowvale	√	√√			
		Within gully runoff	Discharge based on depth and velocity in gullies			√	√√	√√√
Evidence				Evidence suggests increasing cover on hillslopes will result in progressively lower runoff coefficients for early wet season events, but annual runoff will not change significantly. Sediment concentrations should improve but evidence is weak to date (Bartley et al., 2014)	See Table 1, although very little data on pasture, with the main focus on trees	See Table 1	See Table 1	See Table 1

3 STUDY LOCATION

3.1 The Burdekin catchment

The Burdekin basin is $\sim 130,000 \text{ km}^2$ and drains into the Great Barrier Reef (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 $10.29 \times 10^6 \text{ ML}$, and is the largest contributor of anthropogenic derived fine sediment to the GBR lagoon (Kroon et al., 2012). The Burdekin river directly influences $\sim 47,000 \text{ km}^2$ 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).

3.2 Trial sites

Four properties were chosen in the Burdekin catchment: two in the Upper Burdekin (Virginia Park and Meadowvale), one in the Bogie (Strathbogie) and one in the Don catchment (Minnievale). All sites are commercial grazing properties. The four sites represent a range of property sizes (3000 to 39,000 ha), however, geologies, rainfall and dominant pasture species are relatively similar (Table 3). The soil types do vary, with Strathbogie residing on a mixture of granite and basalt lithologies (Figure 3 and Figure 4). Virginia Park and Meadowvale are dominated by Red Chromosols and Yellow to Brown Sodosols with dispersive B horizons (Rogers et al., 1999; Roth, 2004). Granite-derived soils such as granodiorites, and basalt-derived soils such as Vertosols, are known to contribute fine sediment at high rates to rivers in the Burdekin basin, based on sediment source tracing using geochemistry and clay mineralogy (Bainbridge et al., 2016; Furuichi et al., 2016). All properties lie within the 500-900 mm rainfall gradient (Figure 5) and thus they have similar vegetation cover (Figure 6). Chromosol soils are known to have a relatively high density of gully erosion (Wilkinson et al., 2013). The density of gully erosion does vary between properties with the highest gully densities at Minnievale (0.22 km/km^2) compared with Strathbogie (0.06 km/km^2) (Table 3). The gully treatment options used at each of the sites are described in Section 3.3.

Table 3: Description of the four study sites (Virginia Park, Meadowvale, Strathbogie and Minnievale). Note that the gully density data was based on Tindall et al., (2014) except Minnievale () which was based on the NLWRA (2001) data.**

Property	Virginia Park	Meadowvale	Strathbogie	Minnievale
Management Unit (sub-catchment)	Upper Burdekin	Upper Burdekin (and Haughton)	Bogie	Don
Local stream name and size	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)
Size of property (ha)	~7000 ha	~3000 ha	~39,000 ha	~3750 ha
Soils	Chromosol Landscape	Chromosol Landscape	Vertosol (Black Soil) gullies in chromosol landscape	Chromosol Landscape
Geology	Granite and Granodiorite	Granodiorite	Granite, Basalt	Granodiorite
Terrain (% slope property)	2-3%	2-3%	6-7% (due to high relief in south)	3-4%
Terrain (% slope of gully upslope catchment area)	2-3%	2-3%	1-2%	1-2%
Average annual Rainfall (mm)	~ 660 mm	~ 680 mm	~ 750 mm	~ 880 mm
Vegetation over-story	Widely spaced Narrow-leaved Ironbark and Bloodwood	Widely spaced Narrow-leaved Ironbark and Bloodwood	Widely spaced Narrow-leaved Ironbark and Bloodwood	Widely spaced Narrow-leaved Ironbark and Bloodwood
Vegetation groundcover	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch	Dominated by Indian Couch
Gully density (km/km²)	0.17 km/km ²	0.15 km/km ²	0.06 km/km ²	0.22 km/km ² **
Lat Long Treatment Gully	-19.891629, 146.512731	-19.838936, 146.591086	-20.221489, 147.556607	-20.193492, 148.072038
Lat Long Control Gully	-19.902937, 146.51609	-19.828862, 146.588209	-20.20425, 147.558102	-20.194344, 148.077696

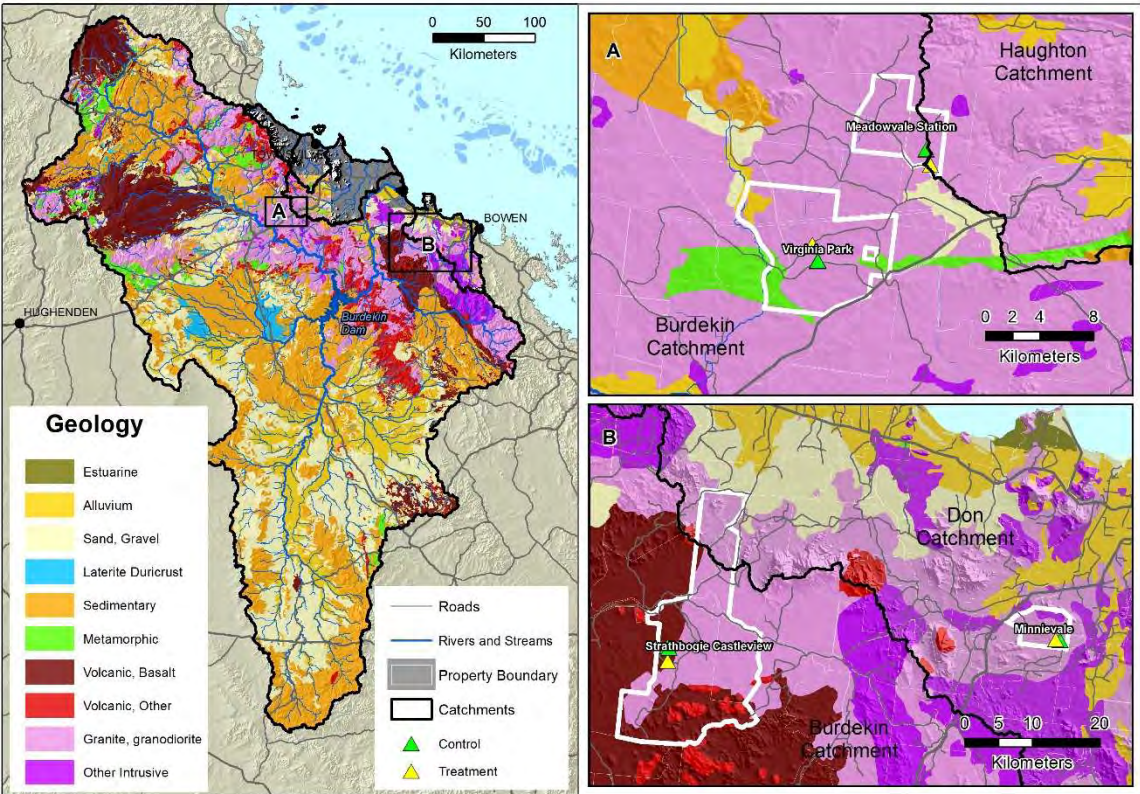


Figure 3: Underlying geology at each of the trial properties (Source: GeoScience Australia)

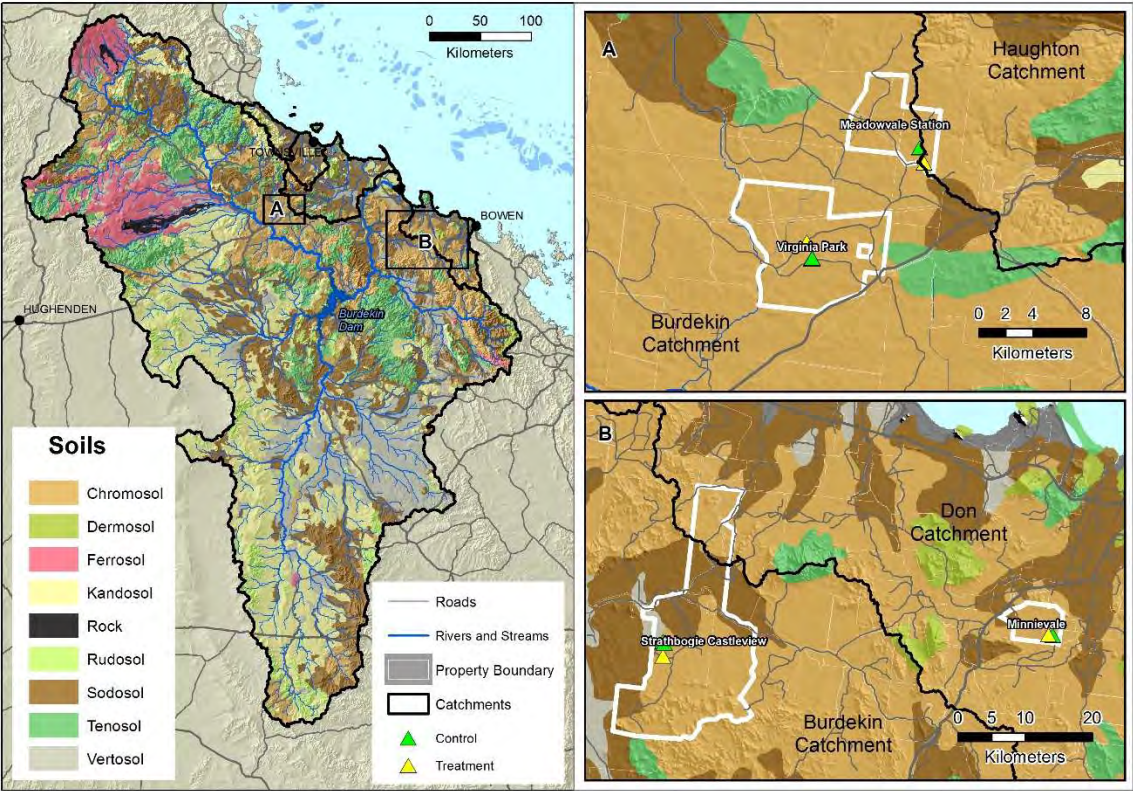


Figure 4: Underlying soil type at each of the properties (Source: Atlas of Australian Soils)

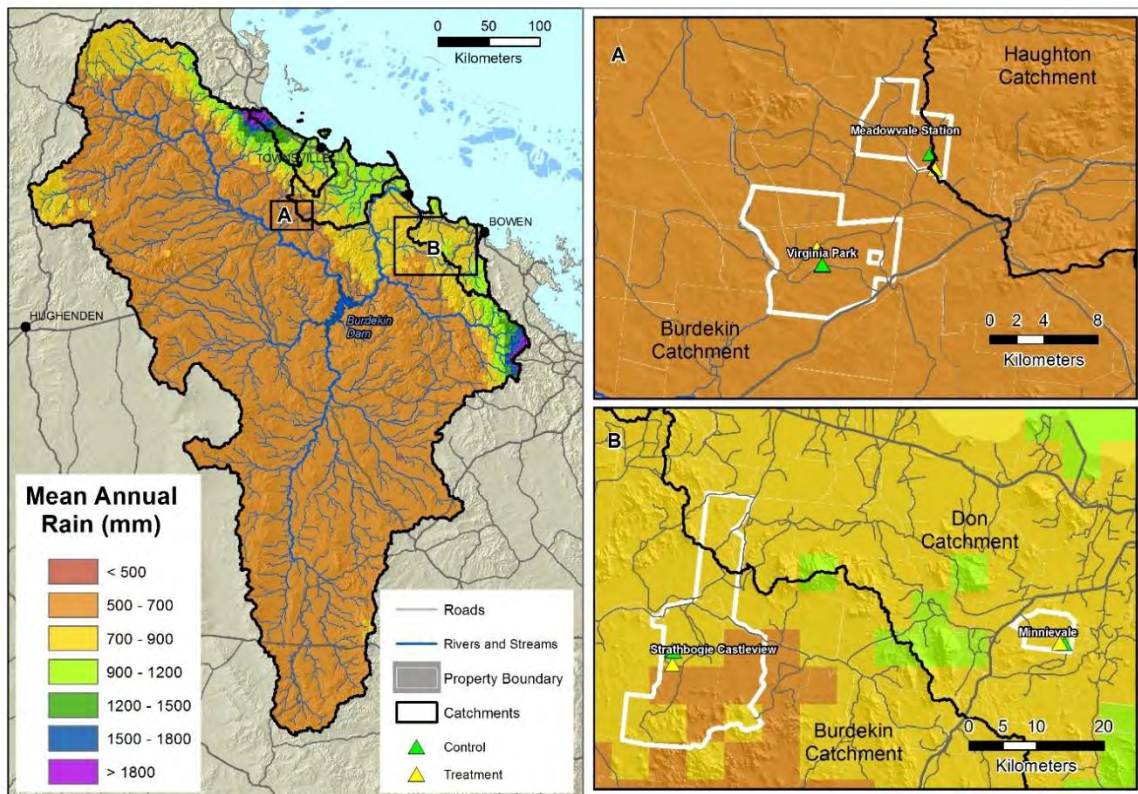


Figure 5: Rainfall distribution for each of the properties (Source: SILO 5 km grid)

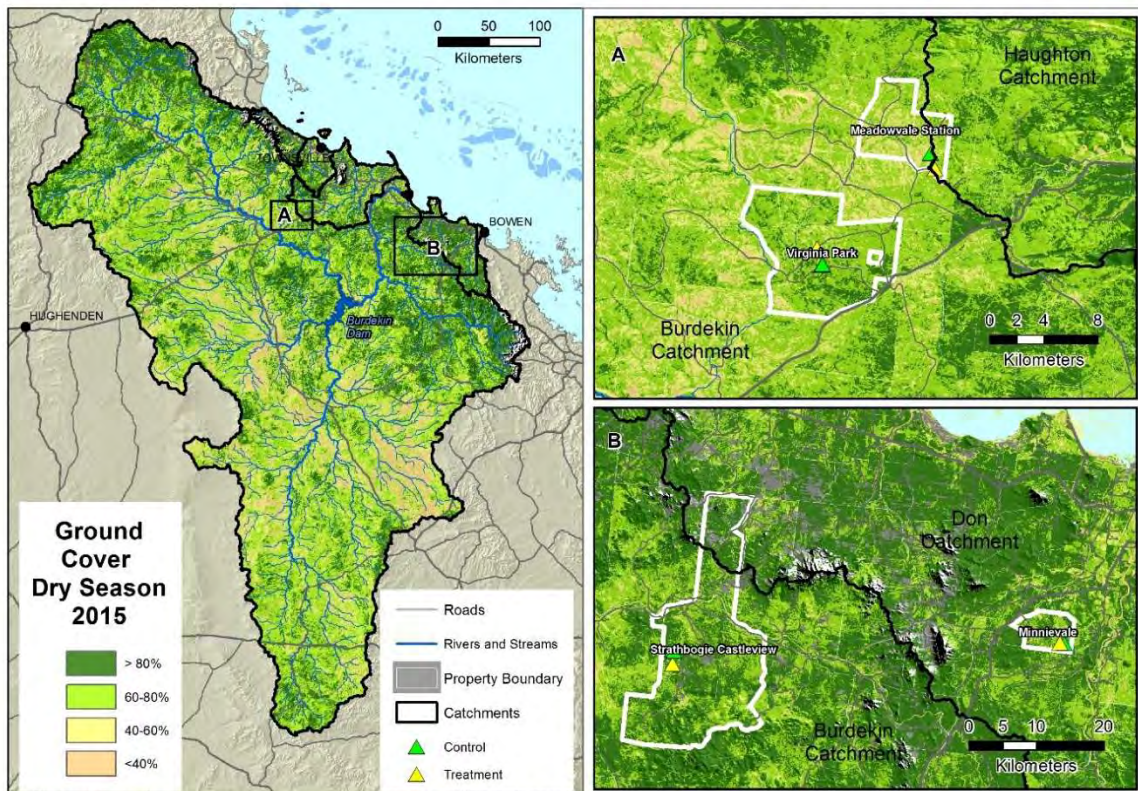


Figure 6: Total ground cover (2015) for each of the properties (Source: Queensland Government fractional ground cover product)

3.3 Treatments applied at each site

The main treatment options for each of the gully sites were selected from the Gully Toolbox (Wilkinson et al., 2015c), as well as through consultation with the delivery partners and landholders. The final choice and installation of the remediation at each site was the responsibility of a third party, being NQ Dry Tropics in the case of Strathbogie, and Greening Australia at Minnievale. CSIRO organised the treatments at Meadowvale which was paid for by the NESP program, and at Virginia Park which was paid for by the Paddock to Reef Program (in 2010). The treatments across the four properties represent a spectrum of remediation options, and a summary of the approaches used are outlined in Table 4.

Although the monitoring equipment was installed by November 2016, the treatment structures were not complete at Meadowvale and Strathbogie before the first rainfall event in January 2017. Therefore for these sites, this first year of monitoring represents a 'baseline' prior to treatment implementation. The final treatment options at Strathbogie are to be advised (TBA) in 2017. Diagrams showing the locations of the treatments and associated measurement infrastructure are presented in Section 5.

Table 4: Description of treatment history at each site

Activity	Virginia Park	Meadowvale	Strathbogie	Minnievale
Managing organisation	CSIRO	CSIRO	NQDT	Greening Aust.
Date control site monitoring began	2000	2000	2016	2016
Date treatment was initiated	2010	2017	2017	2016
Date treatment site monitoring began	2010	2016	2016	2016
Fencing – electric fence	√ Two strand	√ Four Strand	√	√
Fencing – permanent fence				
Wet season resting from stock in paddock upslope	√			√
Stock exclusion	√	√	√	
Retention structures on gully bed	√ n = 5 stick traps		TBA	√ Total n = 135
Hillslope treatment	√ Disc plough above the treatment gully		TBA	√ Ripped (with narrow boot, sprayed and seeded)
Hillslope flow diversion			TBA	
Active revegetation with seed				√ e.g. Creeping blue grass, R.Rhodes, V8 stylo
Alternative stock watering points				√
Source of funding for the treatment	Paddock to Reef	NESP	Reef Trust	Reef Trust

4 METHODS

4.1 Vegetation and pasture metrics

Vegetation metrics were measured above each gully at the end of the dry season (October–November) and then again at the end of the wet season (April). Landscape and vegetation condition transects were installed upslope of the uppermost head section on both the treated and control gullies at all sites. Transects were run 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 (30 quadrats were sampled for each treatment/control area). Metrics included the main pasture species and/or functional group composition and frequency, above-ground pasture biomass (DMY), total cover, litter cover, basal-area %, defoliation level and key soil surface condition metrics (Tongway and Hindley, 1995). In addition landscape condition was 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 weighed quadrats respectively. Biomass standards were oven dried to attain dry matter yield, removing vegetation water retention error between treatments. A real time kinematic (RTK) survey ran from upslope of the vegetation survey to the valley section for each gully system.

Gully vegetation cover and biomass were also measured within each gully, on the gully walls and gully floor. The sampling methodology was very similar to the hillslope survey. A minimum of three transects were measured across each gully, representative of the head, middle and valley sections. At each transect, % cover, biomass and dominant cover type was assessed using 0.25m² (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. Analysis of the statistical differences between control and treatment sites were undertaken using Microsoft Excel 2013 and Sigmaplot Version 13. In most cases a t-test for means and non-parametric Mann-Whitney rank sum test were conducted. The within gully vegetation surveys were all recorded post-wet season for 2016/17. The hillslope surveys were both pre and post wet season.

4.2 Gully erosion

4.2.1 Historical rates of gully erosion: historical air photo interpretation

As part of the BACI design, an estimate of the rate of gully erosion ‘before’ the treatment is required. This was derived by assessing the historical aerial photography for the available air photo record at each gully (Table 4). To derive gully erosion rates through time, the air photos were georeferenced using ArcMap 10 GIS. The 2012 image was rectified with a known co-ordinate system (GDA 1994 Australia Albers Central Meridian), and used as the base photo. All preceding photos were then assessed against the base photo and a minimum of 7 control points per photo were used to rectify the images using a first or second order polynomial transformation and nearest neighbour resampling. Once the photos were rectified, gully length was measured at each site. Gully length was measured using the ruler tool in ArcMap starting from where the gully meets the streamline for consistency between years.

Table 2. Aerial ortho-photo years chosen for historical gully erosion analysis for each of the four properties.

Virginia Park	Meadowvale	Strathbogie	Minnievale
1961	1956	1969	1960
1965	1961	1972	1971
1975	1964	1985	1977
1977	1974	1994	1980
1981	1977	2000	1983
1999	1981	2003	1995
2001	1990	2006	1998
2002	2002	2007	2007
2006	2006	2009	2009

4.2.1 Current rates of gully erosion: terrain analysis

Terrain mapping of the gullies was used to (i) provide metrics on 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. Soil erosion can generate both fine (<63 µm) and coarse (>63 µm) sediment. Terrain analysis, expressed as DEM's of difference (DOD's) will capture erosion of the entire soil profile, including fine and coarse material. The water quality monitoring (Section 4.4) will focus on the fine sediment only.

To estimate upslope catchment areas for the treatment and control gullies, Lidar data (0.5-1.0 m) was used for Virginia Park and Meadowvale, and the Shuttle Radar Terrain Model (SRTM) derived DEM was used at Strathbogie and Minnievale. Ten centimetre DEM's from airphotos will be available for Strathbogie in 2017/18. Three surveying techniques were used to capture terrain data in this study.

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 +/- 12mm in the horizontal plane and 15mm in the vertical. The slope of the gully bed was surveyed by traversing the entire gully channel, collecting survey points along the deepest part of the channel, representative of each reach.

Zebedee

The Zebedee, a portable, handheld laser scanner (<http://www.csiro.au/en/Research/D61/Areas/Robotics-and-autonomous-systems/Sensing-and-mapping-our-environment/Zebedee>), consists of a rotating 2D laser scanner and an inertial measurement unit (IMU) mounted on a spring that causes the scanner head to sway in response to the movement of the operator as they walk. This movement creates a 3D point cloud with a range extending up to 35 m and a precision of 1–3 cm.

Repeat scans of each gully system (~300 m) were conducted by walking up and down the sites and around each reflector to create a closed loop survey for DEM generation. For the gully site, a single survey consisted of two transects - one upstream and one downstream. For the gully site, a single survey consisted of one closed loop transect. Reference marker locations surveyed by RTK GPS were used to align the Zebedee surveys into real world coordinates

The raw data files were uploaded from the recording device to a processing server and automatically transformed into a 3D point cloud using the proprietary simultaneous localization and mapping (SLAM) algorithm (Bosse et al., 2012). All point clouds collected on the same day were then aligned to one another using a Merge routine on the processing server which combines a place recognition routine (Bosse and Zlot, 2009) with fine-tuning by SLAM. The resultant point clouds are then coincident with one another. The merge routine does not explicitly use the reflector locations to aide in the alignment, but the reflectors were subsequently identified in the point clouds and then used to register all data to the reflector coordinates. The error associated with this technique was presented in Bartley et al., (2016) and is estimated to be $\pm 0.09 - 0.12$ m.

RIEGL Terrestrial laser scanner

The 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 star picket driven 50 cm 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.

Change detection

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 5cm x 5cm XY interval. A 3 x 3 median filter was then applied to the resulting grid to remove spurious values. Common extents were required for comparison of the DEM's. For the gully, 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 6 pixel (50 cm) buffer was then applied to ensure full capture of the gully edges.

To statistically separate 'true' from 'false' geomorphic change, a ± 0.1 m threshold was set in the DEM's of difference (DoD's) and will account for propagated error. This is considered conservative based on the previous work carried out at Virginia Park (Bartley et al., 2016), however, it is appropriate given the diversity of gully morphologies across the eight sites (Goodwin et al., 2017). A sediment bulk density of 1.5 t/m^3 is assumed to convert erosion volumes into tonnes of sediment. This is considered an average for granodiorite soils under different grazing management practices, where the values range from 1.35 to 1.85 t/m^3 (Bartley et al., 2010).

4.3 Runoff

An automatic monitoring station was installed at each of the treatment gullies (Figure 7A). The monitoring station recorded rainfall, stage height, turbidity and water temperature at 1-min intervals during runoff events. The station also housed an ISCO auto-sampler that collected 1-L water samples at programmed intervals across the hydrograph. These samples were processed according to the methods in Section 4.4. A camera was installed at the treatment sites to capture photos during runoff events.

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 collected manually after each (accessible) event

using poly-pipe rocket structures (Figure 7B). Data from both the treatment and control sites had telemetered communications to allow remote access of data.

To estimate discharge at each of the sites, Hec-Ras Version 5.0.3 was used to generate rating curves. Cross-sections were extracted from the Zebedee profiles of the gully cross-sections. The cross-sections were spaced at ~10 m spacing down the length of each gully. Estimates of the channel bed elevation were interpolated using the base level of the cross-sections in conjunction with the RTK surveys. Roughness estimates were estimated using Manning's n (Chow, 1959). The model was run in mixed-flow-flow regime mode to enable representation of super and sub-critical flows zones.



(A)



(B)

Figure 7: (A) Example of a treatment gully set up and (B) and example of a control gully set up including two rising stage samplers

4.4 Water quality and particle size

A description of the water quality sampling procedures for this project is outlined in Baker et al., (2016). In brief, following significant runoff events that triggered the samplers, the ISCO bottles were collected and the samples were filtered and frozen if collected within 24 hours of the event. These samples were analysed for TSS and the full suite of nutrients (total nitrogen, total dissolved nitrogen, NH_3 , NO_x , total phosphorus, total dissolved phosphorus, FRP) at the JCU TropWater Laboratory, Townsville. Samples that were not collected within 24 hours were analysed for TSS only. A sub-set of the samples collected were also sent for particle size analysis. The samples were processed on a Malvern Mastersizer which is a laser diffraction analyser with a lens range of 0.02 – 2000 μm .



(A)



(B)



(C)



(D)

Figure 8: The treatment (left) and control (right) instrumented gullies at each property. (A) Virginia Park (B) Meadowvale (C) Strathbogie and (D) Minnie Vale

5 RESULTS

The results presented in this section represent a combination of baseline data (Meadowvale and Strathbogie) and treatment evaluation (Virginia Park and Minnievale). Post wet season cover data (on the hillslopes and gullies) were not yet recorded at Minnievale due to the access road being destroyed by Cyclone Debbie. These post-wet measurements are scheduled for June 2017.

5.1 Treatment location and survival

5.1.1 Virginia Park

The Virginia Park Treatment site represents the longest running of all of the treatment sites. This is the 7th wet season of water quality monitoring at this 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). A fence around this treatment gully, and instream structures, were installed in 2010 (Figure 9). Some treatment of the hillslope above the gully with a disc plough was also undertaken in 2010. There are five porous check dams (PCD's) or stick traps installed within the gully; three are above the water sampling site, and three are below. The PCD's have required no maintenance over the seven 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 years. Figure 10 demonstrates how one of the PCD's in the treatment gully has evolved over time. The backwater area upstream of each PCD has now filled with sediment, and therefore they may have reached their maximum effectiveness in terms of sediment trapping. They will hopefully continue to be effective by slowing the water down enough so that sediment and associated seeds are trapped. It is the vegetation that will grow from these seeds that are the long term mechanism for stabilising these smaller gullies.

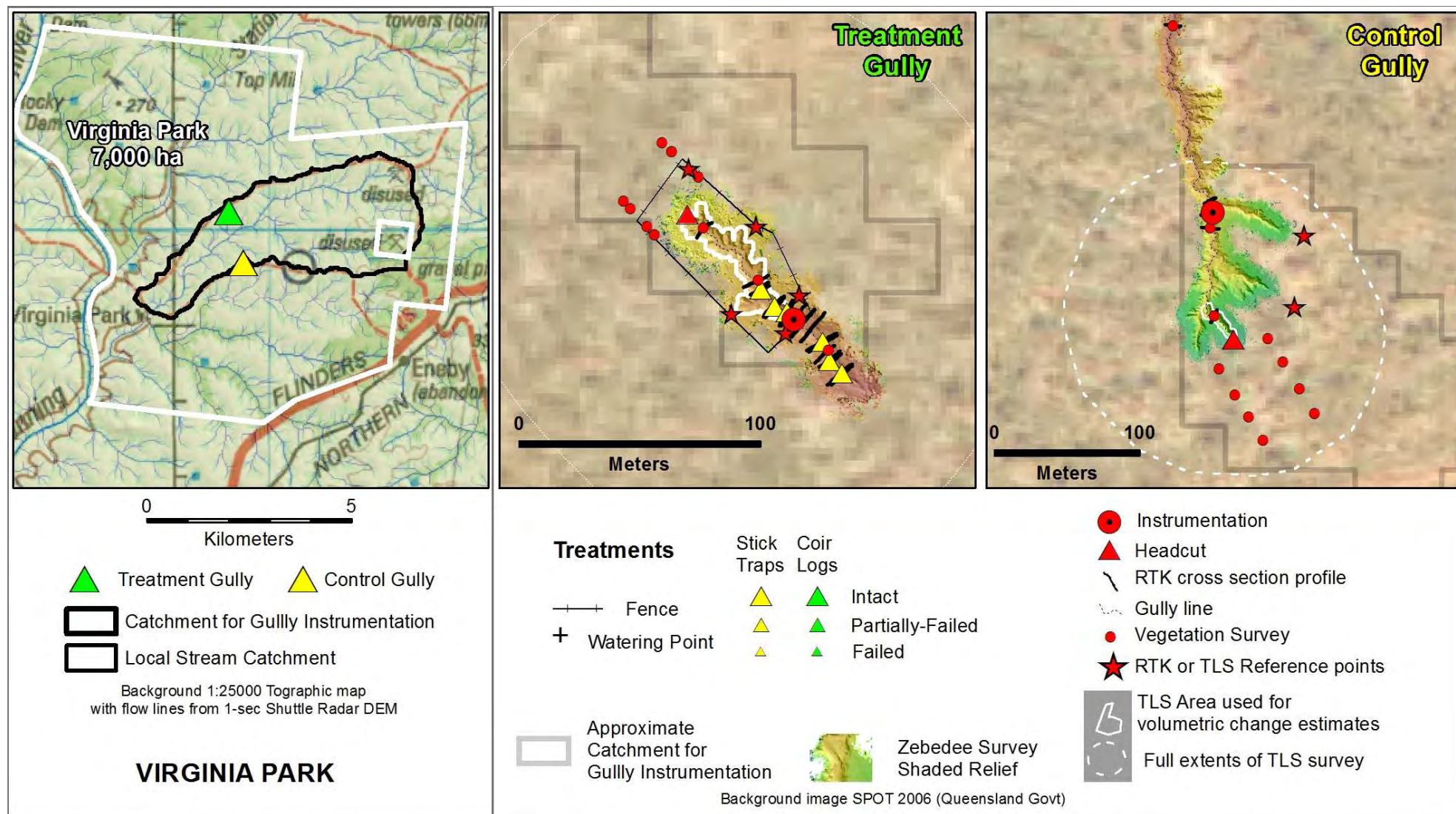


Figure 9: Location of the Virginia Park site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.



3 Nov 2010



30 Nov 2010



Feb 2011



Feb 2012



May 2012



March 2013



Dec 2013



July 2014



Jan 2015



April 2015



Jan 2016



March 2017

Figure 10: Changes in the vegetation adjacent to a check-dam structure (#1) in the Treatment gully (upstream is to the right) (adapted from Wilkinson et al., 2015b).

5.1.2 Meadowvale

The Meadowvale site has the simplest of all of the treatments being cattle exclusion fencing only. The gully exclusion fence was completed in 2017 and therefore the water quality data collected at this site represents a base line year to compare the treatment and control sites. The next wet season will be the first 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 11).

This site also builds on previous research by CSIRO (Hawdon et al., 2008). The treatment gully is adjacent to a re-instated long term runoff trough, initially installed by DPI in the 1980's. The hillslope treatment includes a 4 Ha area that has had light or no cattle grazing since 1986, and almost complete cattle exclusion since 2002. So approximately half of the hillslope above the treatment gully has had cattle exclusion for more than 15 years. The control gully at Meadowvale has been monitored for 16 years (1999 – 2016) using erosion pins, topographic survey techniques and vegetation transects.

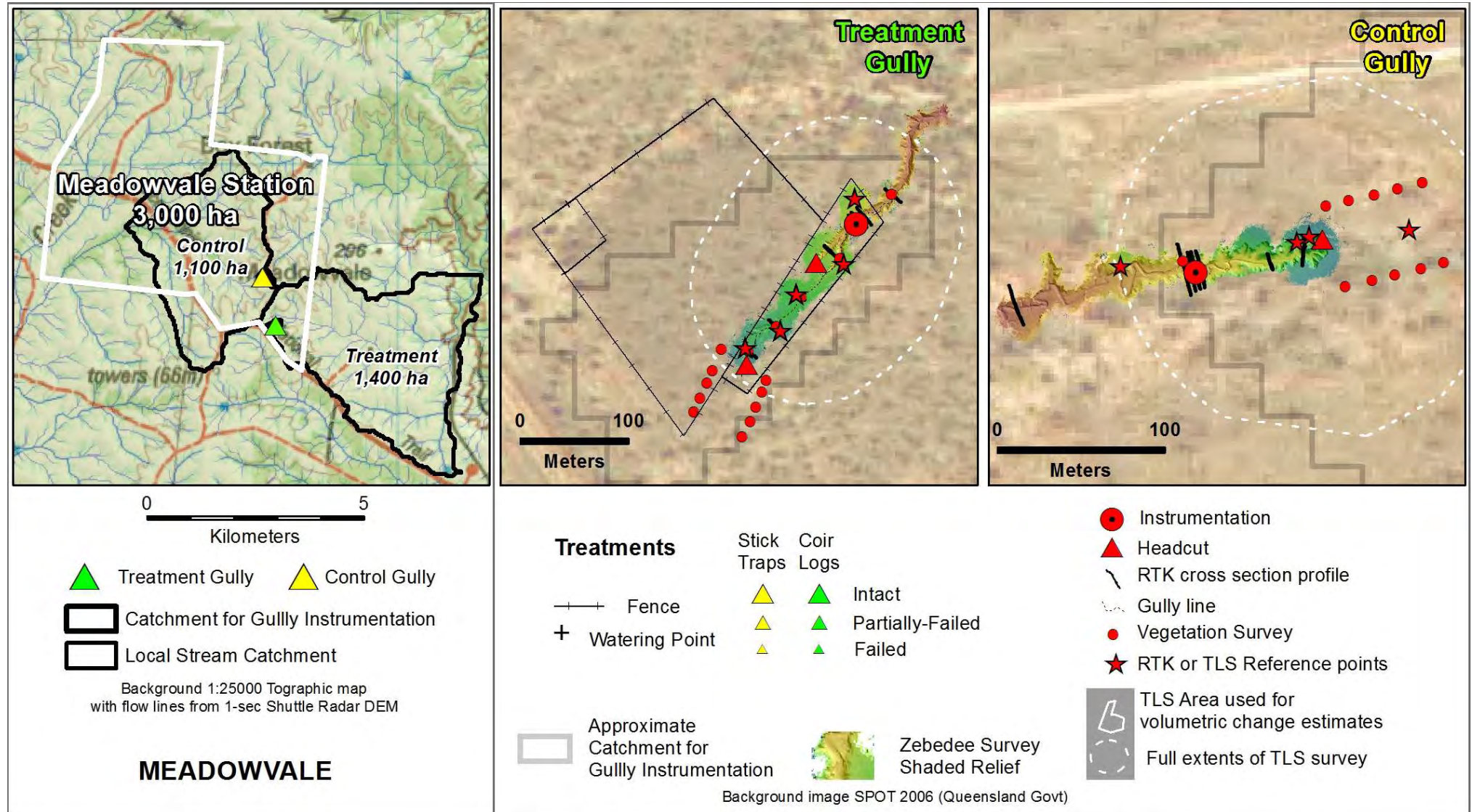


Figure 11: Location of Meadowvale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.

5.1.3 Strathbogie

The Strathbogie site is a Reef Trust 2 gully remediation site being managed by NQ Dry Tropics. This site did not have its treatments installed prior to the 2016/17 Wet Season. Therefore the water quality data collected at this site represents a base line year to compare the treatment and control sites. The next wet season will be the first to evaluate the gully treatments. At this stage the plans are for a combination of stock exclusion fencing, within gully trapping structures and potentially some hillslope diversion banks (Figure 12).

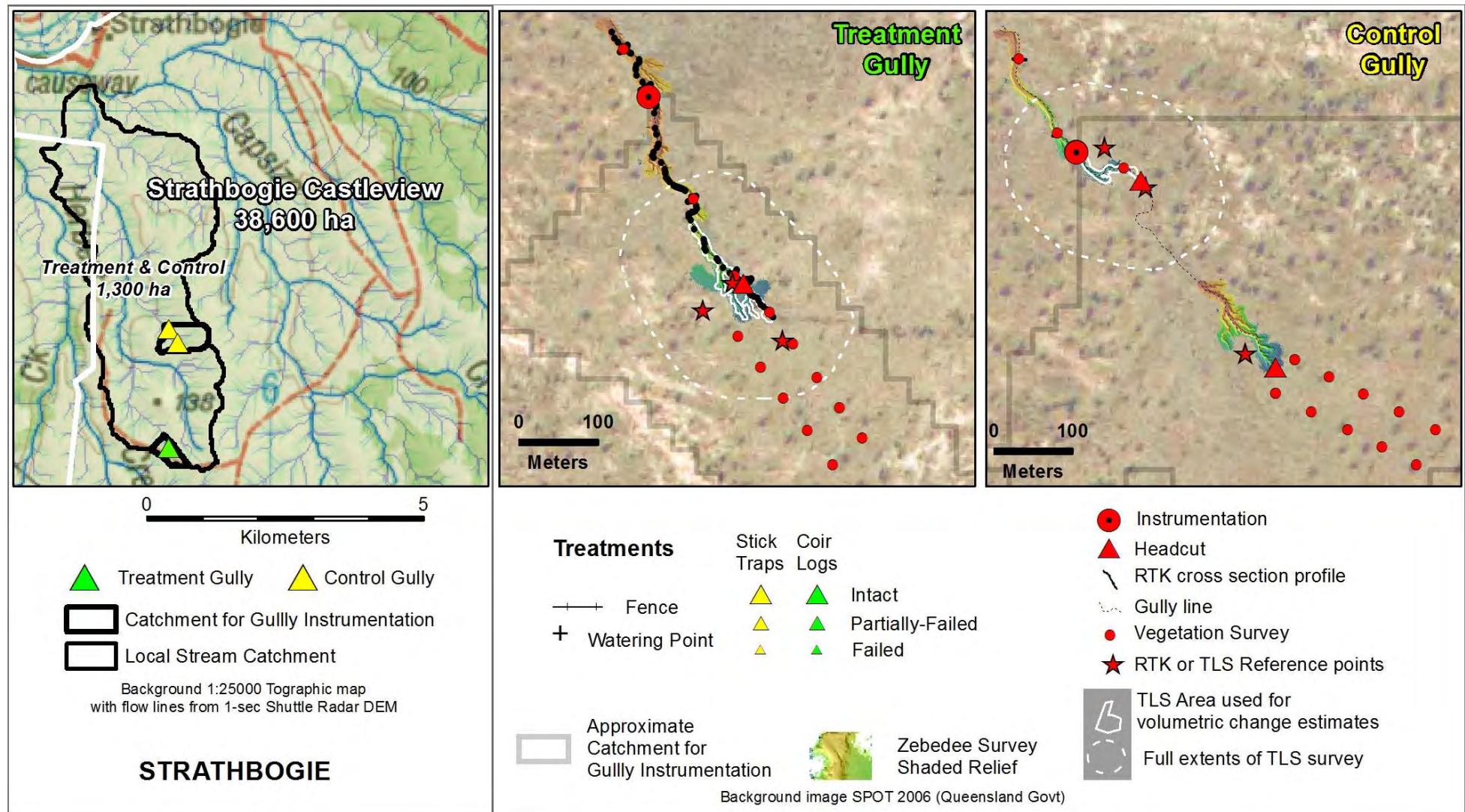


Figure 12: Location of Strathbogie site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.

5.1.4 Minnievale

The Minnievale site is a Reef Trust II gully remediation site being managed by Greening Australia. This site has had the most significant number of remediation works undertaken. The main treatment gully has been fenced off (~4 km of fencing) and there were a total of 135 within gully structures installed (Table 5). There were two types of structures (Coir logs and Stick traps or PCD's) and they were installed in the main arm of the gully and the side arms of the main gully (Figure 13). Ripping and seeding of the catchment directly upslope of the treatment gully was undertaken using exotic pasture species. A pasture restoration site was also implemented in association with the Don River Trust and DAFF, however, this is just outside of the drainage boundary of the treatment gully. Monitoring points and baseline vegetation surveys and land condition assessment were also undertaken by Greening Australia, however, they are not presented in this report, and are instead part of their Reef Trust reporting.

Of the 135 structures installed, there was a large (95%) failure rate of coir logs in the main channel (Table 5). The coir logs were more effective in the smaller side channels of the gully which suggests that the coir logs are not suitable for locations that receive high runoff depth and discharge (Figure 14). The stick traps had a good (~80%) success rate, however, these structures were only installed in the smaller side gullies. The direct cost associated with the installation of coir logs (~\$167 each) is much lower than stick traps (~\$350-\$400 each depending on the width required).

In the coming wet season, the focus for this site will be on (i) the development of a Grazing Management Plan (GMP) with the landholder, (ii) the installation of an additional 60 structures targeting the untreated side tributaries, (iii) there will be an increased focus on stick traps rather than coir logs because of the increased permeability and sediment capture. No further work is planned for the main channel due to high flow.

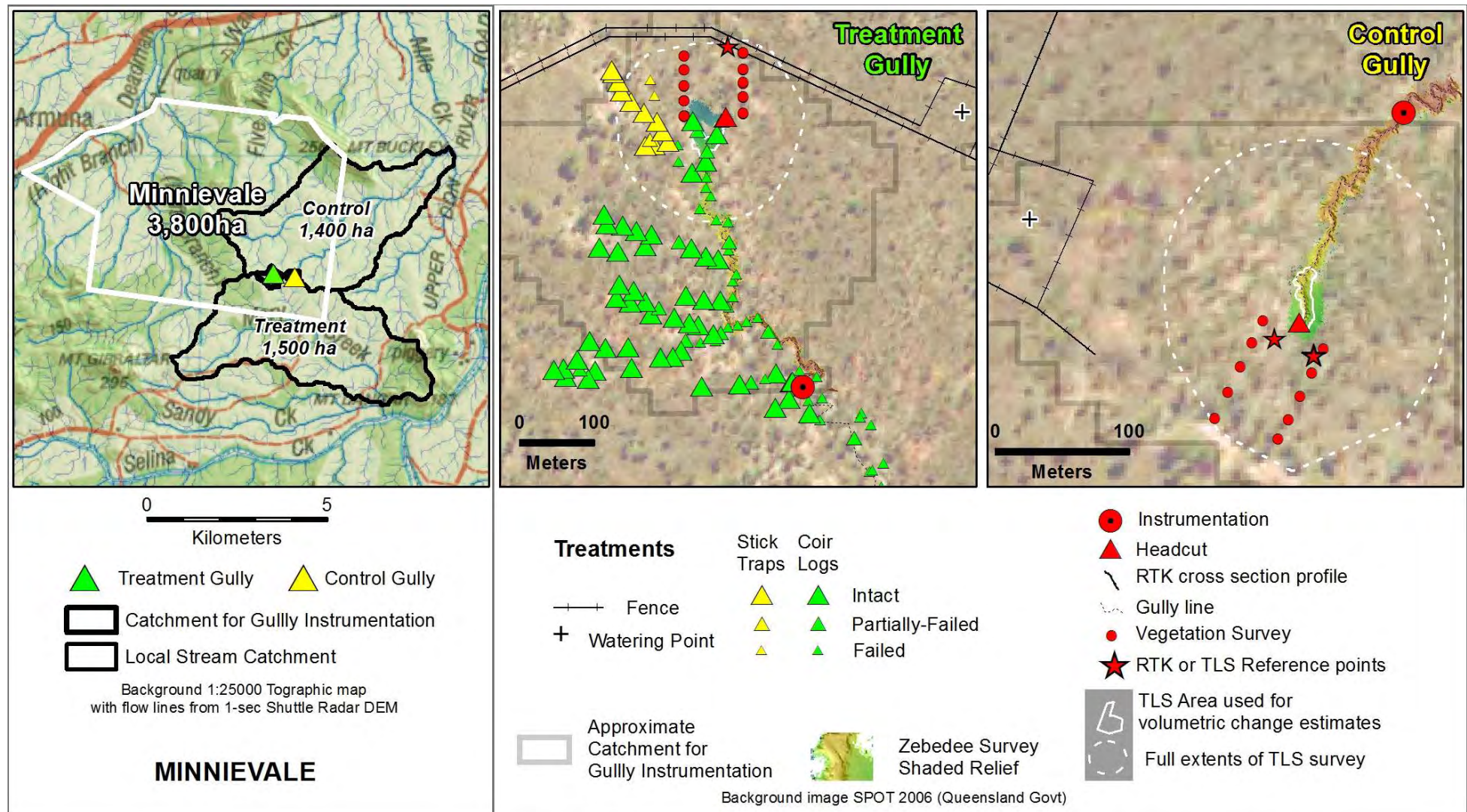


Figure 13: Location of Minnievale site (left) and the Treatment and Control gullies. The location of the treatment structures and monitoring equipment/locations are shown.

Table 5: Response of within gully structures at the Minnievale site following the first event of the wet season (prior to Cyclone Debbie).

	Fail	Partial Fail	Intact	Fail Rate
Coir logs in main channel (55)	89%	6%	5%	95%
Coir logs in side gullies (66)	17%	16%	68%	32%
Stick traps in main channel (0)	0%	0%	0%	0%
Stick traps in side gullies (14)	14%	7%	79%	21%
Total (135)	46%	10%	44%	56%



(A)



(B)



(C)



(D)

Figure 14: The Minnievale site showing (A) in-tact stick trap in a side gully; (B) partial failure of a stick trap that has had been outflanked on one side (C) complete failure of a coir log and (D) and partial failure of a coir log in the main gully (Photos: Greening Australia).

5.2 Landscape condition

Table 6 presents the land condition classification results based on data collected on the hillslopes above each gully on each of the four properties. Land condition is dominated by C (poor) and D (very poor) class states for all sites. Treatment and control conditions at each site are similarly poor to very poor or C-D condition. There appears to be some change towards slightly better condition in the Virginia Park and Meadowvale post wet measurements compared to post dry measures while treatment and control remain the same at Meadowvale post wet, Virginia park exhibits some change. Condition at all other sites remain fairly stable between the post dry and post wet period and between treatment and control sites.

Table 6: A, B, C, D Land condition classification for each of the properties in this study

	Landscape condition (%)			
	A	B	C	D
Virginia Park				
Treatment: post dry (Nov)			12	88
Control: post dry (Nov)			7	93
Treatment: post wet (April)		16	72	12
Control: post wet (April)			60	40
Meadowvale				
Treatment: post dry (Nov)			17	83
Control: post dry (Nov)				100
Treatment: post wet (April)			43	47
Control: post wet (April)			49	51
Strathbogie				
Treatment: post dry (Nov)		3	56	40
Control: post dry (Nov)			44	56
Treatment: post wet (April)			49	51
Control: post wet (April)			39	61
Minnievale				
Treatment: post dry (Nov)			39	61
Control: post dry (Nov)			44	56
Treatment: post wet (April)			-	-
Control: post wet (April)			-	-

5.3 Vegetation and pasture metrics

5.3.1 Hillslope

The vegetation and pasture metrics for the hillslope above each of the treatment and control gullies is presented in Table 7. A summary of these metrics is also presented with the water quality data in Table 11. There was no significant difference between the majority of treatment and control vegetation metrics at sites in both the post dry and post wet periods. Virginia Park exhibited a significant difference between the treatment and control for the end of wet period for cover and litter, and for the end of end of dry and end of wet, for biomass. Importantly, although biomass is much higher at the Virginia Park treatment site than at all other sites, 66% of the biomass was composed of exotic legumes or stylo (Appendix A: Table 12). This is not ideal for soil conditions, and does not result in a high basal area for the site. High plant basal area is important for infiltration and to reduce runoff from these hillslopes. There is also a significant difference between treatment and control for biomass at Meadowvale during the end of dry period, and also at Minnievale for the same period. Species functional group composition (Appendix A: Table 12) describes differences between treatment and control for the pre wet and post wet periods.

5.3.2 Gullies

The vegetation metrics for the gully floor and walls are presented in Table 8. There was a significant difference between the % cover and biomass between the Virginia Park Treatment and Control gullies, which is likely to be due to the presence of the PCD's in the bed of the gully that have significantly increased the amount of vegetation over the last 7 years (see Figure 10). There are, however, also some significant differences in the cover and biomass for the gully walls at Meadowvale and Strathbogie, neither of which have active treatments in place. This suggests that the natural variability between gullies can be significant and this needs to be taken into consideration in future years when we are trying to determine the causal processes as to why there are differences between the water quality at the various sites. The correlation between % cover and biomass (kg/ha) is strong for gully floors ($r^2 = 0.9$), moderate for gully walls ($r^2 = 0.6$) and weaker for hillslopes ($r^2 = 0.45$) (Figure 15). It is likely that the potential growth of vegetation on the gully walls is more dependent gully morphology (wall slope) and soil type than the gully floors.

Table 7: Amount of cover on the hillslope at the end of the wet season. Standard deviation shown in parentheses. Where the text is highlighted in blue/bold, there is a significant difference between the Treatment and Control gullies

	Virginia Park			Meadowvale			Strathbogie			Minnievale		
	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff
End of Dry (Nov) Cover (%)	61 (15)	59 (30)	P=0.794	58 (35)	46 (35)	P=0.142	52 (22)	54 (22)	P=0.719	67 (32)	53 (33)	P=0.130
End of wet (April) Cover (%)	86 (12)	76 (18)	P=0.009	76 (28)	66 (28)	P=0.136	94 (12)	94 (9)	P=0.990	-	-	-
End of Dry (Nov) Biomass (kg/ha/yr)	1375 (612)	500 (296)	P=0.000	57 (67)	9 (11)	P=0.000	411 (133)	355 (164)	P=0.204	318 (134)	259 (96)	P=0.045
End of wet (April) Biomass (kg/ha/yr)	225 (3381)	814 (793)	P=0.023	255 (100)	242 (55)	P=0.530	883 (525)	1830 (2769)	P=0.076	-	-	-
End of Dry (Nov) grass basal area (%)	0.38 (0.33)	0.46 (0.40)	P=0.430	0.62 (0.48)	0.55 (0.59)	P=0.561	0.46 (0.48)	0.25 (0.36)	P=0.095	0.64 (0.72)	0.37 (0.37)	P=0.062
End of Wet (April) grass basal area (%)	0.67 (0.69)	0.67 (0.34)	P=0.982	0.39 (0.34)	0.48 (0.36)	P=0.296	0.47 (0.31)	0.41 (0.36)	P=0.536	-	-	
End of Dry (Nov) Litter (%)	19.29 (20.19)	26.21 (33.55)	P=0.474	28.48 (31.26)	18.73 (28.69)	P=0.085	5.63 (8.68)	3.73 (3.49)	P=0.246	15.04 (27.85)	20.27 (25.91)	P=0.521
End of Wet (April) Litter (%)	23.69 (26.07)	6.59 (13.48)	P=0.002	19.43 (27.65)	8.03 (16.76)	P=0.087	4.27 (8.25)	2.03 (2.34)	P=0.174	-	-	-

Table 8: Amount of cover on the gully walls and floor at the end of the wet season (April 2017). Standard deviation shown in parentheses. Where the text is highlighted in blue/bold, there is a significant difference between the Treatment and Control gullies.

	Virginia Park			Meadowvale			Strathbogie			Minnievale		
	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff	Treatment	Control	Sig. Diff
Gully walls										na	na	
% cover	34 (27)	27 (26)	P = 0.142	30 (29)	24 (17)	P = 0.887	24 (33)	52 (33)	P = 0.013	na	na	
Biomass (kg/ha/yr)	1.36 (1.19)	1.68 (2.79)	P = 0.109	0.60 (0.00)	0.70 (0.12)	P = 0.001	0.84 (0.75)	2.26 (1.50)	P = 0.003	na	na	
Gully floor										na	na	
% cover	53 (31)	16 (19)	P < 0.001	13 (8)	12 (16)	P = 0.053	24 (18)	14 (12)	P = 0.104	na	na	
Biomass (kg/ha/yr)	1.67 (2.75)	0.61 (0.05)	P < 0.001	0.60 (0.71)	0.63 (0.08)	P= 0.505	1.09 (0.97)	0.67 (0.11)	P=0.115	na	na	

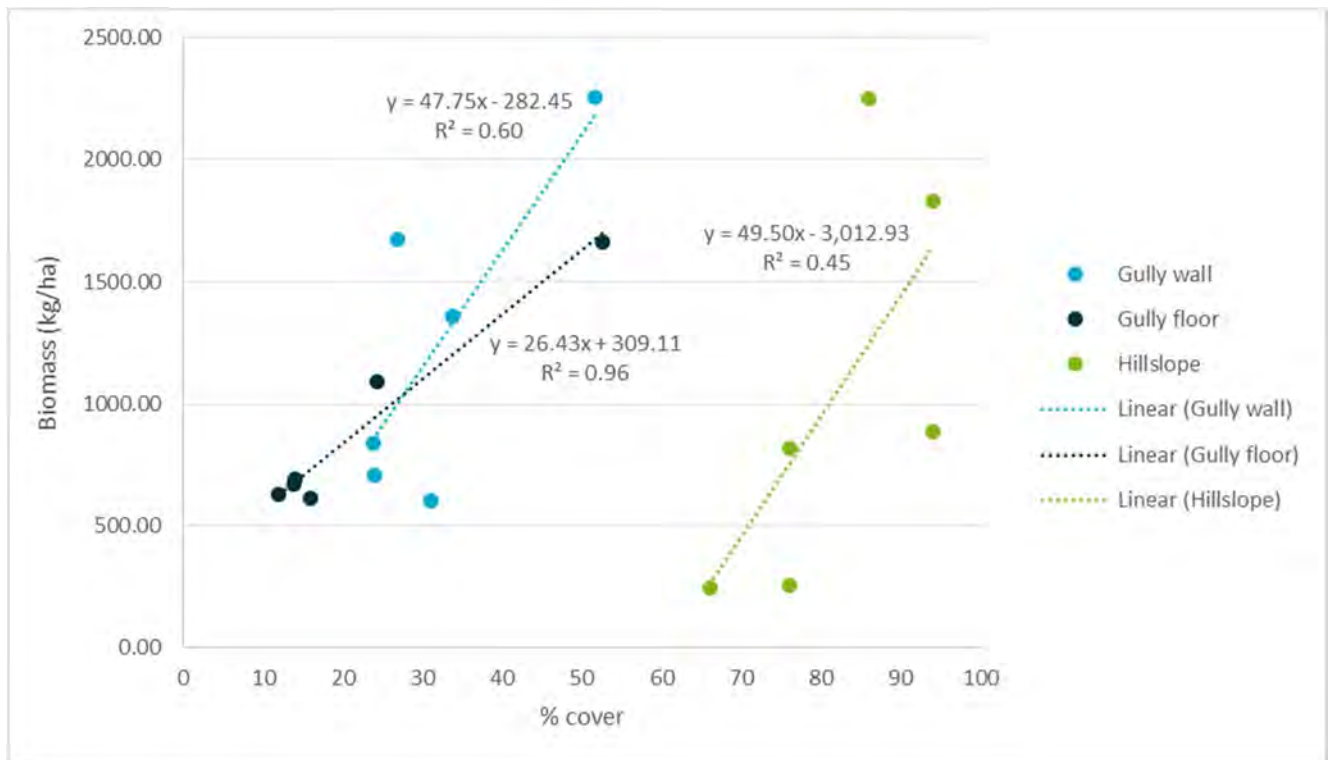


Figure 15: Relationship between % cover and biomass (kg/ha) between the gully wall, gully floor and hillslopes for the post-wet season data. Minnievale not included due to site access.

5.4 Gully erosion rate

5.4.1 Historical rates of gully erosion: historical air photo results

The historical air photo analysis identified that all of the gullies were present in the earliest photos (1956, 1960 or 1970). The average annual rate of gully growth varied from ~0.38 m at the Virginia Park control gully to 3.65 m at the Strathbogie control site, although the standard error for all measurements is very high (Table 9). All of the gullies have grown over the air photo period although there were periods of lower gully growth (1980 -2000) and periods of more rapid gully advancement (generally after 2000) (Figure 16). This may be an artefact of the challenges associated with identifying the gully heads in all years, particularly years of low cover when the contrast between gullies and hillslopes is more difficult to identify. These data suggest that the gullies at Virginia Park and Strathbogie are still actively eroding. The Meadowvale and Minnievale gullies have had a steadier growth pattern over the ~50 year record.

The historical air photo analysis suggests that the rates of gully growth have been similar between the control and treatment sites for the Meadowvale and Strathbogie properties. However, at Virginia Park and Minnievale, there are relatively large differences in the pattern of growth between the control and treatment gullies, although the annual average growth rates are most similar at Minnievale (Table 9). This will be taken into consideration when evaluating the responses, or lack of, following treatment. Given the challenges with defining gullies in historical air photos, the data indicate the relative rates of change between gullies. Absolute values related to erosion rates should be treated with caution for individual gullies.

Table 9. Rates of recent gully extension estimated by air photo interpretation.

Site	Treatment	Period	Annual average rate of gully extension (m/y) $\pm$ SE
Virginia Park	Treatment	1961—2006	1.70 $\pm$ 4.14
	Control	1961—2006	0.38 $\pm$ 0.56
Meadowvale	Treatment	1956—2006	1.30 $\pm$ 1.36
	Control	1956—2006	1.64 $\pm$ 2.12
Strathbogie	Treatment	1969—2009	2.85 $\pm$ 4.37
	Control	1969 —2009	3.65 $\pm$ 6.49
Minnievale	Treatment	1960—2009	1.39 $\pm$ 2.54
	Control	1960—2009	1.59 $\pm$ 1.68

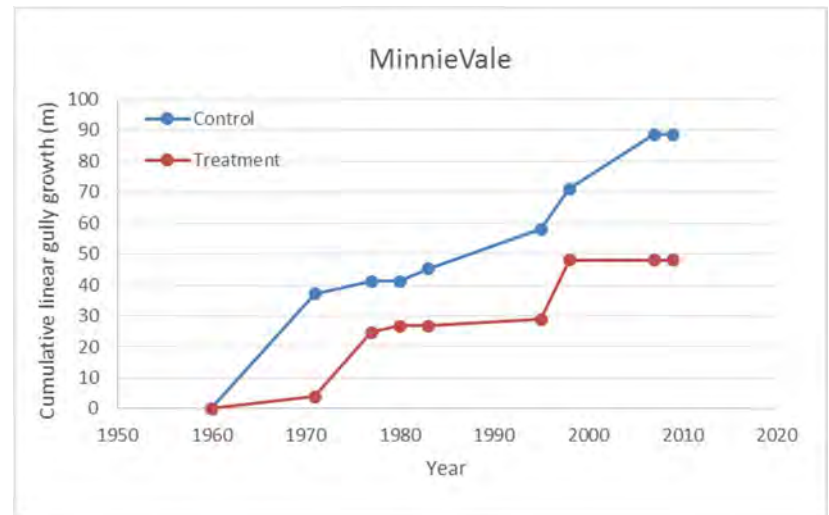
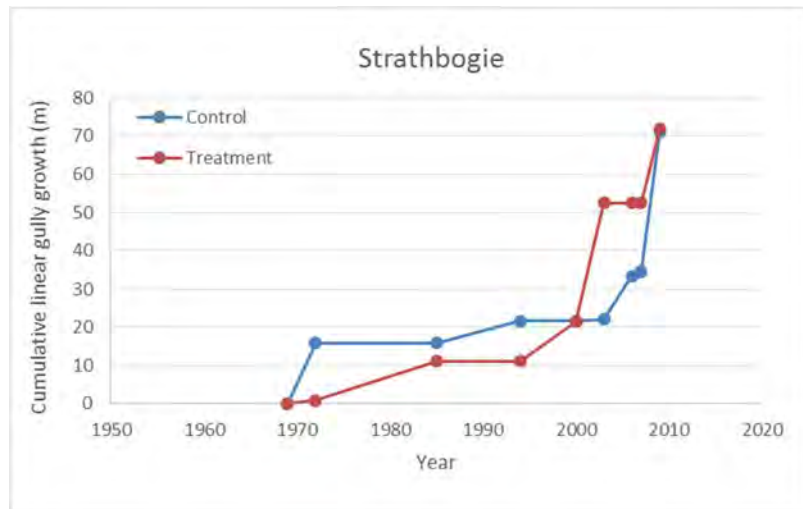
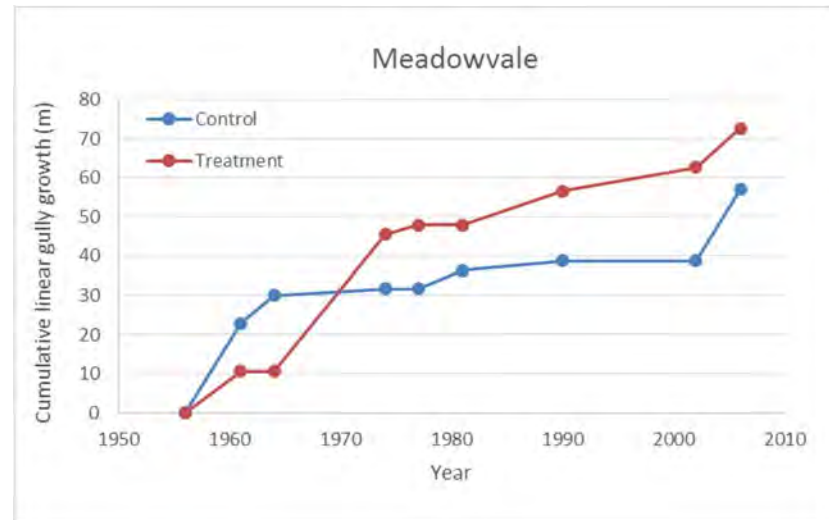
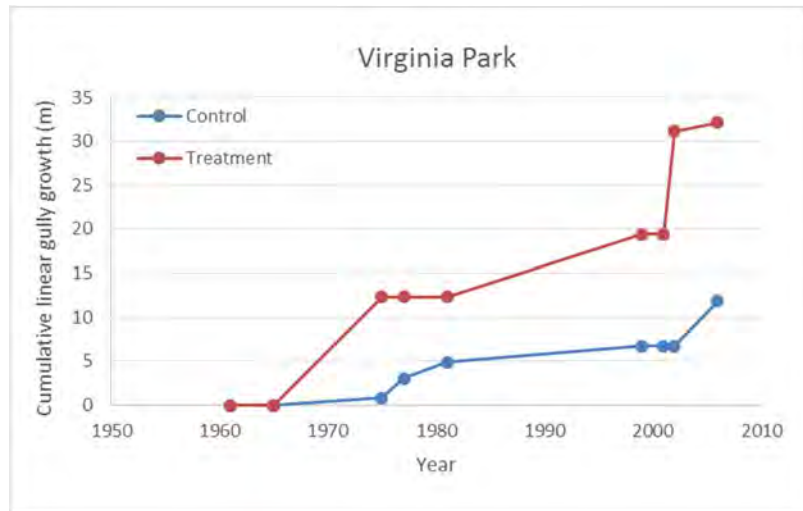


Figure 16: The cumulative rates of gully length for the control and treatment gullies at each site for the available historical photo record.

5.4.2 Current rates of gully erosion: terrain analysis

The total erosion, deposition and net change in the volume of sediment at Virginia Park, Strathbogie and Minnievale are presented in Table 10, and the DoD's are presented in Figure 20 to Figure 26. There were three years of TLS data from the Virginia Park treatment site, so all of the data are presented to highlight the inter-annual variability, however, only the 2015 – 2017 data are presented in Figure 18. The Meadowvale sites were not selected at the time of initial scanning in 2016, and therefore no change detection or DEM's of Difference (DOD) are presented for this site. The scanning length is slightly different at each gully, therefore a normalised erosion metric in tonnes per linear metre (t/m) of gully surveyed is provided (Figure 18).

The results suggest that the erosion distance (m) and rate (t and t/m) is highest at the Strathbogie site and is associated with the large upslope catchment areas at this site (Figure 17 and Table 11). At the Strathbogie site, there is no treatment in place, therefore this result highlights the natural variability in erosion rates between gullies in the same landscape.

The results for Virginia Park (Figure 18) highlight that the erosion rate in the treatment gully is much higher than at the control site, and this can vary between years. However, when the erosion and deposition are plot separately for these sites it highlights that the proportion of sediment stored in the treatment gully is considerably higher (Figure 19). At the treatment gully, ~63% of the sediment that is eroded is re-deposited in the gully downstream in 2015-16, and ~31% in 2016-17. This compares to only 18% of the eroded sediment being deposited in the control gully. It is likely that this is a direct response to the PCD's within the treatment gully, although additional years of data are needed to confirm this finding.

The Minnievale control and treatment sites exhibited very different responses to the 2016/17 wet season. The fact that the Treatment site had more deposition than erosion suggests that a considerable amount of sediment, from outside of the gully, has been deposited within the gully. The area upslope of the treatment gully did undergo ripping and seeding in 2016, and it is possible that a considerable amount of hillslope erosion has occurred at this site. It is also likely that some of the deposition can be attributed to the remediation structures at this site, but generally the trapping efficiency would be less than 100% of the amount of sediment eroded. All sites experienced survey marker burial to some extent suggesting that there is hillslope erosion and re-deposition occurring at most sites. The only site where the survey markers did not experience partial burial was at the Virginia Park Treatment site.

Based on the contemporary linear gully erosion rates presented in Table 10, the mean annual long term erosion rates estimated for each of the gullies seem sensible, and possibly a gross under-estimate for Strathbogie in the 2016/17 wet season.

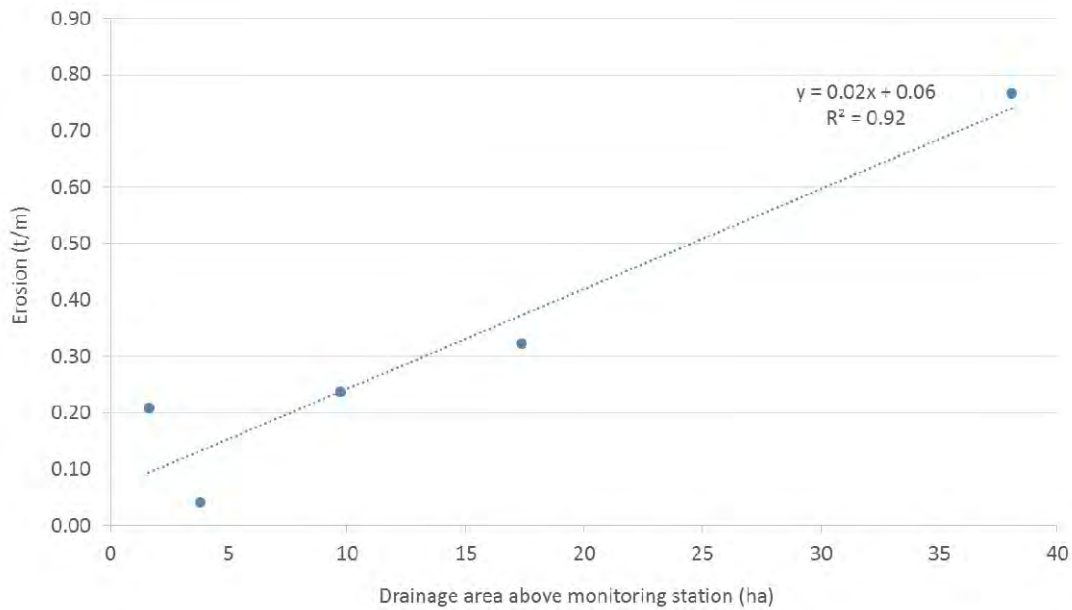


Figure 17: Relationship between upslope catchment area (ha) and TLS measured erosion rate (t/m). Note that Minnievale Treatment gully was not included on the graph as it was net deposition and Meadowvale data are not available

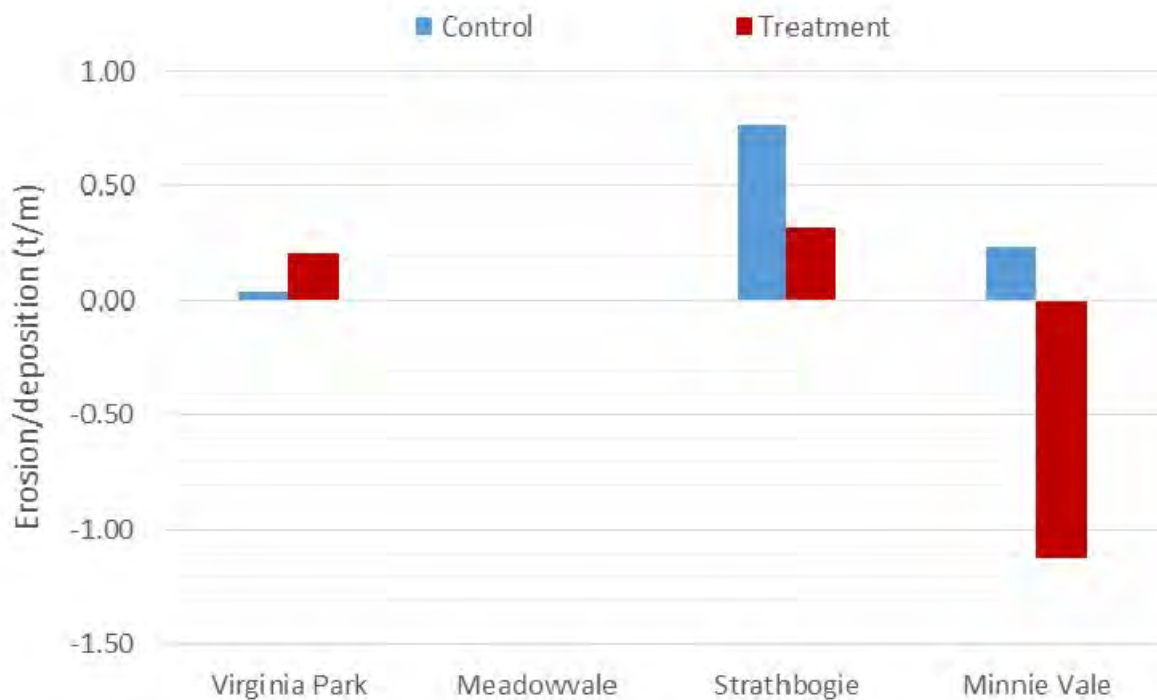


Figure 18: Net sediment movement (tonnes per metre surveyed, t/m) for each of the gully sites. Erosion is represented by positive (+ve) values and deposition negative (-ve) values. The Virginia Park data is for 2015- 2017. The other sites represent 2016/17 only.

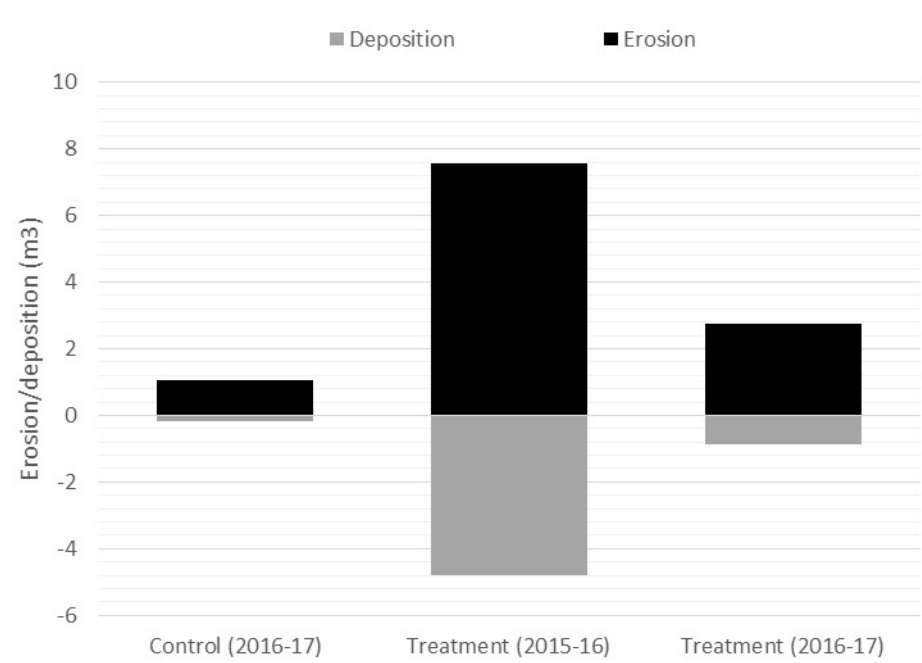


Figure 19: The change in deposition and erosion (m³) for the Virginia Park Control gully in 2016-17 and the treatment gully over 2 consecutive wet seasons (2015-16 and 2016-17)

Table 10: Gully volumetric change results using the RIEGL Terrestrial laser scanner. The negative values represent net deposition and positive values represent net erosion. The U_{crit} threshold for defining erosion/deposition was set as 0.1 m at all sites. Bulk density of sediment is assumed to be 1.5 t/m³.

Property	Gully	Year	Length of area surveyed with the TLS (m)	Erosion (m ³)	Deposition (m ³)	Net change (m ³)	Sediment eroded from surveyed area (t)	Normalised sediment eroded per gully length surveyed (t/m)	Maximum linear Erosion rate (m)	Average Annual Linear Erosion rate (m/yr)
Virginia Park	Control	2016/17	32.00	1.07	0.19	0.88	1.32	0.04	0.35	0.35
	Treatment	2015/16	61.86	7.56	4.78	2.78	7.17	0.12	0.95	0.95
		2016/17	61.86	2.76	0.86	1.9	1.29	0.02	0.46	0.46
		2015/17	61.86	11.2	8.6	2.6	12.9	0.21	1.28	0.64
Meadowvale	Control	Na								
	Treatment	Na								
Strathbogie	Control	2016/17	97.50	61.36	11.44	49.92	74.88	0.77	18.1	18.1
	Treatment	2016/17	172.70	49.70	12.61	37.09	55.64	0.32	4.57	4.57
Minnievale [#]	Control	2016/17	50.10	9.24	1.34	7.90	11.85	0.24	0.84	0.84
	Treatment	2016/17	62.04	19.86	66.18	-46.32	-69.48	-1.12	0.50	0.50

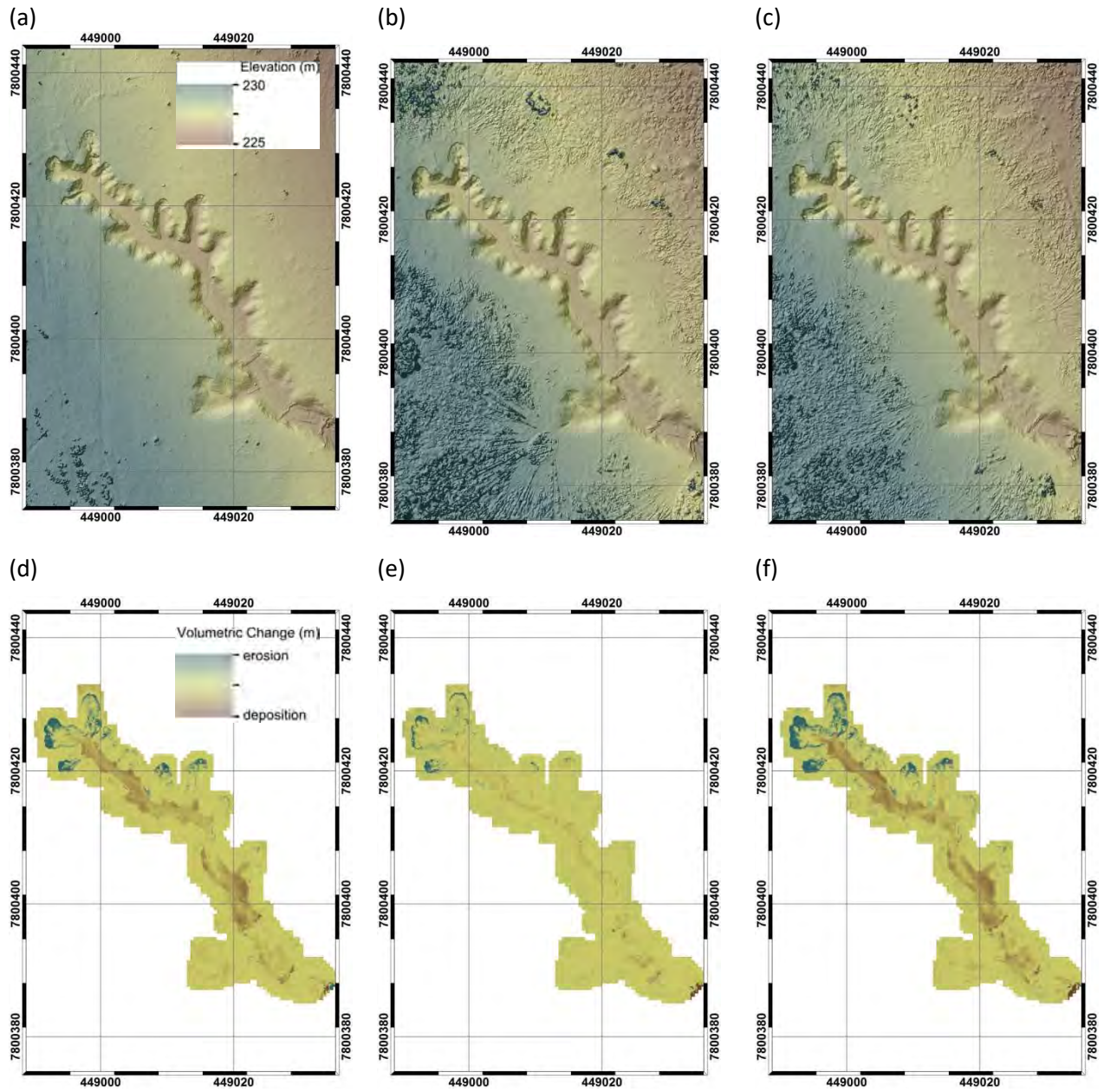


Figure 20: Virginia Park treatment: (a) 2015 DEM, (b) 2016 DEM, (c) 2017 DEM, (d) 2015 and 2016 DoD, (e) 2016 and 2017 DoD, (f) 2015 and 2017 DoD.

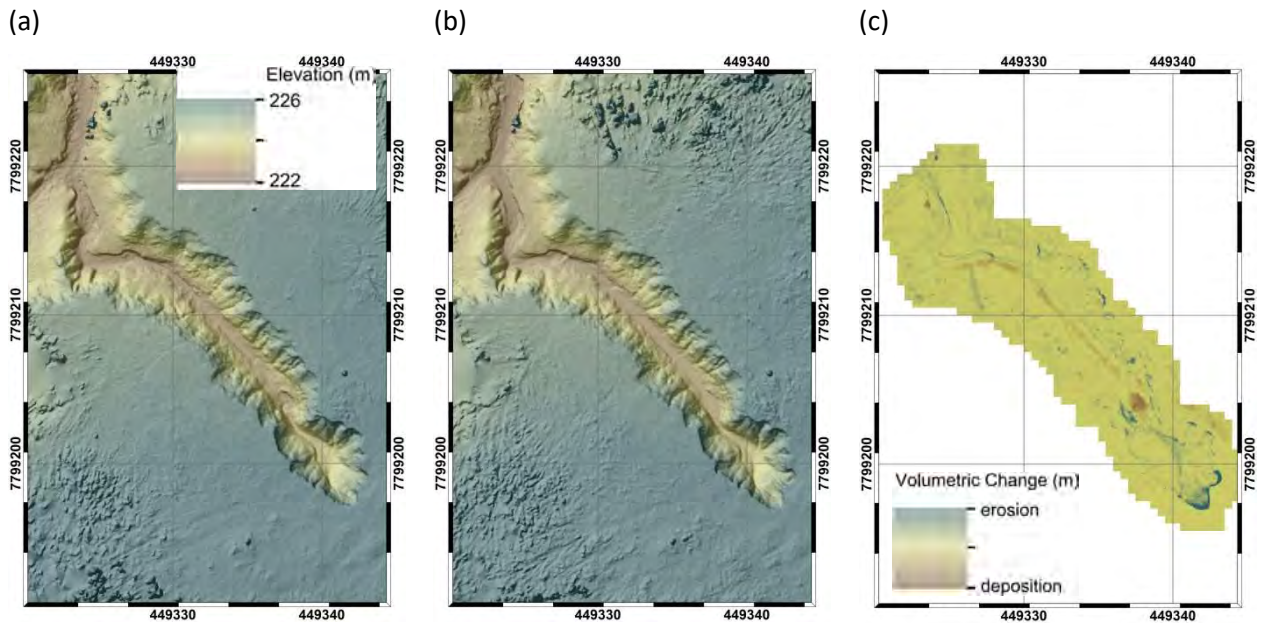


Figure 21: Virginia Park control: (a) 2016 DEM, (b) 2017 DEM and (c) DoD.

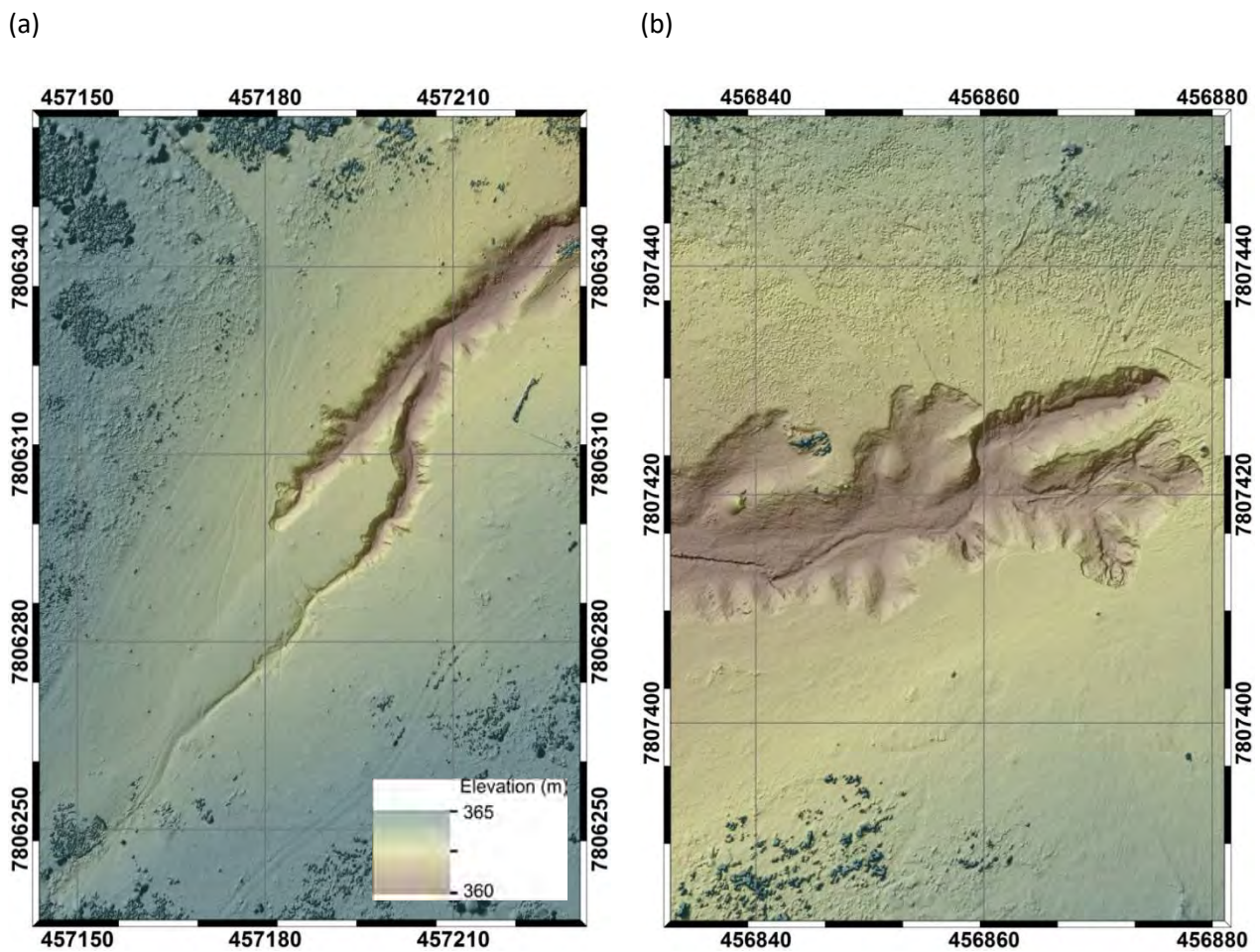


Figure 22: Meadowvale: (a) treatment and (b) control.

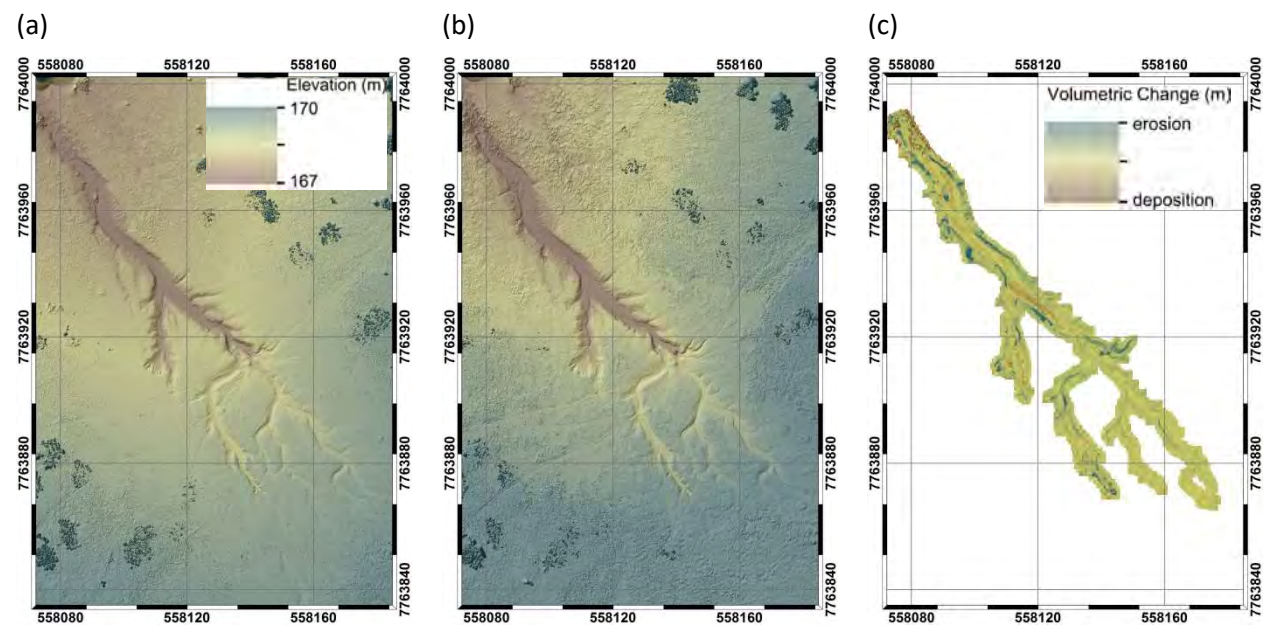
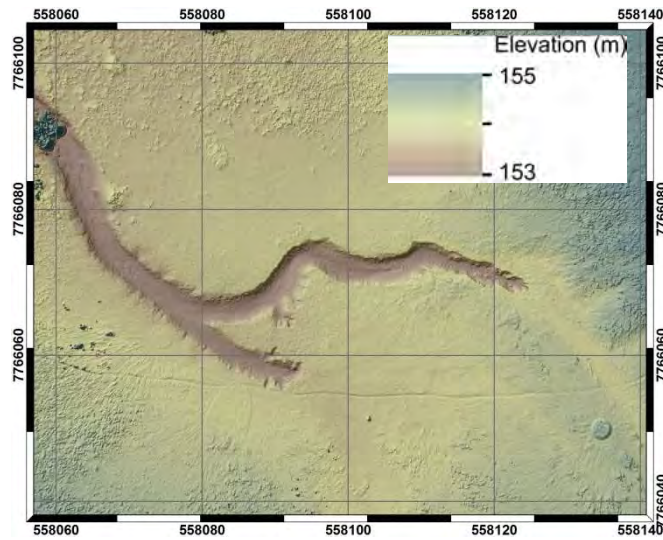


Figure 23: Strathbogie treatment: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.

(a)



(b)



(c)

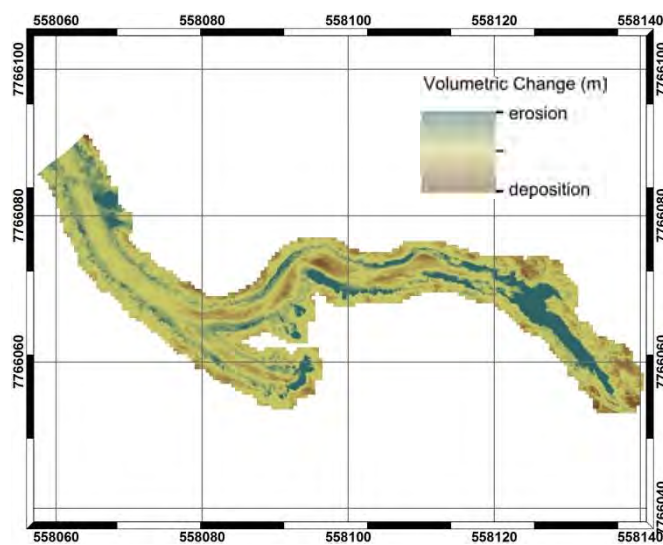


Figure 24: Strathbogie control: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.

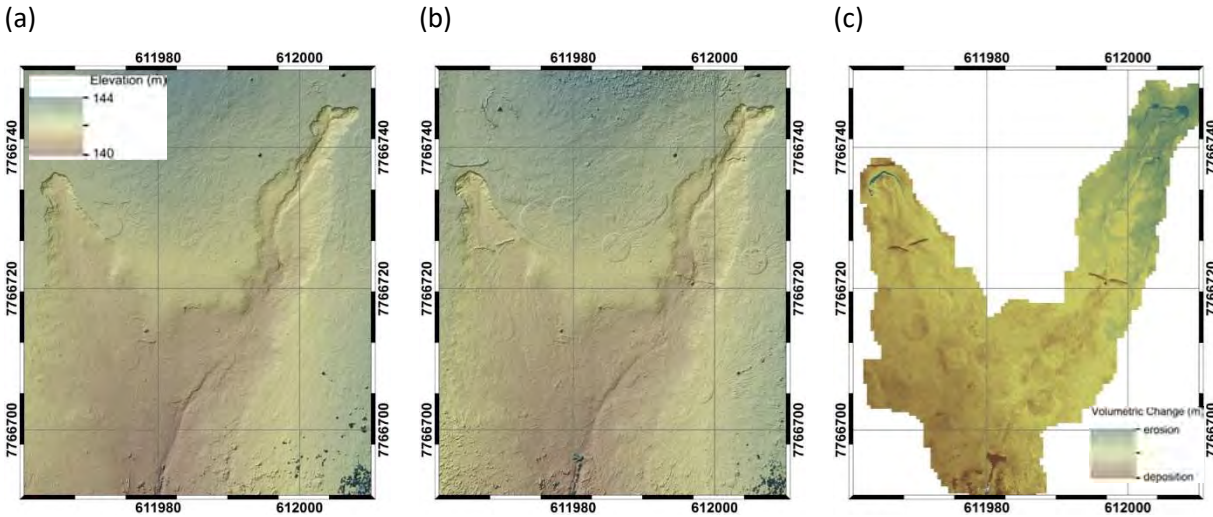


Figure 25: Minnievale treatment: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.

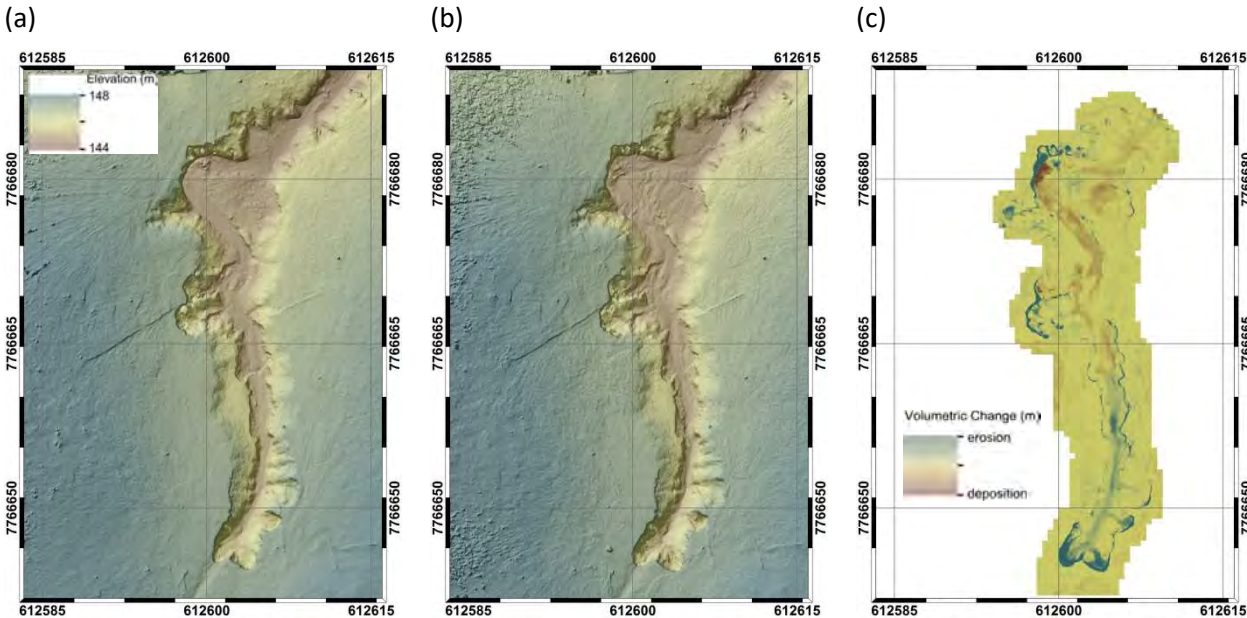


Figure 26: Minnievale control: (a) 2016 DEM, (b) 2017 DEM, and (c) DoD.

5.5 Rainfall, runoff, water quality and particle size

A summary of the rainfall, runoff and water quality data collected during the 2016/17 wet season (November 1 to April 30, 2017) for each of the sites is presented in Table 11. The rainfall and hydrographs for the wet season for each site are presented in Appendix B. Images of each of the four treatment gullies before, during and after an event are presented in Figure 27 to Figure 30.

The rainfall for the Upper Burdekin sites (Virginia Park and Meadowvale) was well below the long term annual average for the region, as this area did not receive any significant rainfall from Cyclone Debbie (Table 11). Interestingly, the rainfall for the Strathbogie and Minnievale sites, which were in the direct path of Cyclone Debbie, was still less than average annual rainfall for the area, but of the rain that did occur at this site ~30-50% fell during the Cyclone Debbie event.

Water depths were recorded in each gully, and were used to generate stage hydrographs from which the samples for water quality analysis were chosen (Appendix A). Unfortunately, after extensive sensitivity testing with the Hec-Ras model, it was decided that the estimated discharge results were too variable and in general the model was under-predicting flow compared with other calibrated monitoring stations installed at the sites. Therefore, no discharge calculations are presented for this wet season at any of the sites. To allow for more accurate estimates of discharge, velocity sensors have been ordered for the eight gullies and they will be installed prior to next wet season. Based on the rating curve that will be generated using the new velocity sensors, discharge estimates will be back calculated for the 2016/17 wet season.

A comparison in the Total Suspended Sediment (TSS) and Total Nitrogen (TN) concentrations between control and treatment gullies for all sites are presented in Figure 31 and Figure 32, and the mean $\pm$ standard error (SE) estimates are presented in Table 11. Overall, there were less samples collected from the control sites as this was an event based sampler only; and only one sample was collected per event. The treatment sites had many more samples as these were instrumented with the more expensive 24 bottle ISCO samplers that can sample across an event (Appendix B). The system design was based on the instrument funding available.

There were considerably more TN samples collected from the Virginia Park treatment site due to the amount of runoff as well as the proximity and access of this site to CSIRO staff. At the other sites, the samples needed to be collected, filtered and processed or frozen within 24 or at most 48 hours (Baker et al., 2016). This was more challenging at the other sites, and access to Strathbogie and Minnievale was severely restricted immediately after Cyclone Debbie.

The highest TSS concentrations were measured at Strathbogie which reached 10,000 mg/l, and the lowest concentrations were 220 mg/l at the Virginia Park treatment gully (Table 11). The highest TN concentrations were ~8,790 mg/l at Meadowvale, and the lowest TN concentrations were 595 mg/l, again at the Virginia Park treatment gully.

There were insufficient samples for some sites to undertake classic significance testing of the mean values, however, preliminary visual assessment suggests that there is no major difference between the control and treatment mean TSS concentrations at the Meadowvale and Strathbogie sites. This is appropriate and suggests that these gullies are exporting similar amounts of fine sediment in their un-treated condition. At Virginia Park and Minnievale, the two sites that had active treatments, the TSS concentrations were lower in the treatment gully than on the control gully which provides some confidence that the treatments are working to reduce TSS concentrations within the gully, however, the exact mechanism is uncertain.

The TN concentrations between the control and treatment gullies (Figure 32) did not necessarily follow the same pattern as TSS, and possibly reflect the low sample numbers and soil type. There were also ant nests in several of the samplers that may have distorted nutrient values at some sites. Despite the TSS and TN data having slightly different patterns between the control and treatment gullies, there was reasonable correlation ($r^2 = 0.76$) between the TSS and TN concentrations when the data from all sites are grouped together (Figure 35).

Particle size data was collected from each of the treatment gully sites (Figure 33). We know from marine transport studies (Bainbridge et al., 2012) that it is the $< 4\text{-}16\text{ }\mu\text{m}$ sediment that travels the furthest in the marine system, and so based on these data the sediments from the Strathbogie gully are the smallest (mean $= 5.4\text{ }\mu\text{m}$) and most likely to be transported, all other things being equal. The mean particle size of sediments from Meadowvale are considerably larger (mean $= 22.5\text{ }\mu\text{m}$) than all other sites. Virginia Park and Meadowvale soils and landscapes are very similar, and the mean particle size may be lower at Virginia Park (mean $= 7.3\text{ }\mu\text{m}$) than at Meadowvale treatment because of the much higher ground cover and biomass within the gullies. This is supported by the cover and biomass data presented in Table 8 where the % cover at the Virginia Park treatment, which has been active for ~ 7 years, has ~ 3.8 times more % cover and ~ 2.4 times more biomass, than the yet to be treated Meadowvale site. The vegetation would be slowing down the water and dropping out the larger sediment particles. Therefore only the very fine fractions would be moving through to the sampler. Despite Strathbogie having both the highest mean TSS concentration (mg/l) and lowest particle size (μm) there is no relationship between these two sediment descriptors across all four sites (Figure 34), and a weak but positive relationship between gully upslope catchment area and maximum TSS concentration (Figure 36). We were not necessarily expecting a strong relationship between TSS and particle size, as particle size is more closely associated with soil properties, however, we are trying to find any relationships that may be useful for scaling up and extrapolating results to other sites, which would reduce the need for detailed measurements at all locations. There was insufficient data to compare particle size with TN concentration.



Figure 27: Treatment gully at Virginia Park before (left) and during (middle) an event and at the end of reporting period (April 2017)



Figure 28: Treatment gully at Meadowvale before (left) and during (middle) an event and at the end of reporting period (April 2017)



Figure 29: Treatment gully at Strathbogie before (left) and during (middle) an event and at the end of reporting period (April 2017)



Figure 30: Treatment gully at Minnievale before (left) and during (middle) an event and at the end of reporting period (April 2017)

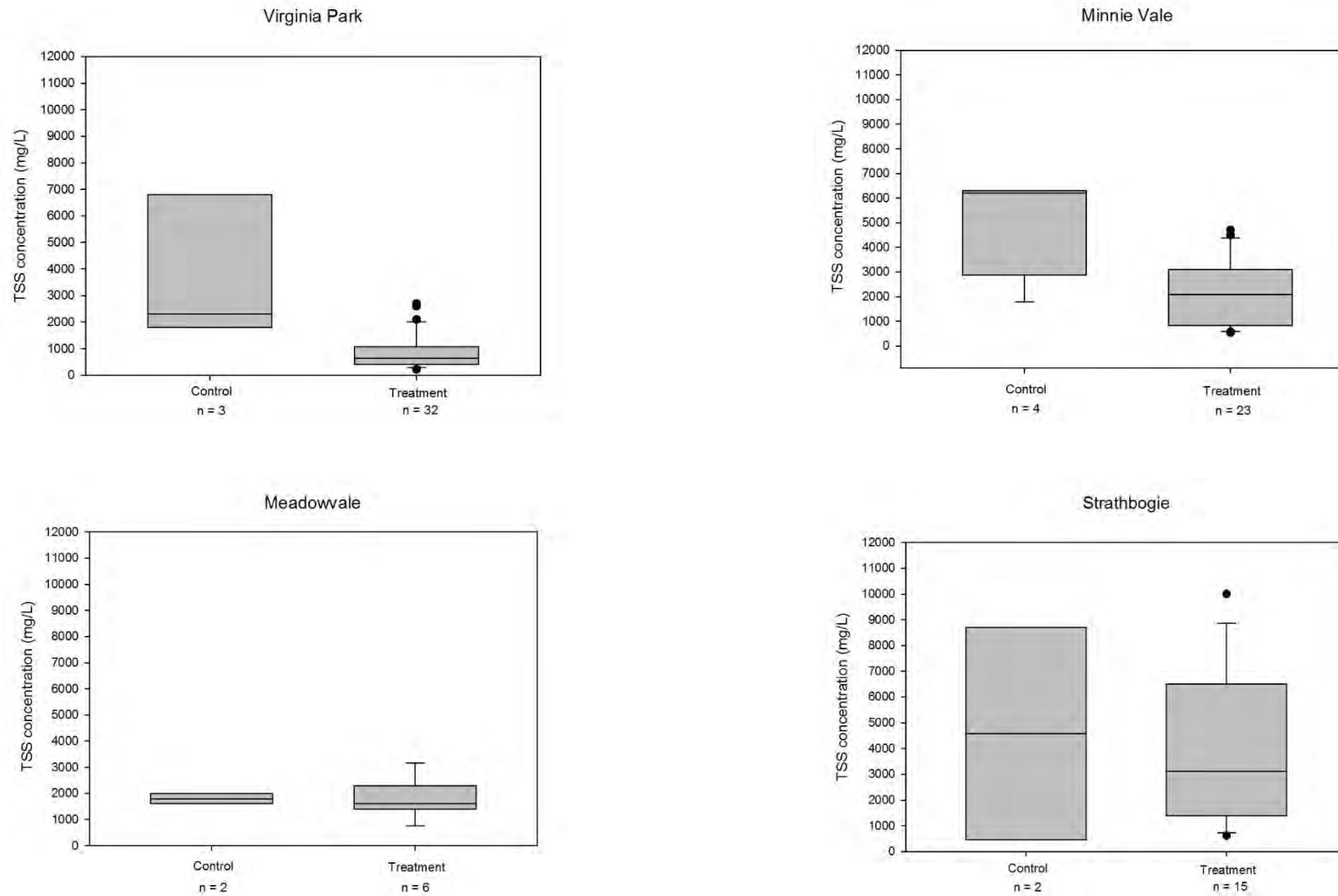


Figure 31: TSS concentration at each site for the Control and Treatment gullies. Note that only Virginia Park and Minnievale have active treatments in place by Nov 2016.

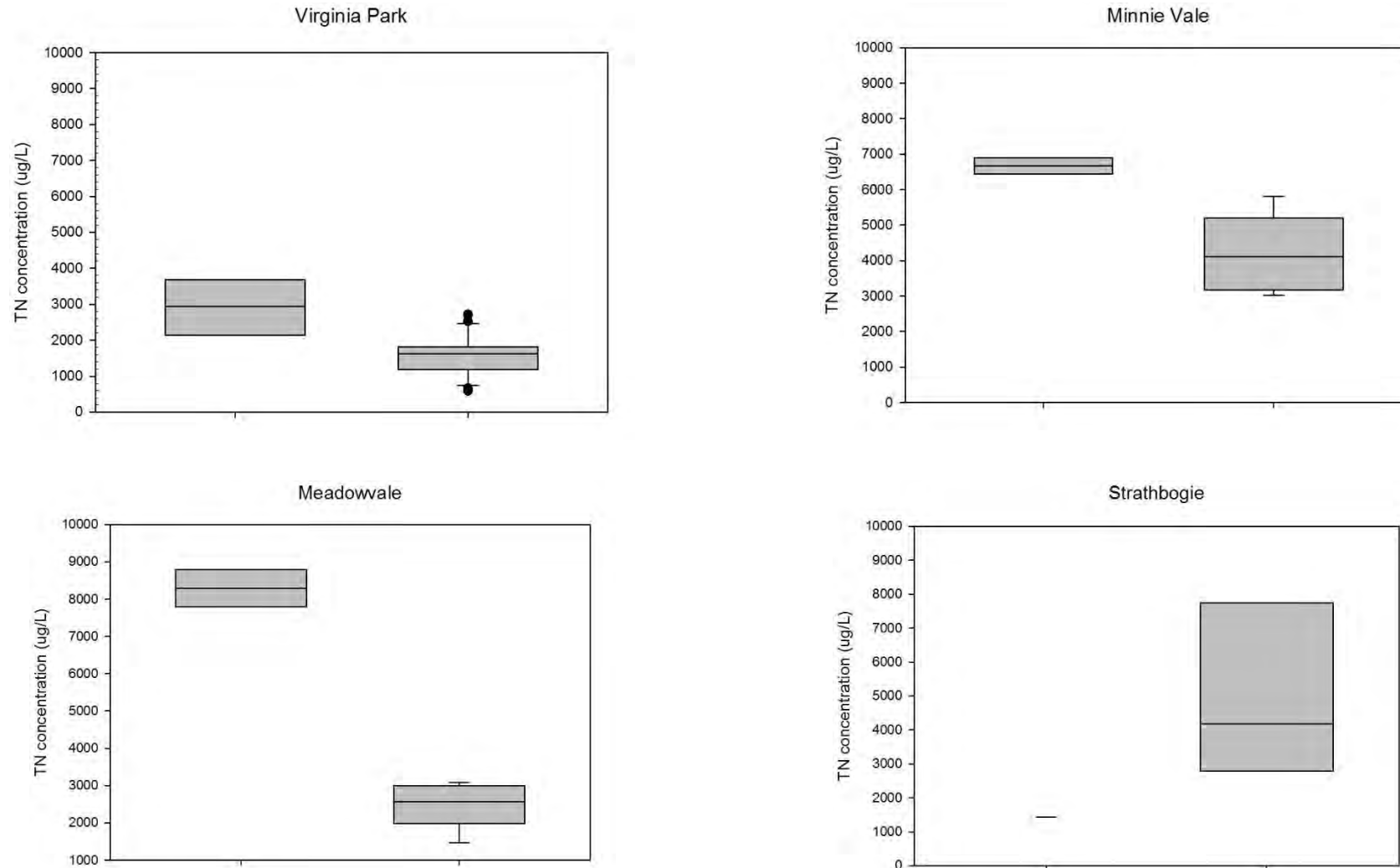


Figure 32: TN concentration at each site for the Control and Treatment gullies. Note that only Virginia Park and Minnievale have active treatments in place by Nov 2016.

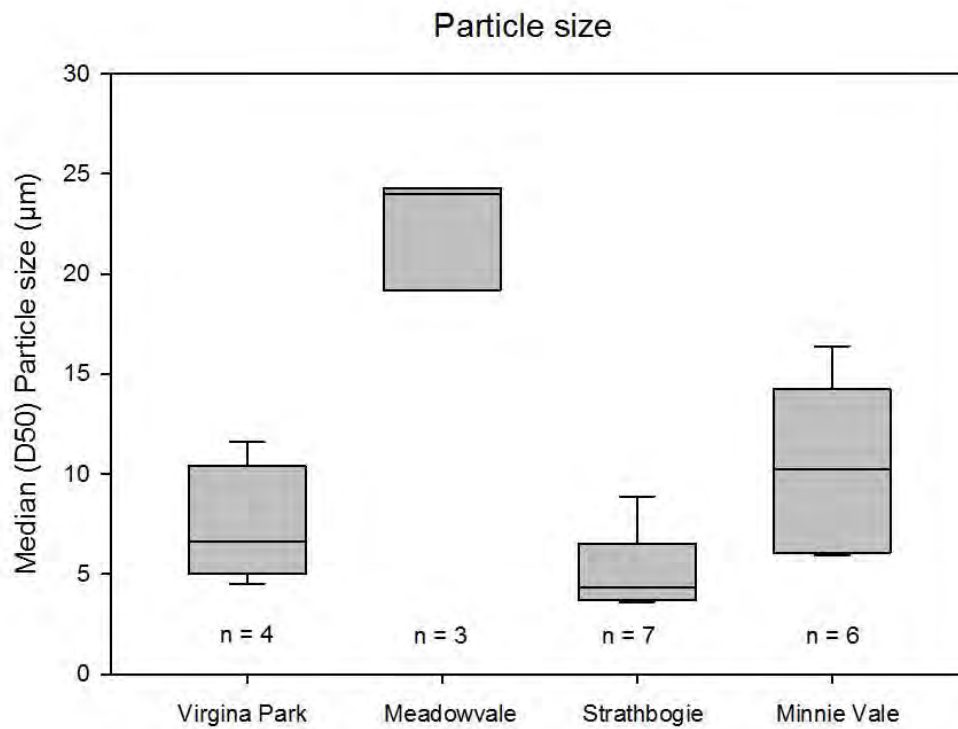


Figure 33: Particle size of suspended sediment collected the Treatment Gully at each of the four sites over the 2016/17 wet season

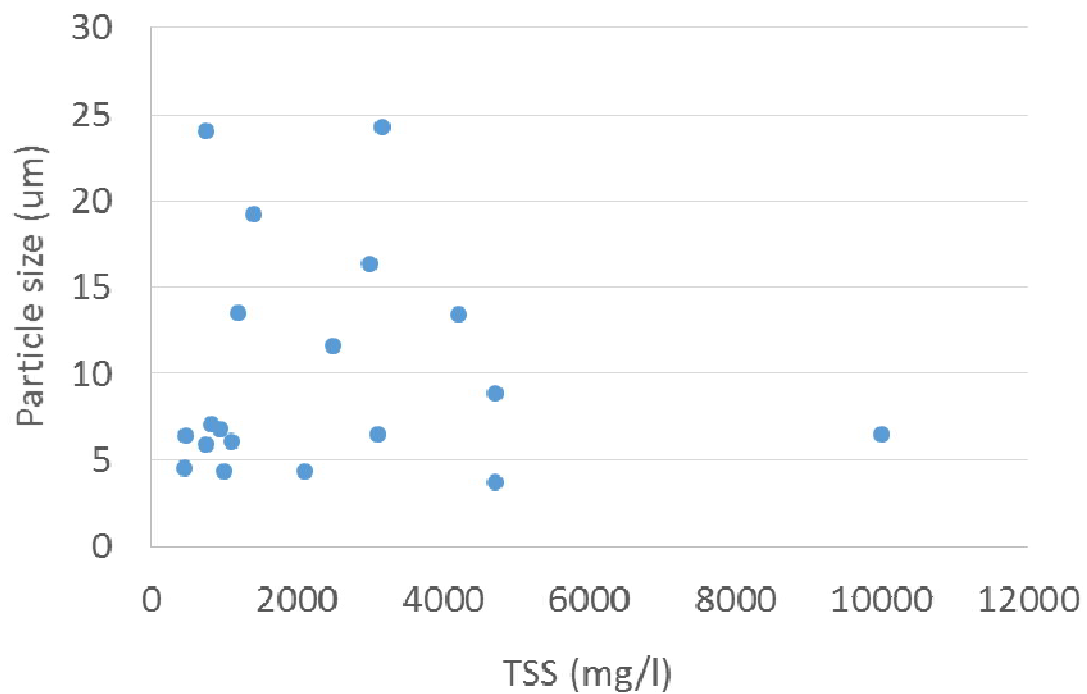


Figure 34: The relationship between TSS (mg/l) and particle size (µm) from samples collected during flow events in the treatment gullies

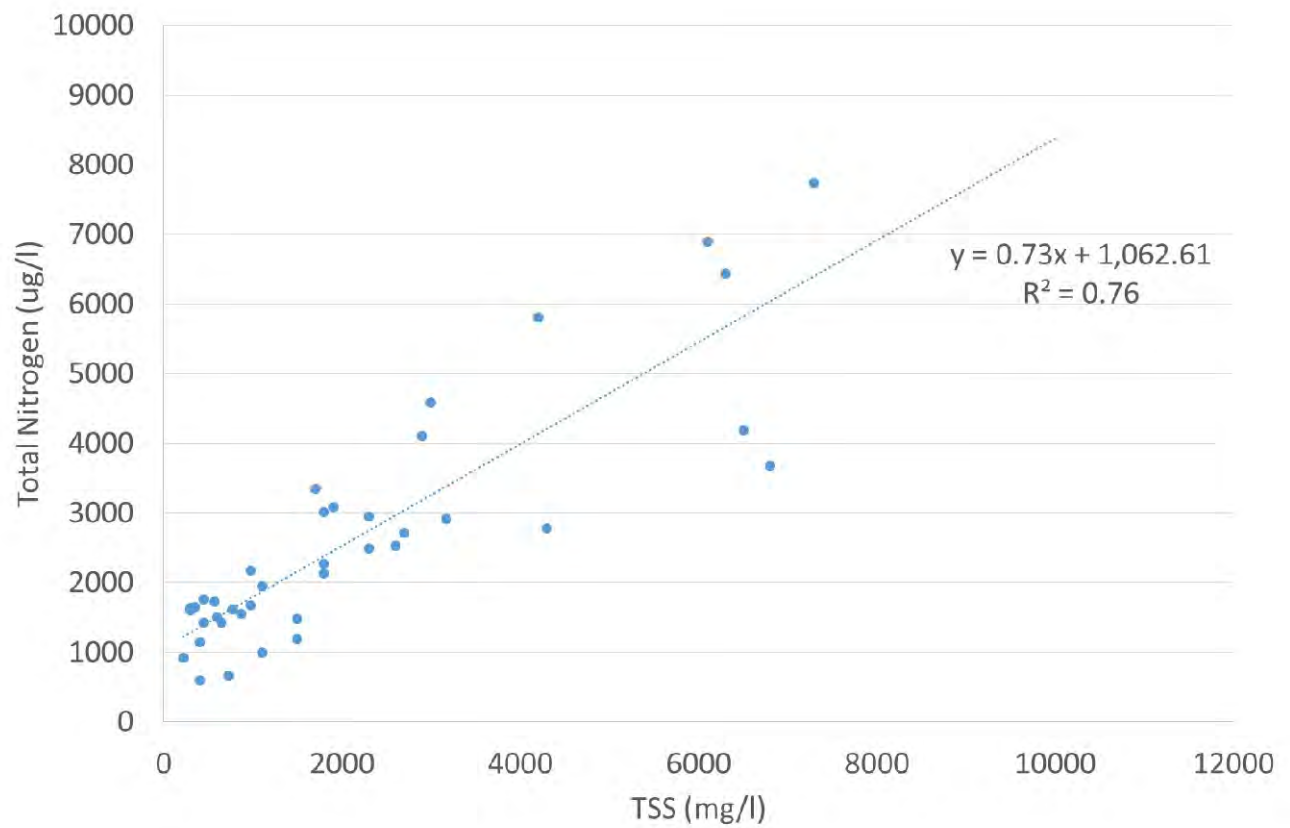


Figure 35: The relationship between TSS (mg/l) and TN (mg/l) for all samples collected during flow events across all eight gullies. Note two extreme outlier values were removed.

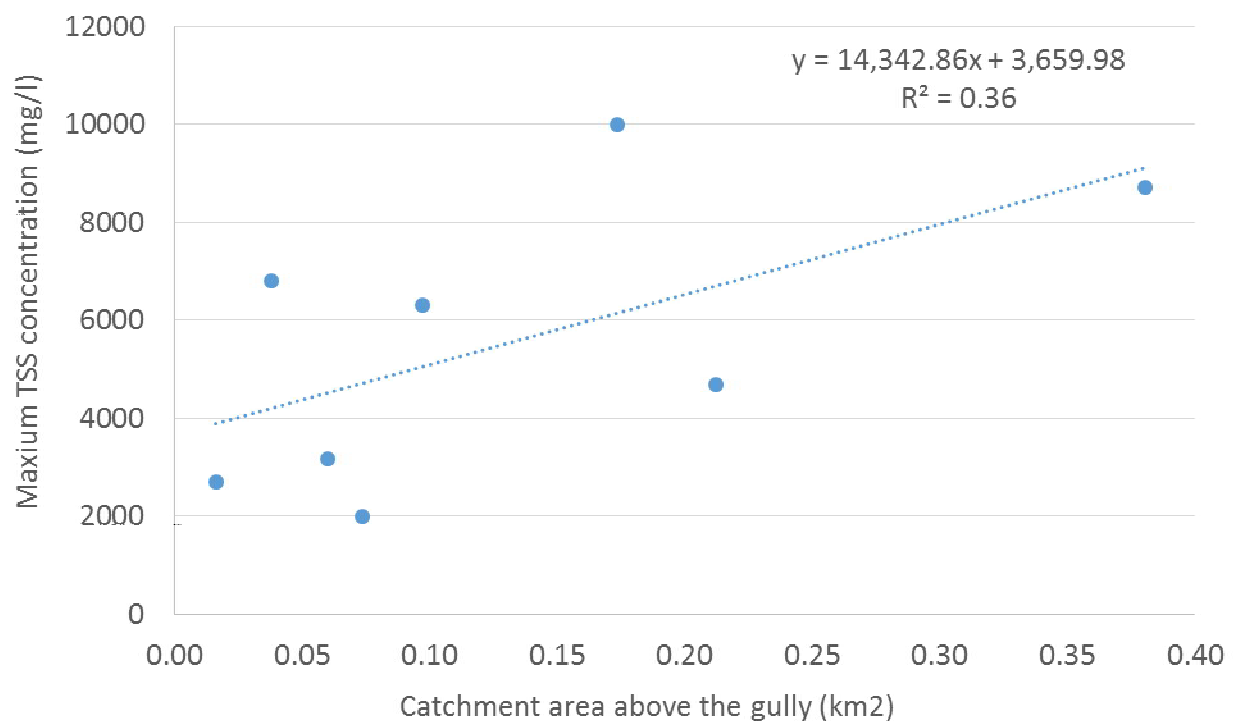


Figure 36: Relationship between upslope catchment area (km²) and the maximum measured TSS value (mg/l).

Table 11: Summary of rainfall, runoff, water quality concentration and loads for each of the sites for the 2016/17 wet season. The Minnievale access road was out of action after the cyclone and the post wet vegetation sampling will be done in June.

		Virginia Park		Meadowvale		Strathbogie		Minnievale	
		Treatment	Control	Treatment	Control	Treatment	Control	Treatment	Control
Site Rainfall (mm)	2016-2017 (Jul-Mar)	345 mm	320 mm	402 mm	342 mm	577 mm	608 mm	730 mm	797 mm
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)	
Number of events		5	2	2	2	2	2	4	4
Catchment area (km ²)		0.016	0.038	0.06	0.074	0.174	0.038	0.021	0.097
Catchment area (ha)		1.6	3.8	6	7.4	17.4	38.1	21.2	9.7
Slope – hillslope above gully (%)		4.3	3.9	2.9	3.0	2.1	2.2	2.0	2.9
Slope – gully bed (%)		1.5	2.9	1.1	1.3	1.0	0.7	0.7	1.1
Hillslope Cover (%)	Pre- wet	61	59	58	46	52	54	67	53
Gully walls (% cover)	Post-wet	34	27	31	24	24	52	TBD	TBD
Gully floor (% cover)	Post-wet	53	16	14	12	24	14	TBD	TBD
TSS concentration (mg L ⁻¹)	Mean ± SE	877 ± 115 (n =32)	3633 ± 1590 (n =3)	1804 ± 289 (n =6)	1800 ± 200 (n =2)	3955 ± 753 (n =15)	4573± 4127 (n =2)	2204 ± 277 (n =23)	5125 ± 1109 (n =4)
	Range	220 to 2700	1800 to 6800	760 to 3170	1600 to 2000	620 to 10,000	445 to 8700	540 to 4700	1800 to 6300
TN (mg L ⁻¹)	Mean ± SE	1587 ± 116 (n= 34)	2919 ± 445 (n=3)	2507 ± 281 (n=7)	8297 ±493 (n=2)	4904 ± 1476 (n=5)	1429 (n=1)	4170 ± 494 (n=6)	6668 ± 228 (n=2)
	Range	595 to 2714	2134 to 3675	1474 to 3087	7803 to 8790	2782 to 7742	-	3014 to 5809	6440 to 6896
Median particle size (µm)	Mean ± SE	7.34 ± 1.5		22.5 ± 1.7		5.4 ± 0.7		10.4 ± 4.6	

6 DISCUSSION

The main aim of this project was to quantify the effectiveness of gully erosion control activities (gully remediation) on erosion processes and water quality. Achieving this within a diverse biophysical landscape is challenging because erosion is dependent on many variables including climate variations. We are accounting for and monitoring as many of the landscape attributes which affect gully erosion (e.g. soil type, geology, rainfall, vegetation, terrain) to increase our ability to identify the effects of erosion remediation activities separate from other factors.

The initial aim of this project was to monitor sites that were part of the Reef Trust Gully Erosion Control Programme. However, due to the timing of activities at those sites, and our requirement for well-matched control gullies at each site, only two out of the four sites are in the Reef Trust Programme. We have consequently also included additional sites used in previous CSIRO research funded by Meat and Livestock Australia and the Paddock to Reef Program.

Of the four sites in this project, two had undergone active remediation prior to the start of the 2016/17 wet season (Virginia Park and Minnievale). The delay in the implementation of remediation activities at the other properties (Meadowvale and Strathbogie) worked in our favour in terms of providing pre-treatment data. However, this will also reduce the number of years that we will be able to report post-treatment within this project. The Virginia Park site has the added benefit that it provides a longer term (7 year) insight into the effectiveness of some of the treatment options.

Despite delays with the remediation activities at some sites, the monitoring instrumentation and infrastructure for the NESP project was installed at all eight gully sites by the start of the 2016/17 wet season. We were able to refine the sampling routines iteratively between early events to best match the gully morphology and rainfall distribution across the sites. Working with partners in the Reef Trust Gully Erosion Control Programme facilitated the collection of water quality samples following events, and also helped to identify some of the challenges with remote site access and sample processing. The installation of cameras at each site also helped to troubleshoot problems with the depth and turbidity probes. Velocity sensors will be installed at all sites in 2017 to provide more robust estimates of discharge.

The ground based landscape condition analysis determined that all of these sites are in C or D condition, with a small proportion (<20%) of the Virginia Park treatment hillslope transitioning to B condition post wet season. The pasture metrics measured on the hillslopes suggest that these sites are all very similar as they are dominated by the exotic, but naturalised pasture species Indian couch, forbs, and/or exotic legumes. This is characteristic of areas where heavy grazing has occurred over long periods, and is typical of State 3 and 4 grazing systems as specified within pasture state and transition models (McIvor and Scanlan, 1994; Ash et al., 2011). In these cases, exotic species have become dominant and replaced native species, the soil has become degraded through an increase in erosion, topsoil compaction and reduction in infiltration. A return to a higher condition from this level requires long time periods (>10 years) of wet season rest and reduced forage utilisation, with pasture composition returning only gradually towards native perennial tussock grasses (Bartley et al., 2014). Mechanical intervention such as ploughing and reseeding may accelerate the process but is not proven. The initial wet season monitoring of forage has indicated that while the % cover and biomass (kg/ha) may be higher at Virginia Park, which has undergone grazing land management over the last decade, the plant basal area is still low. This highlights that a combination of pasture metrics is required to quantify the functional vegetation attributes at these sites, and that reinstating eco-hydrological function in these degraded landscapes is challenging.

The monitoring of ground cover within gullies indicates that livestock exclusion is effective at increasing cover in the long term. However, this monitoring also emphasised that there is significant natural variability between ground cover within gullies independent of treatments, possibly due to differences in gully morphology.

The monitoring of historical and contemporary gully erosion rates has identified that there is large variability in erosion rates within years at the same site, as well as between sites within the same landscape. The linear gully extension rates at Virginia Park in 2016/17 appear to be very similar to the long term average (1960 -2009), however, Strathbogie appears to be above, and Minnievale below, the long term averages at those sites, respectively. Overall, it appears that the catchment area upslope of the gully head-cut is the best predictor of contemporary gully erosion and may be a useful metric for scaling up the results from these individual gully assessments to whole properties or landscapes. Access to Lidar or high resolution DEM's would help with these predictions.

Terrain based monitoring of gully erosion (t/m) is useful for telling us how much soil is eroded from each gully head-cut. It can also tell us the proportion of that sediment that is deposited within the surveyed area. The terrain data does, however, include all of the sediment fractions (fine and coarse). The measured water quality (TSS, TN and particle size) is a more robust representation of the fraction of sediment that is mobilised within the runoff and has the potential to be transported downstream and out to the GBR. Unfortunately there is not yet any useful relationship between the measured amount of sediment eroded (t/m) and TSS concentration between the sites, however, there is moderate relationship between catchment area and TSS ($r^2 = 0.36$). TSS concentrations can exhibit non-linear relationships with flow and catchment conditions (Kuhnert et al., 2012; Gray et al., 2014), and more data is required to understand this relationship. It is hoped that calculations of runoff will improve our understanding of the factors influencing sediment concentration within gullies.

At this stage in the study, Virginia Park is the only site that provides an estimate of the long term effectiveness of gully remediation. Even at this site we only have a single year of TSS concentration data at the control gully to compare against the seven years of treatment data. The erosion rates at the treatment gully are actually higher than at the control gully (despite a smaller catchment area), however, the proportion of sediment being deposited in the treatment gully is higher, and the TSS and TN concentrations are significantly lower at the treatment, compared to the control. This suggests that the porous check dam instream structures are effective at improving downstream water quality. Further monitoring will improve understanding of the primary drivers of this response so that we can extrapolate the results to other areas.

7 CONCLUSION AND AREAS OF FURTHER WORK

This report presents the results from a single, drier than average, wet season. Based on this initial sampling season, there are a number of insights, including that:

- Even dry years can generate considerable sediment loads from hillslope gullies;
- Minnievale and Virginia Park both have similar soils and gully systems and have yielded similar results, which will allow us to more confidently extrapolate the long term observations from the Upper Burdekin Chromosol landscape into the Bowen/Bogie/Don Chromosol landscapes;
- However, the results in Strathbogie show that other hillslope gully types may behave very differently. This means we should expand the number of gully sites to cover more interventions on Vertosols. This could be facilitated either through Queensland State Government Major Investment Projects (MIPs) and/or Reef Trust. This would also need to be supported with high quality monitoring such as that currently used within this NESP project;
- It can take ~10 years to represent the average rainfall period in many areas in the Burdekin (Bartley et al., 2014), and therefore, several wet seasons are going to be required to provide robust results from this project. NESP will best capitalise on this initial investment by extending this project for another 3 years so that a range of wet and dry seasons are captured;
- An extension of this project will also allow greater opportunity for the extension and communication of the results, and provide the opportunity for more grazer involvement.

In the remainder of this project we will continue the monitoring described in this report. In addition to the monitoring, we plan to:

- Install the runoff velocity sensors at each of the eight gully sites to allow the calculation of runoff. This will allow us to investigate if the catchment area vs gully erosion (t/m) still holds for runoff;
- Quantify the difference between the hillslope and gully dynamics, in terms of partitioning runoff, water quality and particle size response. This will be undertaken at the Virginia Park and Meadowvale sites that have legacy hillslope monitoring stations;
- Investigate the longer term pasture dynamics using the GRASP model;
- Investigate the relationship between property management, historical stocking rates and gully density using a combination of data sources;
- Collate and interpret the various costs associated with each of the gully treatments to allow the calculation of cost effectiveness.

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9 APPENDIX A: FREQUENCY AND BIOMASS FUNCTIONAL GROUP DATA

Table 12: Frequency % and biomass represented by vegetation functional groups

Post Dry	Virginia Park		Meadowvale		Strathbogie		Minnievale	
Functional Group	Freq%	Biomass%	Freq%	Biomass%	Freq%	Biomass%	Freq%	Biomass%
Control								
Grasses - native perennial decreaser	15	5	3	1	10	1	20	6
Grasses - native perennial increaser	5	1	0	0	0	0	3	0
<i>Grasses - exotic perennial</i>	95	48	100	94	80	38	100	82
<i>Grasses - native annual</i>	0	0	0	0	0	0	0	0
Grasses - exotic annual	5	0	0	0	0	0	0	0
<i>Forbs - native</i>	25	2	27	5	53	14	37	3
<i>Forbs - exotic</i>	20	1	3	0	90	29	53	6
<i>Legumes - native</i>	70	8	0	0	63	8	30	2
<i>Legumes - exotic</i>	80	34	0	0	47	9	0	0
<i>Sedges</i>	0	0	0	0	3	1	3	0
Treatment								
Grasses - native perennial decreaser	11	0	7	1	3	0	41	10
Grasses - native perennial increaser	39	2	2	0	0	0	4	2
<i>Grasses - exotic perennial</i>	93	29	98	84	87	53	91	73
<i>Grasses - native annual</i>	0	0	0	0	0	0	0	0
Grasses - exotic annual	0	0	0	0	0	0	0	0
<i>Forbs - native</i>	18	1	64	15	67	11	37	4
<i>Forbs - exotic</i>	4	1	0	0	80	22	72	8
<i>Legumes - native</i>	11	0	0	0	50	12	41	2
<i>Legumes - exotic</i>	100	66	5	0	17	1	4	1
<i>Sedges</i>	4	1	0	0	3	0	2	0
Post Wet								
Functional Group	Freq%	Biomass%	Freq%	Biomass%	Freq%	Biomass%	Freq%	Biomass%
Control								
Grasses - native perennial decreaser	12.50	4.71	3.33	0.50	6.67	0.30	-	-
Grasses - native perennial increaser	9.38	3.95	0.00	0.00	0.00	0.00	-	-
<i>Grasses - exotic perennial</i>	100.00	74.18	100.00	93.53	93.33	35.07	-	-
<i>Grasses - native annual</i>	0.00	0.00	0.00	0.00	0.00	0.00	-	-
Grasses - exotic annual	0.00	0.00	0.00	0.00	0.00	0.00	-	-
<i>Forbs - native</i>	31.25	1.30	43.33	3.55	56.67	12.52	-	-
<i>Forbs - exotic</i>	0.00	0.00	3.33	0.03	66.67	24.90	-	-
<i>Legumes - native</i>	68.75	3.76	43.33	1.34	83.33	5.33	-	-
<i>Legumes - exotic</i>	56.25	12.10	3.33	0.37	80.00	21.89	-	-
<i>Sedges</i>	0.00	0.00	6.67	0.67	0.00	0.00	-	-
Treatment								
Grasses - native perennial decreaser	15.63	3.25	20.00	7.84	0.00	0	-	-
Grasses - native perennial increaser	43.75	6.29	13.33	2.82	0.00	0	-	-
<i>Grasses - exotic perennial</i>	100.00	51.01	93.33	59.77	100.00	55.08	-	-
<i>Grasses - native annual</i>	0.00	0.00	0.00	0.00	0.00	0	-	-
Grasses - exotic annual	0.00	0.00	0.00	0.00	0.00	0	-	-
<i>Forbs - native</i>	25.00	0.34	53.33	6.58	100.00	23.39	-	-
<i>Forbs - exotic</i>	6.25	0.19	3.33	0.17	13.33	0.93	-	-
<i>Legumes - native</i>	15.63	0.28	76.67	18.67	83.33	12.96	-	-
<i>Legumes - exotic</i>	93.75	38.53	13.33	3.42	46.67	7.57	-	-
<i>Sedges</i>	6.25	0.12	10.00	0.73	3.33	0.07	-	-

10 APPENDIX A: WATER DEPTH, TURBIDITY AND SAMPLE HISTORY FOR EACH SITE

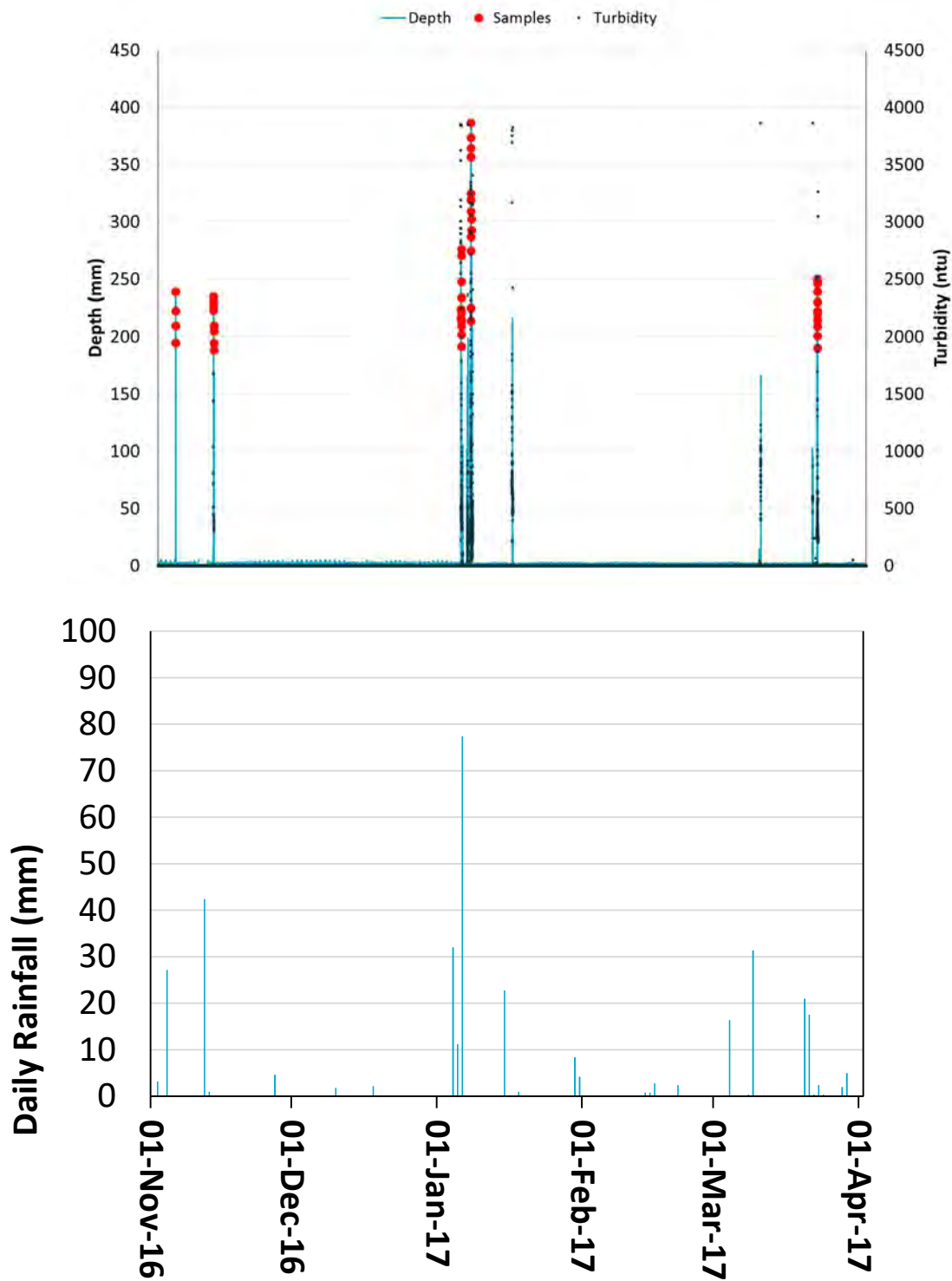


Figure 37: Virginia Park Treatment gully (top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

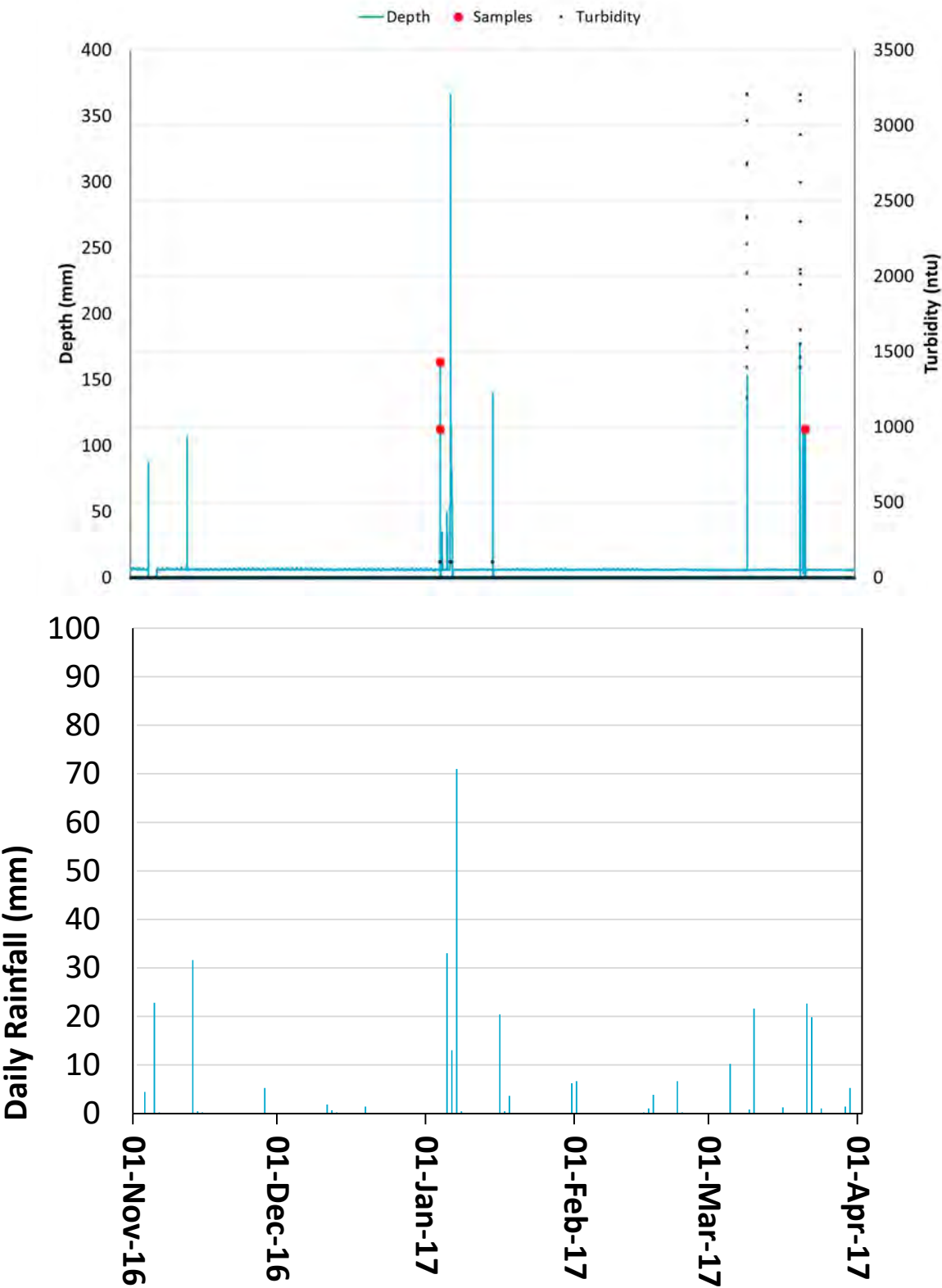


Figure 38: Virginia Park Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

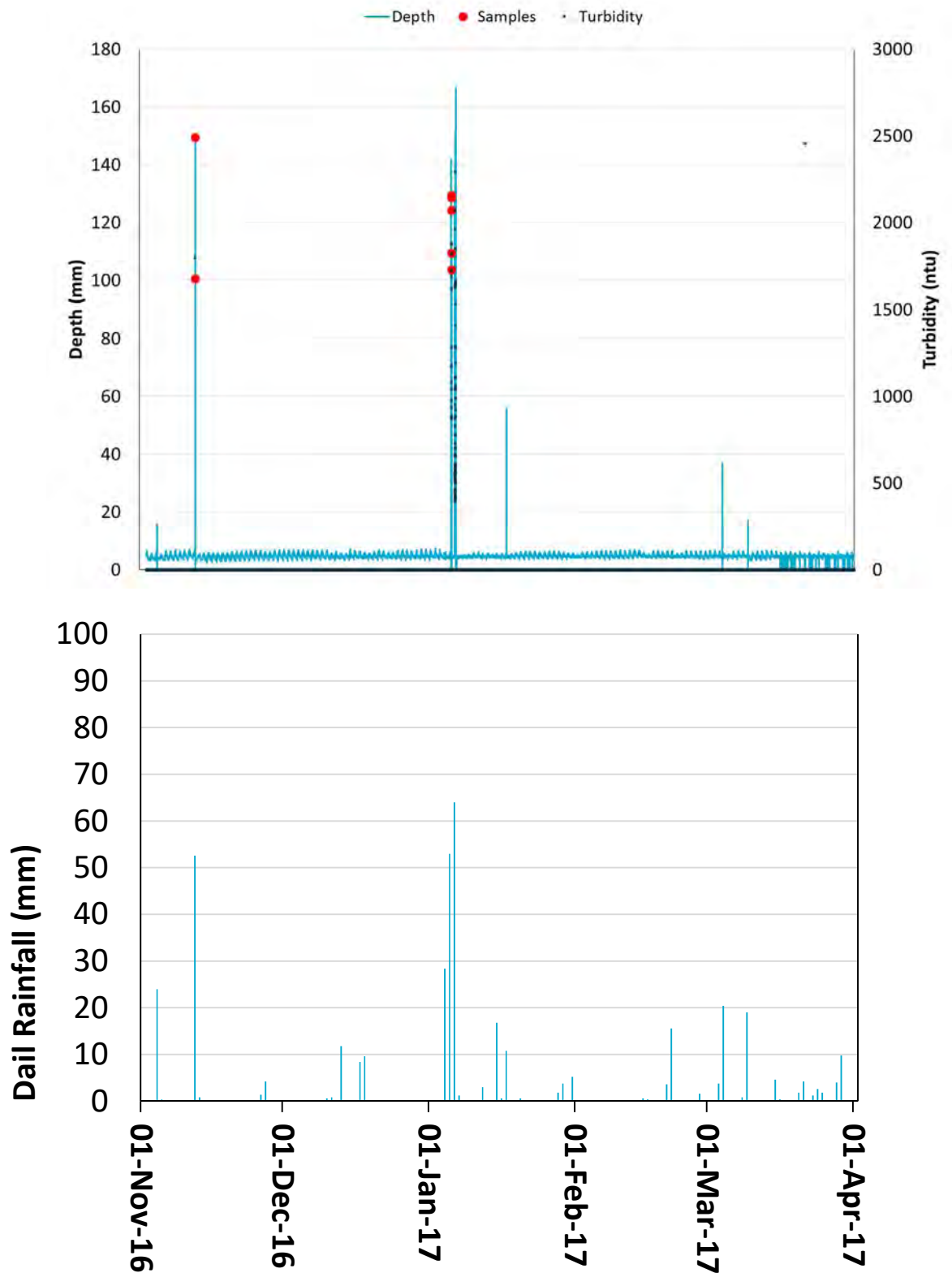


Figure 39: Meadowvale Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

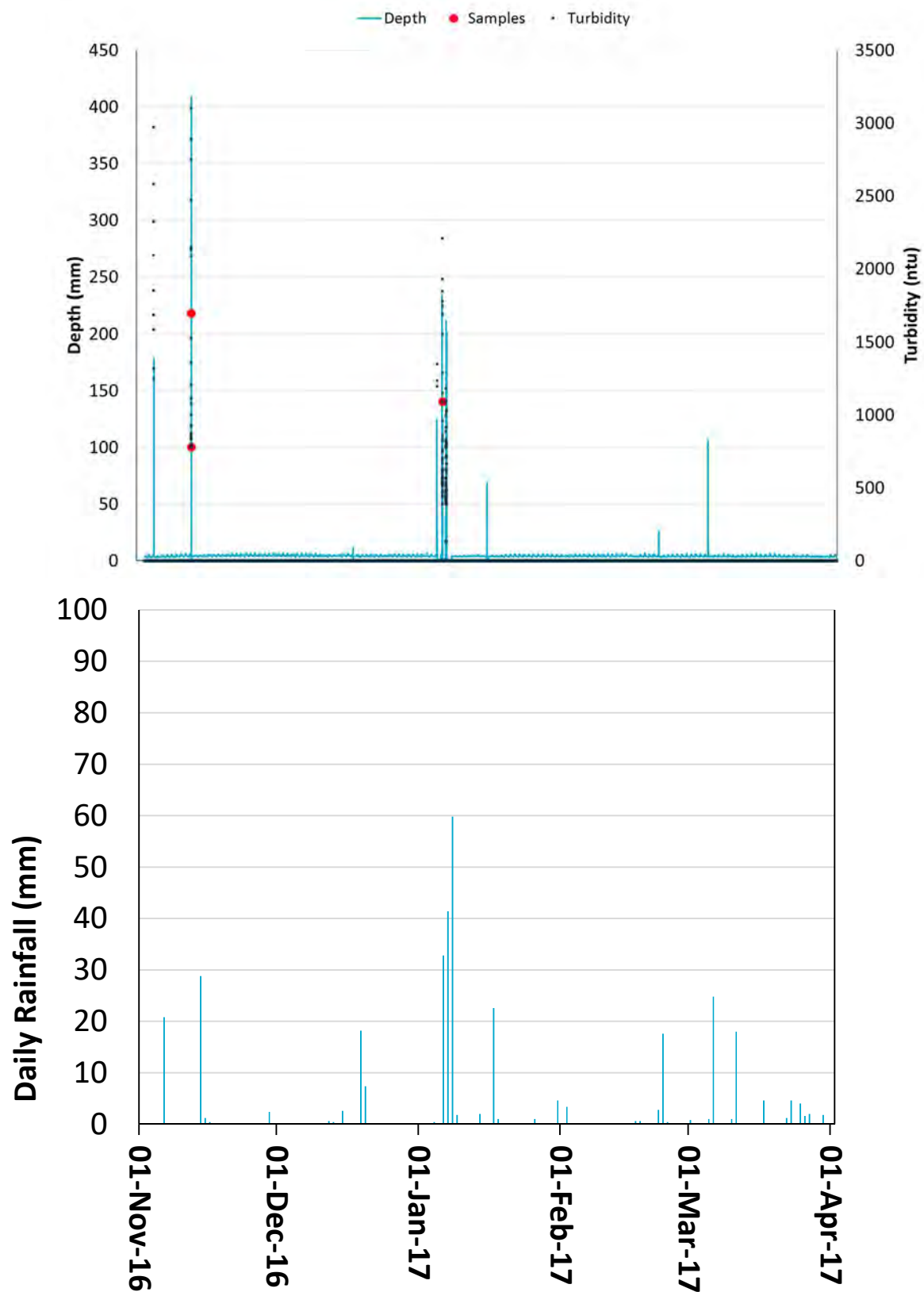


Figure 40: Meadowvale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

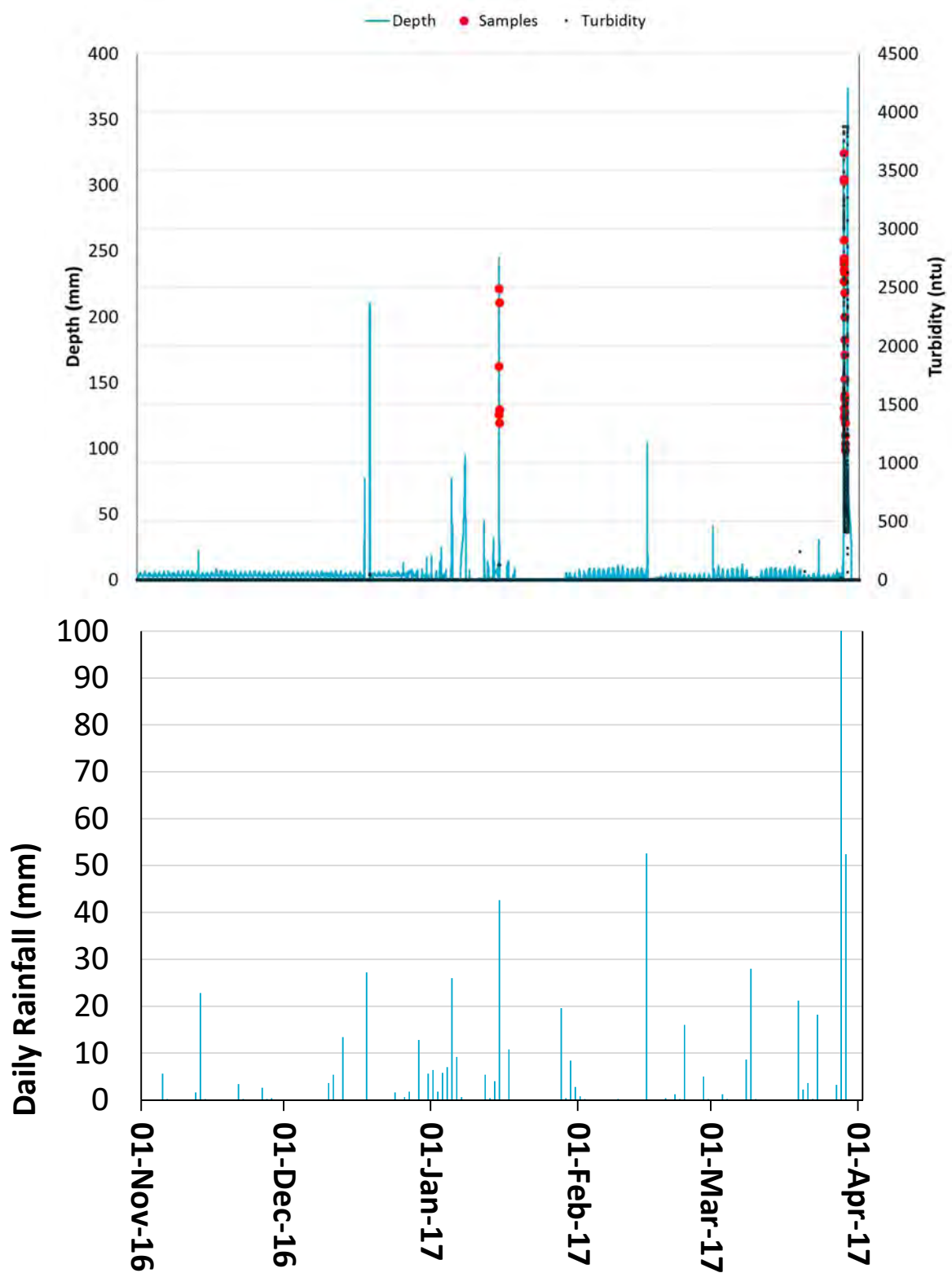


Figure 41: Strathbogie Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

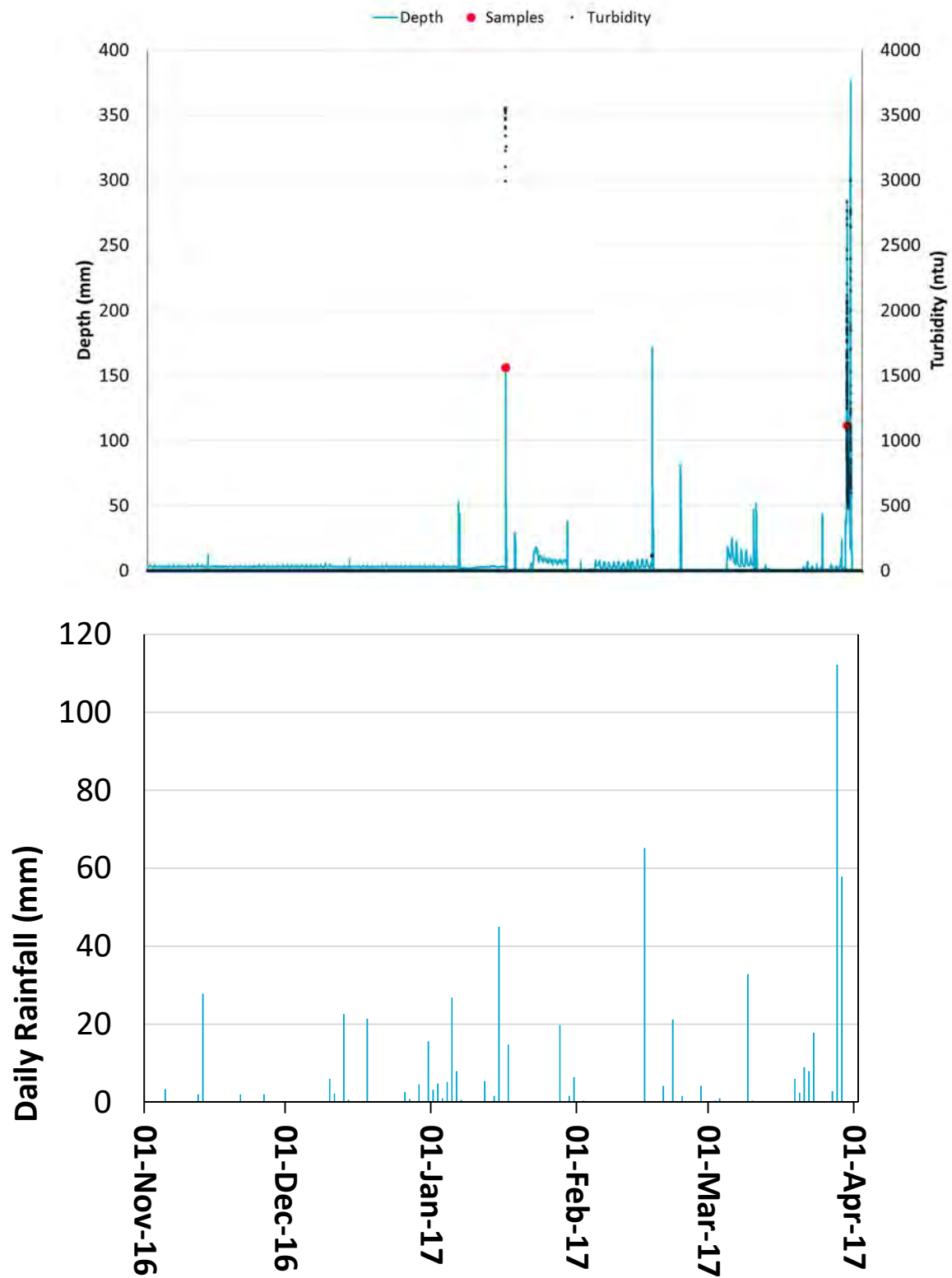


Figure 42: Strathbogie Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

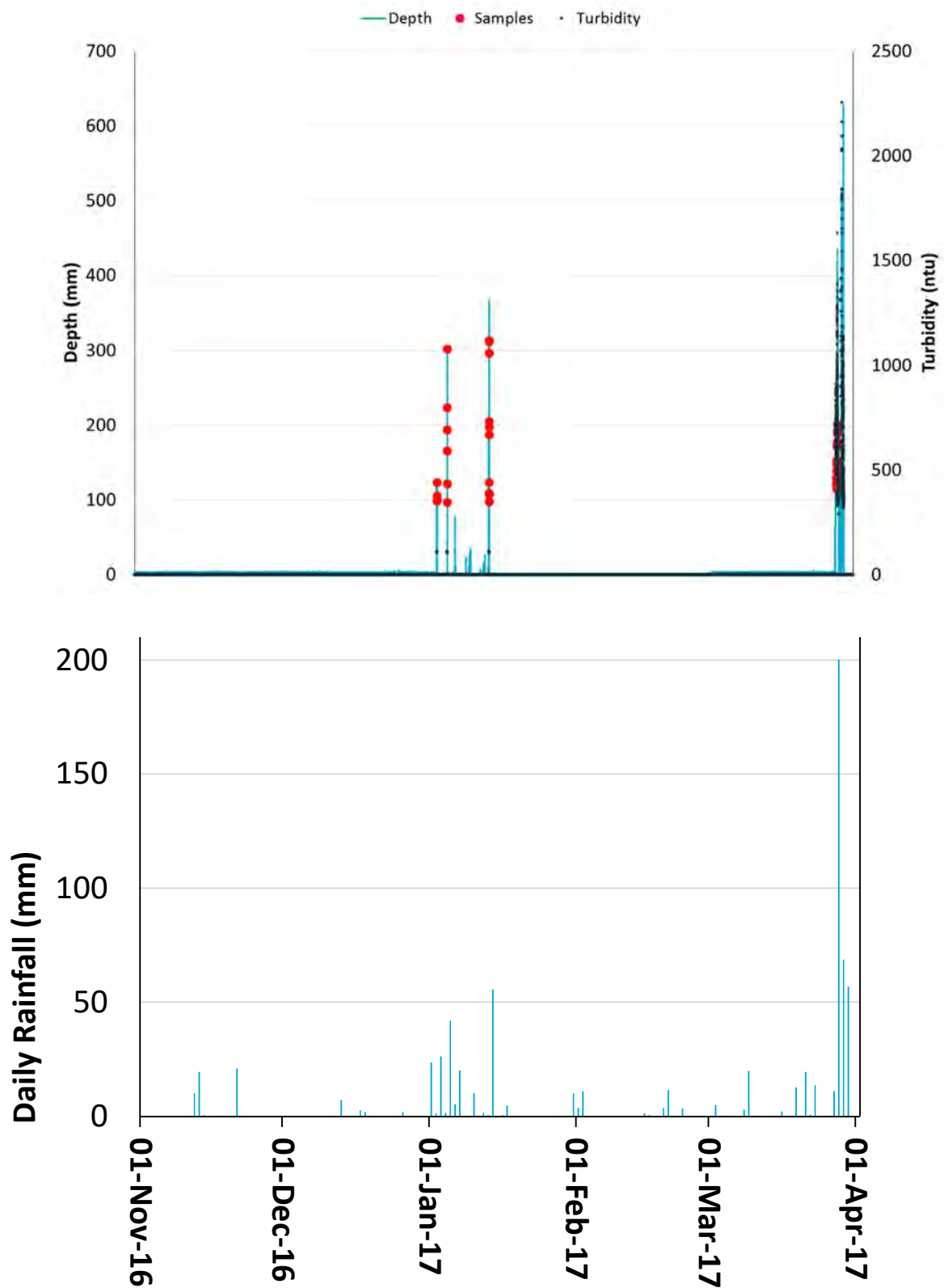


Figure 43: Minnievale Treatment gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

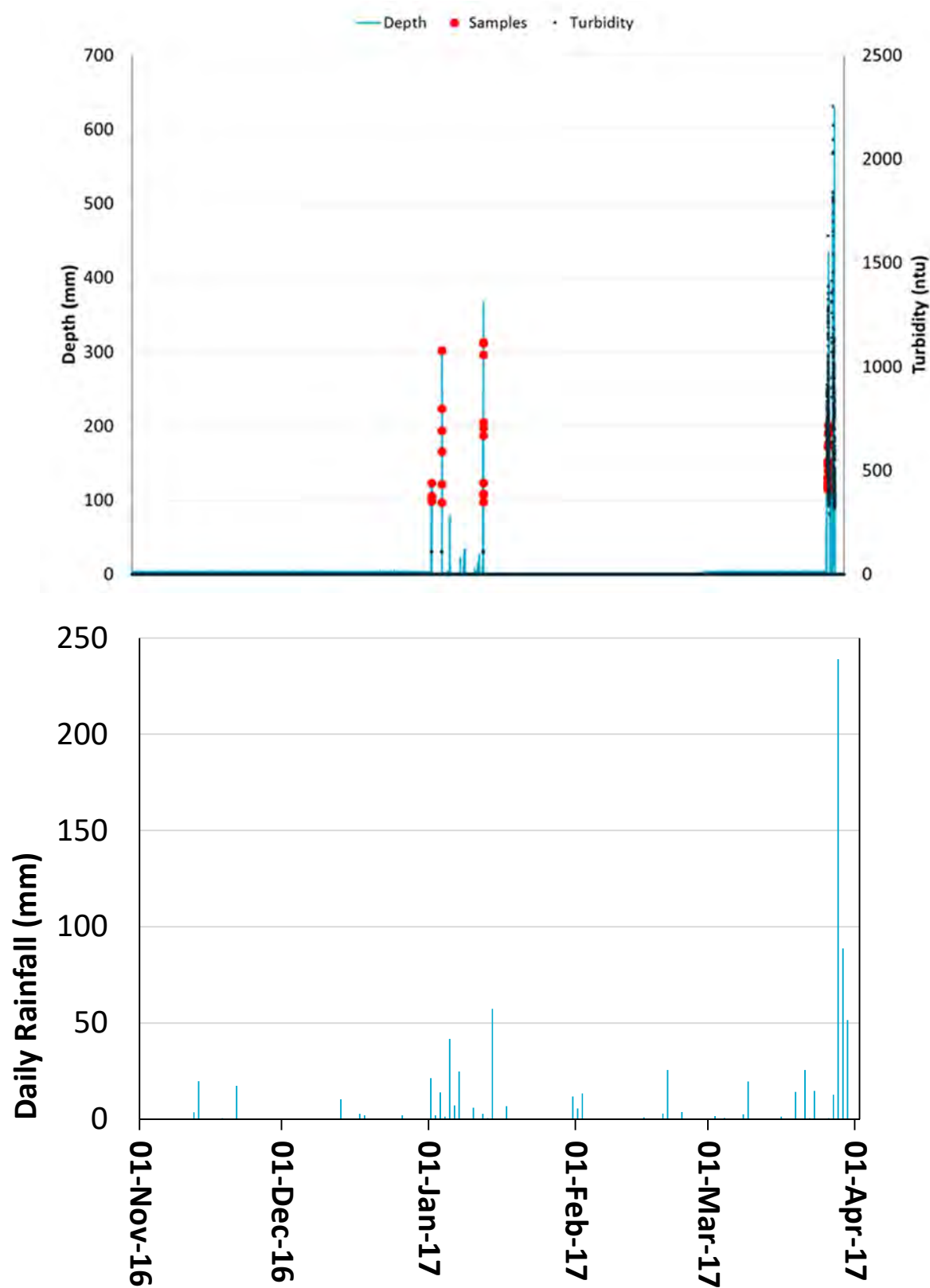


Figure 44: Minnievale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

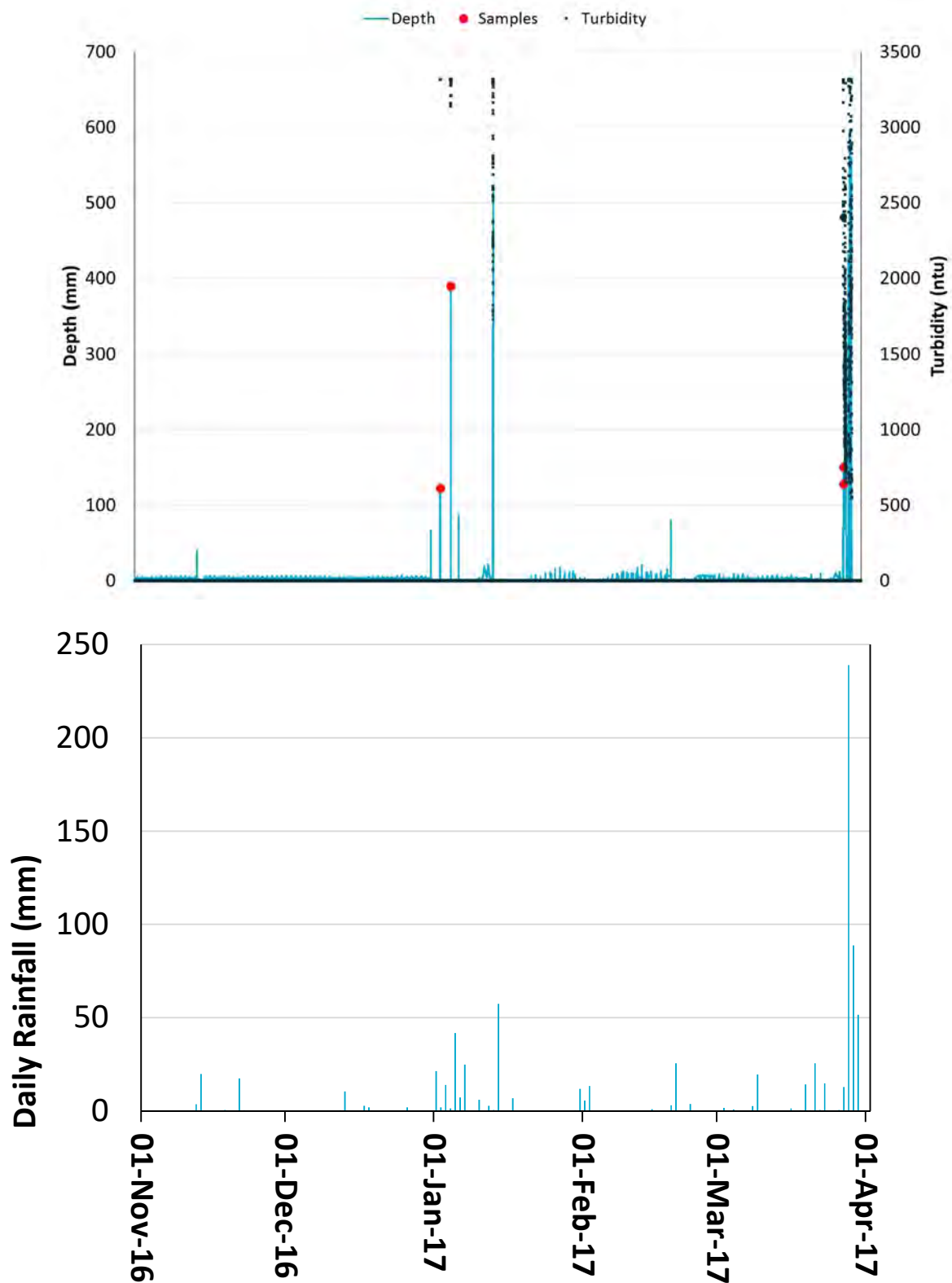


Figure 45: Minnievale Control gully (Top) runoff, turbidity and sample points on the hydrograph and (Bottom) rainfall.

