Gully erosion and its response to grazing practices in the Upper Burdekin catchment

A report to NQ Dry Tropics for the Paddock to Reef program

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Gully erosion is an important source of sediment to the Great Barrier Reef (GBR), affecting water quality and ecosystem condition. Understanding gully erosion processes and their response to grazing practices is therefore vital for informing actions to reduce sediment delivery to the GBR. This study investigated gully erosion processes and the effectiveness of grazing practices in influencing gully sediment yields. It focused on the Upper Burdekin catchment, which is an important contributor to Burdekin River fine sediment loads. The Burdekin basin is the largest sediment source to the GBR.

Grazing practices can influence gully sediment yields, and also the risk of new gullies forming, by (i) reducing hillslope runoff into gullies, (ii) increasing cover on gully walls to protect them from further erosion, and (iii) reducing the sediment transport capacity of gully channels (illustrated in Figure 1, page 3). The study tested how these three principles apply in the Upper Burdekin catchment in four components of research, focusing on (a) establishing the erosion history and contemporary activity of gullies in recent decades both on hillslopes and within alluvium, (b) identifying the processes and drivers of hillslope gully erosion at annual time-scales, (c) assessing the effectiveness of gully erosion management trials, and (d) defining the potential to reduce runoff from grazing lands into gully networks. These research components together involved data from five study catchments in Chromosol (red goldfields) soils, over the period 2002–2012.

Some parts of the Burdekin basin including the Upper Burdekin catchment have extensive gully networks in hillslope drainage lines. Large alluvial gully features are also present in the Upper Burdekin catchment, but are confined along the Upper Burdekin River. Since the 1980s, the hillslope gully networks in a grazed study catchment of degraded land condition (70–90% exotic Indian Couch runner grass pastures of reduced biomass) have been eroding at approximately half the rate averaged over the entire period since gully initiation, estimated to have been around 1900. Recent gully activity was relatively lower in an area of better land condition (>40% native perennial tussock grasses) which has had lighter grazing pressure and higher ground cover levels, suggesting that grazing practices may be effective at reducing gully erosion in the long term.

Sediment yield from mature hillslope gullies is primarily derived from upslope extension of the gully heads and widening of the channel cross section immediately downstream of the heads (Figure 24, page 26). Runoff was a dominant control on head section erosion and net gully yield, suggesting that reducing runoff is an effective way to reduce gully sediment yield in this landscape (Figure 28, page 29). Deposition in the downstream valley sections considerably reduced the net gully yield, especially in dry years. Increasing vegetation cover should enhance this deposition.

Consistent with studies elsewhere, we have demonstrated that gully check-dams (constructed of sticks wired together) are an effective way to trap fine sediment on the gully bed, reduce gully sediment yield, and initiate revegetation of the gully bed, provided they are appropriately sized to the runoff volumes (Figure 40, page 42). Renovation of Indian Couch runner grass pastures in degraded grazing lands, by light cultivation and seeding with perennial species required more than 2 years to return back to pre-treatment levels of stability and infiltration capacity, and was thus was not effective at reducing gully sediment yields in the short term.

Runoff volumes can be >30% higher from degraded catchments relative to those in good condition, with differences occurring especially at rainfall totals <50 mm per day (Figure 47, page 47). We were able to represent this catchment behaviour using a simple conceptual model of runoff processes (Figure 51, page 52). This model showed that reducing runoff can be achieved by increasing the size of moisture stores in the above ground vegetation, soil surface and root zone, by approximately 30%. The published literature indicates that the responses of soil and root zone conditions to reduced grazing pressure are variable depending on the degree of degradation, soil type, pasture composition and other factors. Significant recovery of moisture storage function is likely to take several decades in areas of the Upper Burdekin
catchment where pasture composition is now dominated by Indian couch. In the shorter term, increases in above ground pasture biomass can increase vegetation interception capacity, resulting in some runoff reduction.

The erosion monitoring methods were effective for addressing the questions asked, but more automated LiDAR airborne scanning methods would enable broader application. Further work is required to assess contemporary gully activity in a range of land types and climates in GBR catchments, focusing on areas mapped as having high levels of gullyng. Further monitoring is required before quantitative estimates can be made of the sediment yield reductions resulting from treatments applied, to allow vegetation responses to continue and to represent a wider range of climatic conditions.
## Contents

Executive summary....................................................................................................................................................1

Acknowledgments .................................................................................................................................................. viii

1 **Introduction** ........................................................................................................................................... 1
   1.1 Research context .................................................................................................................................. 1
   1.2 Principles linking grazing practices and gully erosion ......................................................................... 2
   1.3 Research approach and components .................................................................................................. 4

2 **Project area** ........................................................................................................................................... 6
   2.1 Environmental attributes .................................................................................................................. 6
   2.2 Grazing history and practices ........................................................................................................... 8

3 **Gully erosion history and contemporary activity** ..................................................................................... 10
   3.1 Objectives ......................................................................................................................................... 10
   3.2 Methods ........................................................................................................................................... 10
   3.3 Results ............................................................................................................................................ 12
   3.4 Implications for gully sediment supply at basin scale ....................................................................... 16
   3.5 Outcomes ....................................................................................................................................... 18

4 **Gully erosion processes and drivers** ....................................................................................................... 19
   4.1 Objectives ......................................................................................................................................... 19
   4.2 Methods ........................................................................................................................................... 19
   4.3 Results ............................................................................................................................................ 22
   4.4 Outcomes ....................................................................................................................................... 32

5 **Responses to grazing practice change** .................................................................................................... 33
   5.1 Objectives ......................................................................................................................................... 33
   5.2 Methods ........................................................................................................................................... 33
   5.3 Results ............................................................................................................................................ 39
   5.4 Outcomes ....................................................................................................................................... 48

6 **Process changes for reducing landscape runoff** ....................................................................................... 49
   6.1 Objectives ......................................................................................................................................... 49
   6.2 A conceptual framework ..................................................................................................................... 49
   6.3 Methods ........................................................................................................................................... 52
   6.4 Results ............................................................................................................................................ 56
   6.5 Outcomes ....................................................................................................................................... 59

7 **Conclusions** .......................................................................................................................................... 61

References .......................................................................................................................................................... 74
Figures

Figure 1. Principles by which grazing land management practices may influence gully erosion rates and sediment yield. ................................................................................................................................................... 3

Figure 2. Hillside gully study catchments in the Upper Burdekin catchment, and their locations within the extent of Chromosol soils in the Burdekin basin. The Gully probability mapping is reproduced with permission from Gilad et al. (2012). ................................................................................................................... 6

Figure 3. Slope gradient cumulative probability distributions for the Chromosol portion of the study catchments, compared with entire Burdekin basin, and the Chromosol soil portion of the basin. .......... 7

Figure 4. Extent of alluvium in the Upper Burdekin catchment, with the locations of known alluvial gully features. The inset shows the monitoring site on Lassie’s Creek Station. ......................................................... 8

Figure 5. Extent of the mapped gullies in the Weany Creek catchment at the date of each airphoto. The labelled gullies had on-ground monitoring (Section 4). The land surface image was derived from airborne LiDAR commissioned by the Paddock to Reef Program. .................................................................................................................. 12

Figure 6. Change in the total length of mapped hillslope gullies with time for (a) Weany Creek and (b) Main Creek, derived from air photo mapping in the period 1945–2010. The number in green indicates the gully extension rate in the past 30 years (slope of the black line) as a proportion of the rate since gully commencement (slope of the dot-dash line), assuming the mapped gully networks were initiated in the year 1900. First order gullies are those elements connected directly to the stream network, while 2nd and 3rd order represent upstream ‘forks’. ........................................................................................................ 13

Figure 7. Extent of the Lassie’s Creek gully measured using historical air photos, and compared with that derived from 2010 airphoto and Lidar imagery. .............................................................................................. 14

Figure 8. Area of the Lassie’s Creek alluvial gully mapped from air photos 1945–2010, and from surveying in 2013. ................................................................................................................................. 14

Figure 9. Erosion of the Lassie’s Creek gully surveyed over the period 2010–2013. ......................................................... 15

Figure 10. Lassie’s Creek alluvial gully, showing one of the active head lobes with levee bank behind, June 2009. ................................................................................................................................. 15

Figure 11. Dependence of the gully extension rate in Weany Creek during periods between each air photo on (a) catchment area upslope of gully heads, and (b) mean rainfall during each period. .......... 16

Figure 12. Rate of gully extension in the Weany Creek catchment with time since gully initiation (assumed 1900). The line shows an exponential fit to the data. ................................................................. 17

Figure 13. Active gully extension in the Weany Creek catchment following a large wet season, April 2010. Photographed by Mark Silburn (DNRM). .......................................................................................................... 18

Figure 14. Gully cross section erosion pins, Virginia Park. ................................................................................................. 20

Figure 15. Typical setout of gully erosion and deposition monitoring, shown for gully VPXG5. ................................................................................................................................. 20

Figure 16. Water years over which gully erosion and deposition were measured at each gully, using headcut surveys, and erosion pin cross sections. ................................................................................ 21

Figure 17. Weany Creek gully VPXG0; clockwise from top left showing headcut, head cross section, middle cross section looking downstream, valley cross section. Photos taken in July 2010. Grass on the gully bed and walls is the stoloniferous (runner) grass Indian couch (Bothriochloa pertusa). .......................................................................................................... 22

Figure 18. Weany Creek gully VPXG5; clockwise from top left showing headcut, head cross section looking upstream, middle cross section looking upstream, valley cross section looking upstream. Photos taken in May 2009 after 3 wetter than average wet seasons. Grass on the gully bed and walls is the stoloniferous (runner) grass Indian couch (Bothriochloa pertusa). .......................................................................................................... 23

Figure 19. (a) Meadowvale Gully 1, July 2009. (b) Meadowvale Gully 2, Dec 2009. ................................................................. 23
Figure 20. Townsville Field Training Area gully TCG, in October 2009 (Wilkinson et al., 2010).

Figure 21. (a) Widths and depths of the cross sections below gully heads, and (b) overall lengths of the Weany Creek monitored gullies. The lengths of monitored gullies are compared against a length histogram of 30 other Weany Creek gullies mapped from air photos.

Figure 22. Lengths (m) of the sections monitored in each of the Weany and Wheel Creek gullies, used for calculating erosion volumes and tonnes from the erosion pin cross sections. The head section length shown for gully VPXG0 is the longest of 5 head sections monitored.

Figure 23. Gully longitudinal profiles, showing the location of head, middle and valley erosion pin cross sections. The top of the headcuts (shown at 0 m) were also monitored with erosion pins.

Figure 24. Mean-annual erosion or deposition at headcuts and gully cross sections, averaged across 8 gullies in the Weany Creek and Wheel Creek catchments.

Figure 25. Mean-annual erosion or deposition at headcuts and gully cross sections for each monitored gully in the Weany Creek and Wheel Creek catchments.

Figure 26. Mean annual erosion by gully section, in tonnes per year, for monitored gullies in Weany Creek and Wheel Creek catchments.

Figure 27. Cumulative changes in gully bed level for gullies having bed scour chains in the valley sections.

Figure 28. Relationships between (left) sediment yield in each year averaged across Weany Creek monitored gullies relative to annual runoff, and (right) mean-annual sediment yield over 8 years for each gully relative to the catchment area upslope of each gully head.

Figure 29. Annual time series of net sediment yield averaged over the monitored Weany Creek gullies, and also the net yield for headcuts, head and middle sections only, neglecting valley sections. Gully yields are compared against rainfall, and also the runoff and TSS loads measured at the Weany Creek catchment outlet (Bartley et al., 2010c).

Figure 30. Annual total sediment yield for each section of Weany Creek gullies relative to annual surface runoff.

Figure 31. Net erosion per gully section (as t/km) compared to average cross section vegetation cover.

Figure 32. After ripping and seeding above gully VPXG5 on Virginia Park in 2010. (a) Ripping and seeding occurred over a large proportion of the catchment. The track on the right marks the upslope extent of the gully catchment. (b) Some of the existing Indian Couch was retained following ripping. (c) The Buffel grass seed germinated by July 2010.

Figure 33. Installation of permeable timber check-dam structures in gully VPXG5.

Figure 34. Longitudinal profile of gully VPXG2, showing the location of check-dam structures S1–S6, erosion pin cross sections and the Gauge measuring runoff and water quality.

Figure 35. Longitudinal profile of gully VPXG5, showing the location of check-dams (S1–S6), erosion pin cross sections (XS1, XS2, XS3) and the Gauge measuring runoff and water quality.

Figure 36. Looking upstream from the most upstream structure in VPXG5, showing the depositional surface overlayed across the reference gully profile.

Figure 37. VPXG2 facing down slope towards gully head in 2011 (left) and 2012 (right) showing the increase in Stylosanthes spp.

Figure 38. Landscape Function Analysis indices for dominant patch types on the VPXG5 hillslope in (a) 2010 and (b) 2012.

Figure 39. Changes in mean cover at erosion pin cross section for treated and control gullies.

Figure 40. Change in the vegetation adjacent to a check-dam in gully VPXG5. Clockwise from top left: After installation in November 2010, during rainfall 3 weeks later, in February 2011, and in May 2012.
Figure 41. Vegetation cover upstream of the check-dams in (a) 2010 following check-dam installation, and (b) 2012.

Figure 42. Mean yield per gully for treated gullies (VPXG2 and VPXG5), and control gullies in the Weany Creek catchment, as estimated from the erosion pin cross sections. The dashed line indicates the timing of treatment. The treated gully mean yields are also shown including deposition upstream of the check-dams.

Figure 43. Annual sediment yield as estimated from erosion pins and check-dam deposition, for (a) VPXG5, (b) VPXG2, and (c) the control gullies, relative to annual hillslope runoff. Y1 and Y2 refer to the first and second post-treatment years, 2010/11 and 2011/12, respectively. Check-dam deposition is included in the post-treatment yields. Runoff is derived from hillslope flume #1 in the Weany Creek catchment (Bartley et al., In review).

Figure 44. Proportion of silt and clay (<63 µm) in sediment deposited upstream of gully check-dams (sampled in March 2013), relative to control gully bed sediment and to soil cores.

Figure 45. Annual dry season ground cover index for the properties containing each study catchment (or TFTA sectors in the case of Main Creek and Thornton Creek).

Figure 46. Standing biomass and native perennial grass percentage of ground layer vegetation in the 2011 dry season. Data for Main Creek and Thornton Creek are derived from Wilkinson et al. (2012). Data for Weany Creek are derived from Bartley et al. (In review).

Figure 47. Main Creek and Weany Creek daily totals of rainfall and catchment runoff for days with non-zero runoff, over the period 2002–2011.

Figure 48. Headcut retreat rates and catchment areas for Weany Creek and Thornton Creek gullies over the 2011/12 wet season.

Figure 49. The major water fluxes and stores in an idealised savannah hillslope comprising vegetation, bare soil and litter. The stores are labelled with bold symbols, and fluxes are represented as arrows with italic labels. Labels are defined in the text above.

Figure 50. Schematic representations of the relative magnitudes and interaction stores and fluxes shown in Figure 49 for degraded and recovered grazing hillslopes. Changes in the area representing the stores are indicative of changes in storage capacity (mm); changes in arrow width are indicative of the increase or reduction in flux. Subsurface horizontal flow (or interflow) of water from the root zone is assumed to be negligible.

Figure 51. A simplified schematic of water stores and fluxes, where rectangles represent stores and arrows represent fluxes. The changes in the area of the rectangles representing the storages and the width of the arrows representing the fluxes give an indication of expected changes between degraded and recovered states.

Figure 52. Conceptual model modified from (Thurow et al., 1987) for oak mottes (groves). Percentage of storm precipitation reaching mineral soil, evaporated from canopy or litter as it varies with storm size.

Figure 53. Results of model calibration to daily runoff from 2001 to 2010 using $E_{\text{max}} = 0.9$ and $S^*$ (Figure 54) = 0.3, CLS = 1 and 3 mm by fitting $RZ = 161$ mm and 103 mm for dry periods and wet periods, respectively.

Figure 54. Example plant loss functions modified from (Dunin et al., 2001) where $E_{\text{max}} = \text{the maximum value of } ET/PET\text{ for a vegetation type.}
Tables

Table 1. Study catchment areas and environmental attributes.................................................................7
Table 2. Grazing practices and pasture composition in the case study catchments.........................................9
Table 3. Attributes of gullies mapped over time in each catchment. ............................................................9
Table 4. Commencement dates of different treatments for hillslope gully sites, all of which continued
until 2012. The monitoring period is shown in the right-hand column. Blank cells indicate that no change
was made for those treatments at those gullies..........................................................................................11
Table 5. Discharge-depth rating curves for instrumentation in VPXG2 and VPXG5 gullies .........................34
Table 6. Summary of treatment effects in 2011 and 2012. Significant effects are shown in bold. .................39
Table 7. Runoff estimates from instrumentation in VPXG2 and VPXG5 gullies, relative to other estimates. 45
Table 8. Sediment load estimates from instrumentation in VPXG2 and VPXG5 gullies, relative to other
estimates. .........................................................................................................................................................45
Table 9. Water balance model parameters, field measurements and model results for the calibration and
the 20% (BMP = Best Management Practice) and 50% (ungrazed) runoff reduction scenarios for the
period 24 January 2001 to 17 February 2010 at Weany Creek. Wet/dry threshold is the annual rainfall
upper bound where a particular year was deemed to be “drought”. Years with annual rainfall greater
than this were deemed to be “non-drought”. RC indicates runoff the coefficient. ........................................57
Table 10. Interception and canopy storage values for trees, shrubs, grass and litter in low rainfall
environments ...................................................................................................................................................67
Table 11. Sites and parameters for relevant soil hydraulic and soil physical properties in rangeland
experiments......................................................................................................................................................68
Table 12. Australian pasture/rangeland studies and recovery times for soil structure and hydrology........71
Acknowledgments

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1 Introduction

1.1 Research context

Controlling fine sediment loads in Great Barrier Reef (GBR) rivers is important because of the impact sediment and attached nutrients have on seagrass and coral ecosystems in the GBR lagoon (De’ath and Fabricius, 2010; Fabricius et al., 2012). The Reef Water Quality Protection Plan (Reef Plan) is an agreement between the Australian and Queensland governments to halt and reverse the decline in water quality entering the GBR from agricultural landholdings in the catchment (The State of Queensland and Commonwealth of Australia, 2003; Anon, 2009). Under Reef Plan, the Reef Rescue program helps agricultural land managers across the reef catchment adopt improved land management practices that will reduce the discharge of nutrients, sediments and pesticides into the reef lagoon (Commonwealth of Australia, 2008; Caring for Our Country Reef Rescue, 2013).

The purpose of this report is to provide knowledge on gully sediment yield, and the effectiveness of grazing land management practices to reduce gully yield. This knowledge is intended to help guide the investment priorities of the Reef Rescue program, and to help inform gully remediation activities undertaken by graziers in reef catchments. The report was produced for the Paddock to Reef (P2R) program, which is designed to evaluate the efficiency and effectiveness of practice change implementation under Reef Plan, and to report on progress towards the Reef Plan water quality targets (Carroll et al., 2012).

To achieve effective reductions in sediment loads it is important to identify and address the major sediment sources (Lu et al., 2004). There is considerable evidence that gully erosion became much more widespread in south-east Australian landscapes following introduction of livestock grazing, and associated degradation of ground vegetation cover (Prosser et al., 2001). Gully erosion is increasingly recognised as a major source of fine sediment in grazing lands of reef catchments (McKergow et al., 2005; Bartley et al., 2007; Hughes et al., 2009; Wilkinson et al., 2013). Mapping and modelling of gully extent indicates there are at least 80,000 km of gully in GBR catchments (Thorburn and Wilkinson, 2013). Recent research has further increased the mapped extent of gullies in the Burdekin and Normanby basins (Gilad et al., 2012; Brooks et al., 2013). However, the activity of gully networks, and their contribution to sediment yields, relative to other sources of subsoil such as rilling and streambank erosion, is not well understood (Hancock et al., In press).

Failure to correctly target gully or channel erosion as the major sediment source in river basins has previously resulted in failure to reduce sediment loads (Wasson et al., 2002; Boomer et al., 2008). Evidence from the Burdekin basin to date is that reducing pasture utilisation to increase vegetation cover and reduce rates of sheetwash and rill erosion on hillslope surfaces does not significantly reduce catchment sediment yields in gullied landscapes within 10 years (Bartley et al., 2010c), although these actions may deliver water quality benefits in the longer term.

Targeting areas of high erosion rate and sediment contribution is also key to efficient and cost effective load reductions (Wilkinson et al., 2005a; Wilkinson et al., 2005b). The Burdekin basin is the largest source of fine sediment to the GBR lagoon (Kroon et al., 2012). Grazing land is the largest sediment source to the GBR by landuse, covering 80% of GBR catchments and 95% of the Burdekin basin. There is a gradient across the Burdekin basin in the catchment contribution to sediment yields; the Upper Burdekin is the largest source area in the basin (Kinsey-Henderson et al., 2007a). The contribution is mitigated somewhat by deposition in the Burdekin Falls dam (Lewis et al., In press), however despite this, the Upper Burdekin contributes approximately one quarter of the Burdekin River total suspended sediment yield (Kinsey-Henderson et al., 2007).

Relative to hillslope surfaces, where increasing ground cover is widely recognised as the key to reducing erosion rates (Renard et al., 1997), the practices for most effectively reducing gully sediment yields are less well understood. Like elsewhere, gully erosion in GBR catchments appears to be initiated by historical
degradation of ground vegetation following over-grazing and drought. Individual gully features can also be associated with roads and fencelines, where these have altered the vegetation cover and surface drainage. However, the geomorphic evolution of gullies (extension, then deepening, widening and infilling) can fuel the perception that it is difficult to influence gully erosion through changes in land management.

Two types of gully erosion occur within GBR catchments. The most prevalent form of gully erosion is as linear or branching features along hillslope drainage lines, where overland and shallow subsurface flow over the gully headwall causes the headwall to migrate upslope, leading to the term ‘headcut’. These gullies are termed colluvial or hillslope gullies, and are most commonly connected to the channel network. There is considerable literature on methods for controlling hillslope gullies (Valentin et al., 2005). Some engineering approaches such as diversion banks and check-dams can be expensive and require careful design to be effective. The main alternative is to improve land management to increase vegetation cover and biomass and reduce catchment runoff. Given the large extent of hillslope gullies in GBR grazing lands, and their occurrence throughout grazing properties in some areas, this report focused on how gully erosion is influenced by grazing management and relatively simple techniques to remediate vegetation cover at the scale of individual gullies.

A distinct form of gully erosion occurs in deep alluvial soils, which is characterised by more irregular gully planform shape not necessarily aligned with overland flow pathways (Brooks et al., 2009). Similar to hillslope gully erosion, this is probably initiated by localised vegetation disturbance along drainage lines. This form of erosion has been observed along some larger river channels in GBR catchments including the upper Burdekin and Bowen. However, once alluvial gullies are established, mass failure at their edges occurs when the soil becomes saturated, either by local rainfall or by inundation from nearby rivers during flow peaks, and can be independent of surface runoff (Shellberg et al., 2013). It is unclear how grazing land management can easily influence the rate of erosion of established alluvial gullies. However, this study sought some understanding of the historical behaviour of alluvial gullies in the upper Burdekin catchment.

Prior to this study, there were limited previous investigations of gully erosion processes in GBR catchments, or of the effect on gully erosion of grazing management practices including site remediation. Some general field guidelines on gully management were available (http://www.nrm.qld.gov.au/factsheets/pdf/land/l81.pdf), but their effectiveness had not been tested.

1.2 Principles linking grazing practices and gully erosion

To ensure that investments in changing grazing land management practices are effective in reducing gully sediment yields, an understanding of gully erosion processes is required. Gully erosion represents a major instability in the hydrological functioning of a landscape. Attempts to stabilise them must be well-targeted and well-designed. History has shown that gully management can succeed or fail based on how well it works with, rather than against, the erosion processes at a site. It has proven important to understand the stage of development or ‘maturity’ of a gully system, the spatial patterns in runoff energy and soil stability, and the appropriate locations to target within a gully.

Gully erosion occurs where the runoff energy concentrated within a hillslope drainage line exceeds the capacity of the soil surface and its vegetation cover to resist scour. Soil saturation can destabilise the soil profile leading to dispersion or mass failure. Once surface incision has occurred, the runoff energy is further concentrated as it cascades over the gully head and is laterally confined within the formed channel. The driving force for most gully erosion is the energy of surface runoff, which is related to runoff volume, terrain slope and the depth of the gully headcut. Therefore, the rate at which gully erosion progresses tends to decay over time (Graf, 1977), with the catchment area upslope of the gully head becoming smaller as the gully head advances upslope, thus reducing the hydraulic energy driving erosion. Conversely, thresholds of terrain slope and catchment area can be defined above which incised drainage lines exist and below which the natural hillslope surface is stable under surface runoff (Montgomery and Dietrich, 1989). Downstream from the gully head, the erosive power of runoff can reduce as the gradient declines and the gully channel becomes wider. Additional factors which also influence gully extent include terrain slope, soil thickness (depth to bedrock), soil strength and soil hydraulic properties (Prosser and Abernethy, 1996).
The initiation of gully incision into a hillslope surface is more sensitive to changes in vegetation than changes in runoff (Prosser and Slade, 1994). However, once a headcut is established and the initial phase of gully extension is complete, the ongoing erosion rate is sensitive to the runoff volume, because vegetation cover is always poor at active gully headcuts, where hydraulic forcing exceeds vegetative resistance. Gully headcut retreat is correlated with runoff volume at annual timescales (Wijdenes and Bryan, 2001). Higher gully erosion rates have been observed in cropland areas where runoff was higher (Chaplot et al., 2005), and changing landuse to increase runoff can increase the headcut retreat rate of individual gullies (Neller, 1988). In contrast, minor changes in pasture vegetation cover on their own may not significantly modify the thresholds of runoff or contributing area and terrain slope at which gully heads become stable (Montgomery and Dietrich, 1989; Rutherfurd et al., 1997).

Numerous gully remediation studies have shown that increasing the vegetation biomass and ground cover is an important component in reducing long-term sediment yield from gullied areas, due to the effects of reducing surface runoff volumes, increasing the resistance of gully walls to erosion, and enhancing sediment trapping within a gully channel (Heede, 1979; Morgan and Davidson, 1986; Gomez et al., 2003; Chen and Cai, 2006). Conceptually, grazing land management practices may reduce the rate at which gullies approach stable dimensions, and the also reduce the total volume at which the gully becomes stable and ceases to deliver sediment downstream. Such changes may be evident at the scale of years to decades.

Previous studies of gully erosion and gully remediation can be synthesised to identify three principles by which grazing land management practices may influence the erosion rates and sediment yield of established gully networks, and also the risk of new gullies forming (Thorburn and Wilkinson, 2013):

1. Reducing runoff from upslope into the gully decreases the rate of headward extension of the gully. Reducing runoff also decreases the sediment transport capacity of the gully channel, so increasing retention of mobilised sediment within the gully.
2. Increasing cover on gully walls decreases sheetwash and rill erosion from the walls, which can comprise 10–30% of gully erosion (Blong et al., 1982; Crouch and Blong, 1989). Increasing cover on hillslopes reduces the risk of initiation of new gullies (Prosser and Dietrich, 1995).
3. Reducing the sediment transport capacity of the gully channel, by reducing the slope gradient or increasing roughness, can enhance sediment deposition on the gully floor (Molina et al., 2009) and reduce the net export of sediment from the gully.

These principles are illustrated in Figure 1.

![Figure 1. Principles by which grazing land management practices may influence gully erosion rates and sediment yield.](image-url)
gully headcuts and reduce gully wall angles to assist revegetation, but if the subsoil is dispersive earthworks can instead cause additional destabilisation. The process of revegetation, and the resistance of that vegetation to ongoing erosion, depends heavily on the characteristics of local climate, soil and vegetation.

This report investigates the three principles listed above in the context of the soils, climate and vegetation characteristics in the Upper Burdekin catchment. The key question addressed is what effect may typical practice improvements have on gully erosion and why, including forage management, wet season spelling, and redistribution of grazing pressure away from gullied areas.

Research in GBR catchments to date provides some justification for expecting runoff responses to practice change. As well as being a key driver of gully erosion, surface runoff is the main mechanism by which sediment eroded on hillslope surfaces is delivered to streams in tropical savannah (Kirkby and Chorley, 1967; Hairsine and Rose, 1992). Importantly for graziers, retaining rainfall onsite better supports forage production (Wilkinson et al., 2013a). However, expected magnitudes of runoff response are unclear and further research is required to define the process changes. Aboriginal-managed landscapes were more productive and resource-conservative (Gammage, 2011), and some limited runoff observations which suggest that the runoff difference between grazed and non-grazed hillslopes can be large (Thornton et al., 2007; Hawdon et al., 2008). Increasing pasture vegetation cover from below 50% can improve the soil surface condition and reduce runoff volume where native tussock pastures are intact (Connolly et al., 1997; Owens et al., 2003; Roth, 2004; Silburn et al., 2011a). However, where grazing land has been degraded by historical over-grazing and erosion, pasture biomass is now dominated by Indian couch (Bothriochloa pertusa), which has low root mass and structure. In these landscapes significant reductions in annual runoff have not been observed even 10 years after grazing pressure was reduced (Hawdon et al., 2008; Bartley et al., 2009; Bartley et al., 2010a).

1.3 Research approach and components

This report investigates the behaviour of gully features in the Upper Burdekin catchment, and the influence of grazing management practices on that behaviour. Field monitoring plays an important role in this research. Existing preliminary models of gully erosion processes are not robust even within the catchments within which they were developed (Chaplot et al., 2005), and require careful calibration based on measured gully morphology and dynamics (Sidorchuk, 1999). Empirical data on gully erosion is also valuable to constrain catchment-scale modelling of sediment and nutrient budgets in GBR catchments (Wilkinson et al., 2013c). This research built on an existing gully erosion field monitoring program in the upper Burdekin catchment. That program commenced in 2002 for the purpose of establishing a catchment budget of sediment sources and transport in Burdekin grazing lands. A budget based on gully erosion pin cross sections in several gullies was reported from the first 3 years of monitoring data (Bartley et al., 2007). The limited duration of the current project meant that detecting complete responses to treatments imposed by the project could be impractical. Therefore, we also employed historical air photos and conceptual hydrological modelling to extend the time-scale of findings.

The research comprised four components. The objectives, methods and findings from these are detailed in the following sections:

- Section 3 chronicles the historical changes in gully erosion in the study area and defines the contemporary activity of the gully networks, by using air photo interpretation over a time-scale of several decades. Sediment yield can be expected to decline as a headcut proceeds upslope and the catchment area delivering runoff declines (Graf, 1977). Thus, understanding the maturity of a gully is a pre-requisite for studying shorter term processes. Differences in gully activity between sites are explored, and the likely changes in gully behaviour in future decades are assessed. Both hillslope and alluvial gullies are included in this historical component.
- Section 4 defines the site-scale processes of hillslope gully erosion over individual wet seasons, to provide a robust context for investigating how grazing practice changes may influence and slow the erosion rate at which established hillslope gullies ‘recover’ or ‘stabilise’. This activity continued the
existing erosion pin monitoring, collected a range of further contextual site data, and extended monitoring to additional sites.

- Section 5 investigates the effectiveness of a range of grazing treatments at reducing the erosion rates of hillslope gullies. This experiment further tests inferences made in Section 4 about responses of sediment yield to changes in runoff, and the vegetation cover on gully walls and in the channel bed.

- Section 6 uses conceptual hydrological modelling, calibrated to the climate, vegetation characteristics and soil parameters of the Upper Burdekin catchment, to investigate the types of process change required for reduced grazing forage utilisation to reduce runoff, the realistic potential for such change, and how current grazing practices measure up to that potential. Modelling enabled simulation of long-term responses to practice change, which could not be fully detected within the duration of this monitoring project.

Each of the above sections concludes with short Outcome statements. Overall conclusions are given at the end of the report. To set the scene for these research components, Section 2 describes the environmental attributes and grazing land management history in the study area.
2 Project area

2.1 Environmental attributes

To identify the impact of different grazing management practices on hillslope gully erosion processes and rates in the Burdekin basin, we confined the study to a region within which environmental attributes known to affect gully erosion were relatively consistent, including rainfall and slope gradient (Hughes and Prosser, 2012). Other studies have also found that region, and geology or soil type (which underpins the land type mapping in Queensland) are a key determinant of the gully erosion extent at a landscape scale in GBR catchments (Trevithick et al., 2008; Kuhnert et al., 2009).

![Figure 2. Hillslope gully study catchments in the Upper Burdekin catchment, and their locations within the extent of Chromosol soils in the Burdekin basin. The Gully probability mapping is reproduced with permission from Gilad et al. (2012).](image)

This research focuses on hillslope gully erosion in Chromosol soils within the Upper Burdekin catchment. Chromosol soils occur predominantly in the northeast side of the basin (dark shaded area in Figure 2), where erosion rates and fine sediment contributions to the GBR are the highest in the basin (Fentie et al., 2006). Chromosol soil is known locally in the Upper Burdekin catchment as red goldfields soil. The soil is often a textured sandy clay loam, over Granadiorite lithology (Isbell, 1996; Bartley et al., 2010a). Weakly dispersive soils are exposed on some areas of lower slopes, although the soils are more commonly weakly slaking rather than dispersive. The total organic carbon content of soil cores taken by the Paddock to Reef Program was 1.3% within 0–20 cm depth, and 0.5% for 20–100 cm depth. The terrain is naturally dissected,
with many drainage lines. Bedrock is exposed at ~3 m depth near the head of some deeper hillslope gully features.

Gully erosion is more prevalent within Chromosol soils than other soil types in the Burdekin basin; while they cover 12% of the 130,000 km² Burdekin basin, recent gully erosion mapping by Gilad et al. (2012) identified that approximately 25% of the area with medium or higher probability of gully erosion is within Chromosol soils.

The hillslope gully erosion research used 4 study catchments on the eastern side of Upper Burdekin River, each having numerous hillslope gully features (Figure 2). Chromosol soils covered the entire extent of all the study catchments except Thorton Creek (Table 1). The catchments have mean rainfall in the range 600–800 mm/yr. The study catchments were representative of the Chromosol soil area across the Burdekin basin, of which almost three quarters had slopes of less than 5.1%. The Chromosol portions of the study catchments all had median slopes between 2.2–2.6%. There was a slightly wider range of slopes in Main Creek and Thorton Creek Chromosol soil area compared with Weany Creek and Wheel Creek catchments (Figure 3).

### Table 1. Study catchment areas and environmental attributes.

<table>
<thead>
<tr>
<th>CATCHMENT</th>
<th>CATCHMENT AREA (KM²)</th>
<th>CHROMOSOL AREA (%)</th>
<th>MEAN RAINFALL (MM/YR)¹</th>
<th>MEDIAN SLOPE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weany Creek</td>
<td>13</td>
<td>100</td>
<td>686</td>
<td>2.3</td>
</tr>
<tr>
<td>Wheel Creek</td>
<td>11</td>
<td>100</td>
<td>738</td>
<td>2.2</td>
</tr>
<tr>
<td>Main Creek</td>
<td>13</td>
<td>100</td>
<td>782</td>
<td>2.6</td>
</tr>
<tr>
<td>Thorton Creek</td>
<td>81</td>
<td>6</td>
<td>609</td>
<td>2.3 ²</td>
</tr>
</tbody>
</table>

¹ Estimated using the nearest 5 km by 5 km pixel in the AWAP gridded monthly rainfall dataset for Australia (1900–2012), hosted by the Bureau of Meteorology (Jones et al., 2009).

² For the portion of the catchment with Chromosol soil.

Prior research and ongoing monitoring in the Weany Creek catchment has focused on the sources of sediment (Bartley et al., 2007), and how hillslope and catchment runoff and soil loss respond to reduced forage utilisation and wet season spelling (Bartley et al., 2010a; Bartley et al., 2010c). In the Wheel Creek catchment, hillslope runoff and soil loss has been monitored for 10 years on grazed and non-grazed...
hillslopes (Hawdon et al., 2008; Bartley et al., 2010a). Sediment tracing in Weany Creek and Main Creek catchments identified sub-surface soil as dominating event suspended sediment (Wilkinson et al., 2013c).

The study also included an alluvial gully site outside of Chromosol soils, being within the alluvium adjacent to the east bank of the Upper Burdekin River on Lassie’s Creek Station. Similar alluvial gully features are evident along both sides of the Upper Burdekin River up to 50 km upstream and downstream of this site (Figure 4). However, in the upper Burdekin catchment the alluvium and therefore occurrence of alluvial gullies, is generally confined to a narrow corridor adjacent to the river channel, unlike the Normanby and Mitchell basins where alluvial gully erosion is widespread (Brooks et al., 2009; Brooks et al., 2013).

The Lassie’s Creek gully was 16 ha in area, with a maximum depth of 15 m. This depth of river channel incision into the landscape results from past catchment uplift and climate changes (Ciesiolka, 1976), and provides the potential for large alluvial gully features to result from vegetation disturbance adjacent to the channel. The studied alluvial gully is immediately south of the river crossing of a railway line which once serviced the Greenvale nickel mine, and a levee bank 2 m high was constructed around the east side of the gully during railway construction 1972–1974 (see inset, Figure 4). The similarity between the shape of the levee bank and the current shape of the gully suggests that the extent of the gully has changed relatively little since that time.

![Figure 4. Extent of alluvium in the Upper Burdekin catchment, with the locations of known alluvial gully features. The inset shows the monitoring site on Lassie’s Creek Station.](image)

2.2 Grazing history and practices

Livestock grazing (predominantly of cattle) was introduced to the study catchments during the period 1855–1865. Valley of Lagoons in the far north of the Upper Burdekin catchment had sheep and cattle by 1867. Gold was discovered on the Star River in 1865, and on the Cape River west of Charters Towers in 1867, providing a local demand for meat. In 1869 there were 140 men mining at Ravenswood (Bolton,
Gold was discovered in Charters Towers in 1870, leading to a major population boom in following years. The railway from Townsville to Charters Towers was completed in 1882, passing close to the Weany Creek catchment divide. Following introduction of livestock grazing a dry period would have been required for sufficient vegetation degradation to initiate the widespread gully erosion seen today. A major drought in the 1890s may have been one trigger for this to occur. During this period, large floods in the Upper Burdekin River at the Flinders Highway are recorded in 1870, 1890, 1911 and 1918.

Across the study catchments there has been a range of grazing land management practices including grazing pressure in recent decades (Table 2). Weany Creek and Wheel Creek have had continuous grazing landuse since the 1800s. Stocking rates in Queensland rangelands increased markedly in the 1970s, and by 1980 were approximately double the long-term safe carrying capacity around Charters Towers (McKeon et al., 1990). The history of Main Creek and Thorton Creek has been more varied. By 1916 the Dotswood Station surrounding Main Creek and Thorton Creek was stocked with 15,000 cattle and horses (Cohen, 1988). Military training replaced grazing as the primary land use in 1989 and grazing leases operated around training activities after this time, ceasing altogether in 2001.

Consequently, the land condition, an indicator of its capacity to produce useful, also varies between catchments. In the Burdekin basin, four classes of land condition have been defined, with A-class representing good condition and D-class very poor condition forage (Chilcott et al., 2003; CSIRO, 2007; Karfs et al., 2009). Main Creek and Thorton Creek catchments have predominantly native perennial tussock grasses corresponding to A land condition, while Weany Creek and Wheel Creek pastures are dominated by an invasive exotic stoloniferous (runner) grass Indian Couch (Bothriochloa pertusa), corresponding to C or D land condition depending on location. This pasture is associated with land degradation and ongoing declines in forage productivity (Ash et al., 1995; McIvor et al., 1995b), increasing runoff generation into gullies.

### Table 2 Grazing practices and pasture composition in the case study catchments.

<table>
<thead>
<tr>
<th>STUDY CATCHMENT</th>
<th>PROPERTY</th>
<th>CURRENT GRAZING PRACTICE</th>
<th>PASTURE COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weany Creek</td>
<td>Virginia Park (VP)</td>
<td>Since 2002; variable light to moderate stocking based on forage budgeting; wet season spelling in alternate years (B practice) Prior to 2002; Continuous stocking at or above long-term carrying capacity (LTCC) (C practice).</td>
<td>70–90% Indian Couch(^a)</td>
</tr>
<tr>
<td>Wheel Creek</td>
<td>Meadowvale (MV)</td>
<td>Continuous stocking above LTCC, at somewhat reduced rates since 2000 (C/D practice).</td>
<td>&gt;90% Indian Couch(^b)</td>
</tr>
<tr>
<td>Main Creek</td>
<td>Townsville Field Training Area (TFTA)</td>
<td>Since 2001; Grazing excluded, burning every 1–3 years. Prior to 2001; Light to moderate stocking (B practice). Early 1900s; Moderate stocking</td>
<td>&lt;50% Indian Couch, &gt;40% Native perennial tussock(^d)</td>
</tr>
<tr>
<td>Thorton Creek</td>
<td>Townsville Field Training Area (TFTA)</td>
<td>Since 2001; Grazing excluded with some incursions, burning every 1–3 years (A practice). Prior to 2001; Moderate stocking (B to C practice).</td>
<td>&lt;40% Indian Couch, &gt;40% Native perennial tussock(^d)</td>
</tr>
<tr>
<td>Lassie’s Creek gully</td>
<td>Lassie’s Creek</td>
<td>Since 2009; Grazing excluded from the gully feature. Prior to 2009; Grazed at unknown stocking rates.</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)The A, B, C, D grazing practices are defined in part on how available forage biomass is considered when setting stocking rates and the ground cover levels maintained during dry seasons and droughts (Van Grieken et al., 2010; Carroll et al., 2012).

\(^b\)(Bartley et al., In review)

\(^c\)(Wilkinson et al., In prep)

\(^d\)(Wilkinson et al., 2012)
3 Gully erosion history and contemporary activity

3.1 Objectives

The contemporary activity levels of well-established gully networks, in recent decades, are influenced by the length of time over which they have developed, and the land use history. Initiation of gully networks often follows intensification of landuse, particularly degradation of vegetation cover in drainage lines (Prosser and Slade, 1994). Individual hillslope gully features tend to have their largest sediment yields in the first decades following gully initiation, associated with rapid gully extension and deepening. After this time sediment yields progressively decline, as the upslope migration of the gully headcut reduces the area of upslope catchment supplying runoff (Graf, 1977). Historical rates of gully extension are therefore an indicator of future rates (Rutherford et al., 1997). Gully maturity can be defined as the area above the head as a proportion of the head area at the time of gully initiation; i.e., at the downstream end of the gully.

For networks of intermediate activity, simply reducing grazing pressure may be effective in reducing the sediment yield, while very active networks may be much more difficult to control. In the very long-term, or following a subsequent decline in landuse intensity and runoff, gully networks can complete their adjustment to the change in hydrological forcing, become inactive and deliver little sediment.

In addition to information on gully erosion response to grazing practice change, the P2R program requires estimates of contemporary gully activity for constraining catchment modelling of sediment sources and transport. These estimates are used to specify a model parameter in the sediment budget modelling of GBR catchments within the Source Catchments framework, being the sediment yield in recent decades, as a proportion of the mean-annual sediment yield since the gully network was initiated (Wilkinson et al., 2013b).

The objectives of this section are to:

- Quantify the contemporary gully activity in recent decades relative to the long-term average of hillslope gullies and alluvial gullies in the Upper Burdekin catchment
- Investigate whether gully activity can be explained by the maturity of gully networks (based on the remaining catchment area upslope of the gully head), or variations in rainfall.
- Investigate the sensitivity of gully activity to different land management histories
- Infer future gully activity if historical trends continue.

3.2 Methods

3.2.1 QUANTIFYING GULLY ACTIVITY

The contemporary activity of hillslope gullies was quantified relative to the long-term average over the life of the gully network by measuring gully length at points in time using historical air photos. The date of initiation of the gully networks was estimated considering the timeframe in which livestock grazing was introduced.

This indirect approach to estimating the rate of changes in gully volume was employed because the change in location of the gully headcut is more reliably quantified in historical air photo imagery of limited resolution than are changes in gully width or area, which are more subject to variations in ground cover on gully walls. However, the general pattern of gully evolution is for linear extension to occur relatively early, followed by deepening, widening and finally infilling. Once gullies are established, a considerable amount of the sediment yield may be derived from the gully walls (Blong et al., 1982). On that basis the activity estimated in terms of changes in gully length may under-estimate the activity in terms of changes in gully volume.
volume. On the other hand, changes in planform area may tend to over-estimate the current activity of mature gullies if gully mean depth is reducing as a result of reduction in gully wall angles, and by deposition within the gully. Section 4 demonstrates that the predominant sediment source in the hillslope gullies studied remains the head section, and estimating contemporary activity in terms of linear extension can be justified on that basis. The gullies studied are generally laterally confined by topography.

Estimates of gully activity were made for three of the five study catchments; hillslope gullies in Weany Creek and Main Creek, and the alluvial gully at Lassie’s Creek Station. Weany Creek and Main Creek were included because they covered a range of grazing practices, with the vegetation condition and ground cover in Main Creek indicating a history of lighter grazing pressure. These differences are described further in Section 5.

Hillslope gully lengths were mapped from each air photo from gully heads downstream to the first creek/gully intersection to exceed a 50 ha upstream catchment area. This was justified given that channel initiation is related to slope and area (Montgomery and Dietrich, 1989), and creek slope is relatively consistent. The chosen threshold was also consistent with a stream-order threshold previously observed to separate gullies from creeks at Weany Creek (Heine, 2002). To ensure the mapped features were representative at the catchment scale, all branches were mapped in each gully network. The rate of gully growth was determined over each measurement period by dividing the total change in length by the number of years over that period. As there was some uncertainty around the downstream endpoints of gully features, we reported changes in lengths relative to the earliest air photo date (1945) in addition to changes from the assumed gully endpoints.

A different approach was taken to assess the activity of the alluvial gully at Lassie’s Creek. Due to the irregular planform, and the large depth of this feature the gully extent was quantified in each air photo as an area rather than a length.

A large number of gully features were mapped in Weany Creek and Main Creek, covering a total of 41 km (Table 3). Based on a previous estimate of mean gully density for the Weany Creek catchment of 4.5 km km\(^{-2}\) (Heine, 2002), the sample represented 40% of total gully length in that catchment.

| Table 3. Attributes of gullies mapped over time in each catchment.  |
|----------------------|----------------------|----------------------|
|                      | WEANY CREEK          | MAIN CREEK           | LASSIE’S CREEK       |
| Number of gully networks | 33                  | 28                   | 2                    |
| Number of gully heads in 2010 | 178                 | 54                   | -                    |
| Total length in 2010 (km) | 25.5                | 15.5                 | -                    |

\(^A\)For this date we used 60 cm resolution Digital Globe imagery.

### 3.2.2 DRIVERS OF CHANGE IN GULLY ACTIVITY

The dependence of gully activity (rate of gully extension) in the period between each air photo, on the catchment area upslope of gully heads at the start of each period was investigated. A significant relationship would suggest that change in activity was driven by reduction in area over time as previously found (Graf, 1977). Decadal variations in rainfall may also cause changes in gully activity, since at annual time-scales headcut retreat is dependent on runoff (Wijdenes and Bryan, 2001). Therefore we also plotted rate of gully extension against the mean rainfall in each period. Differences in landuse history may also explain differences in gully activity between catchments, or over time within a catchment. It can be hypothesised that light grazing pressure should result in lower gully activity for gully networks of similar or lesser maturity (larger catchment area) than in more heavily grazed areas.
3.3 Results

3.3.1 CONTEMPORARY GULLY ACTIVITY

Hillslope gully erosion

The mapped gully networks were located across the Weany Creek catchment (Figure 5). Since 1960, the observed rate of gully lengthening has slowed, and the rate of linear extension during 1981–2010 was approximately half (46%) that of the average growth rate since gully commencement, assuming an average commencement date of 1900 (Figure 6a). In the Main Creek catchment, the rate of extension since 1985 was just 8% of the average rate over the life of the gullies (Figure 6b). The lower gully activity in Main Creek catchment is consistent with lighter historical grazing pressure causing less degradation of vegetation and soil in that catchment.

Figure 5. Extent of the mapped gullies in the Weany Creek catchment at the date of each airphoto. The labelled gullies had on-ground monitoring (Section 4). The land surface image was derived from airborne LiDAR commissioned by the Paddock to Reef Program.
Figure 6. Change in the total length of mapped hillslope gullies with time for (a) Weany Creek and (b) Main Creek, derived from air photo mapping in the period 1945–2010. The number in green indicates the gully extension rate in the past 30 years (slope of the black line) as a proportion of the rate since gully commencement (slope of the dot-dash line), assuming the mapped gully networks were initiated in the year 1900. First order gullies are those elements connected directly to the stream network, while 2nd and 3rd order represent upstream ‘forks’.

If gully erosion actually commenced earlier than 1900 the rate of erosion in recent decades would be a larger proportion of the long-term average rate (60% for Weany Creek assuming an 1870 initiation date). However, significantly earlier gully initiation in Weany Creek is unlikely because assuming an initiation date of 1900 results in the period 1900–1945 having the same rate of extension as the period 1945–1962. Normally rates of gully extension undergo gradual decay after more rapid growth in the initial decades. Most of the gully extension prior to 1945 was derived from first-generation features (the original main stem of each gully), while since 1945 the majority of gully extension was derived from second and third generation ‘forks’ or tributaries to the main stem of each gully network.

Alluvial gully erosion

In 2010, the area of the gully on Lassie’s Creek station was 16 ha, with maximum depth of 15 m. The area of the Lassie’s Creek gully in 1945 was estimated to have expanded by 14% over the 65 years to 2010 (Figure 7). This change is similar to the 22% increase reported by Shepherd (2010) for an alluvial gully elsewhere on the Upper Burdekin River. There was no apparent decay in the rate of area increase over the mapping period 1945–2010 (Figure 8). This is consistent with alluvial gully erosion being driven by soil saturation, rather than by overland flow from a catchment of declining area (Shellberg et al., 2013).

The gully activity over the period 1945–2010, in terms of rate of increase in area, was 16% of the average rate if an initiation date of 1900 was assumed, or 22% if an initiation date of 1860 was assumed. An alternative approach is to extrapolate the measured linear rate of expansion back in time, assuming no decline, which results in an estimated earliest possible initiation date in the year 1367. The smaller mapped Gully 1 has expanded more rapidly since 1945, and extrapolating that rate backwards results in an earliest possible initiation date of 1760.

Therefore, either the gully is an old feature which pre-dates the commencement of cattle grazing, or it developed rapidly following initial incision early in the grazing history, maturing before 1945 to reach a similar extent of activity as hillslope gullies in Main Creek. At this stage we have a weaker basis for estimating a starting date for this alluvial gully than for the hillslope gullies, and neither of these hypotheses can be rejected. In the neighbouring Mitchell River the majority of alluvial gully features have initiated since the introduction of cattle grazing (Shellberg et al., 2010). However, alluvial gullies may be more susceptible than hillslope gullies to initiation by natural causes (e.g., river base level adjustment or large flood events).

Surveys of the gully rim in 2010 and 2013 indicate that the majority of its length eroded less than 0.5 m, although several gully lobes eroded by more than 1 m during the 3 year period (Figure 9, Figure 10).
Figure 7. Extent of the Lassie’s Creek gully measured using historical air photos, and compared with that derived from 2010 airphoto and Lidar imagery.

Figure 8. Area of the Lassie’s Creek alluvial gully mapped from air photos 1945–2010, and from surveying in 2013.
Figure 9. Erosion of the Lassie’s Creek gully surveyed over the period 2010–2013.

Figure 10. Lassie’s Creek alluvial gully, showing one of the active head lobes with levee bank behind, June 2009.
3.3.2 CAUSES OF THE DECAY IN HILLSLICE GULLY ACTIVITY

In both Weany and Main Creek catchments, the rate of change in total hillslope gully length decays over time, which is consistent with increasing maturity of the gully network (decline in catchment area supplying runoff to gully headcuts). In Weany Creek, the differences in gully extension rate for the periods between each air photo are much better explained by reductions in gully head catchment area over time, than they are by differences in rainfall between periods (Figure 11). Therefore, the decay in gully extension rate can be attributed to increasing maturity of the gully network, and rainfall can be dismissed as a causal factor at this timescale.

![Graphs showing the relationship between gully length and catchment area, and gully length and rainfall](Image)

Figure 11. Dependence of the gully extension rate in Weany Creek during periods between each air photo on (a) catchment area upslope of gully heads, and (b) mean rainfall during each period.

It is unlikely that historical changes in grazing pressure are responsible for the decline in gully activity within Weany Creek catchment in recent decades, since regional stocking rates increased markedly in the 1970s (Section 2.2). Once vegetation composition and soil health is degraded reductions in grazing pressure, even where they do occur, don’t result in significant reductions in hillslope runoff within at least 10 years (Bartley et al., 2010a; Bartley et al., In review). It seems likely that grazing pressure in Main Creek catchment has been lower in recent decades than previously due to the transfer to military training land use (Section 2.2), which has probably contributed to Main Creek contemporary gully activity being lower than in Weany Creek (Figure 6).

3.4 Implications for gully sediment supply at basin scale

Accounting for the uncertainties, it can be concluded that the rate of extension of the mapped hillslope gully networks has generally declined with increasing age of the networks (Figure 12). It may be expected that the rates of extension of those mature networks will continue to decline. Differences in contemporary activity between Weany Creek and Main Creek indicate that changes in grazing management have the potential to influence gully erosion rates at property scale. This is investigated further in Section 5.
Figure 12. Rate of gully extension in the Weany Creek catchment with time since gully initiation (assumed 1900). The line shows an exponential fit to the data.

Estimating gully activity across the Burdekin basin should ideally be informed by additional estimates. However, in the absence of such additional estimates, a weighted average representation of gully activity across the Burdekin basin should more heavily weight the Weany Creek estimate than the Main Creek estimate. This is because grazing intensity in the Weany Creek catchment is more representative of grazing intensity in gullied Burdekin grazing lands on Chromosol soils than is Main Creek, and the bulk of Chromosol soils also occur closer to Weany Creek (Figure 2).

Estimating gully activity at basin scale must also consider limitations in the method of this study. As noted in the Methods, estimating hillslope gully activity in terms of linear extension tends to under-estimate the activity of mature gully networks in terms of volume change or sediment yield (Sidorchuk, 1999). The method can also be expected to over-estimate the decline in overall gully sediment yield at the catchment scale because it focused on tracking changes over time in the activity of gully networks that were large (long) in 2010, since they make up the majority of gully network length by definition. New gullies are evident in some parts of the Weany Creek catchment which are often relatively short, but have grown rapidly in recent years of high rainfall (Figure 13). Re-incision of the existing drainage network to a deeper depth is also evident in some areas. If there was no improvement in vegetation cover and land condition in future decades, it can be expected that these processes will continue.

Considering the above, we conclude that the contemporary rates of gully sediment supply in the study area are approximately 50% of their long-term average rate since gully erosion was initiated following introduction of livestock grazing.
3.5 Outcomes

The outcomes of this study can be summarised as follows:

1. In this part of the Burdekin basin, a preliminary estimate is that mature hillslope gully networks are currently eroding at approximately 50% of their long-term average rate, and their activity has been declining since at least 1945.

2. The current activity of gully networks is spatial variable across the Upper Burdekin catchment, and further assessment of gully activity at other sites in the Great Barrier Reef catchments is recommended.

3. The difference in gully activity between Weany Creek and Main Creek suggests that there is potential to influence gully headward extension by improving grazing practices; this is investigated further in Section 5.

4. It can be expected that the activity of mature gully networks will continue to decline in coming decades independent of grazing practices. However, new gully features may also initiate and grow depending on land condition and possibly climate. Mature gully networks can also be re-activated by re-incision of the existing drainage network to a greater depth.

5. Alluvial gully features are evident along the Upper Burdekin River, and should be incorporated into mapping of gully extent in the Burdekin basin.

6. Rates of alluvial gully expansion along the Upper Burdekin River have remained consistent since 1945, and the timing of their initiation relative to the introduction of grazing remains unclear.
4 Gully erosion processes and drivers

4.1 Objectives

This section quantifies how and when erosion occurs throughout hillslope gullies and over time. It also seeks to identify why the erosion occurs, by investigating potential drivers of hillslope gully erosion which may be influenced by grazing practices. According to the conceptual model described in Section 1.1, if gully heads are the dominant source then reducing runoff will be effective. If gully walls and channel beds have some deposition then that could be enhanced by increasing vegetation cover. The goal is to help identify how changes in grazing land management practices may be designed so as to have most impact in reducing gully fine sediment yield. Practice changes will be most effective when they enhance rather than work against gully erosion processes.

In detail, this research component seeks to:

1. Quantify the geometry, vegetation cover and rates of erosion and deposition in different locations within gullies, to indicate the current stage of gully evolution, such as headward extension, deepening, widening, infilling. This may also indicate which locations will respond to changes in grazing practice such as revegetation; if gully walls are unstable then revegetation is likely to be ineffective.

2. Assess the sensitivity of annual gully erosion and deposition rates to variations in rainfall and surface runoff, by examining differences between wet and dry periods, and between gullies of different catchment area.

3. Investigate gully sidewall and channel bed stability and vegetation cover, as additional indicators of gully erosion process and of the potential for grazing land management practices to influence sediment yields. Depending on the flow energy within gullies, the gully walls and channel beds may be revegetated to reduce wall erosion and enhance sediment trapping within gullies (reduce connectivity).

4.2 Methods

4.2.1 GULLY GEOMETRY

The gully width, depth and lengths were measured by survey, to interpret the relative magnitudes of erosion from the gully head and walls. The catchment areas and gradients upslope of the monitored gully heads were determined from DEMs. Gully heads continue to erode upslope until there is insufficient runoff energy to detach soil (Montgomery and Dietrich, 1989). Within a given soil type and climate zone the runoff volume will increase with the catchment area, and also with the slope gradient; thus differences in these parameters can indicate differences in flow energy at the gully heads.

4.2.2 GULLY SECTION EROSION AND DEPOSITION

Erosion and deposition was monitored in a network of gullies across the study catchments using erosion pins and scour chains (Gordon et al., 1992). At each gully, the measurement method involved repeated surveys around the lip of the gully head cut, and 3 cross sections of erosion pins at 0.5 m spacing (Figure 14). The erosion pin cross sections were located in the head, middle and valley sections of the gully, respectively (Figure 15). These cross sections were positioned according to field observations of the predominant process, being erosional in head sections, transport in middle sections and depositional in valley sections (Heine, 2002), and were surveyed to estimate wall gradients. Scour chains were inserted vertically in the sand bed at the downstream end of gullies and quantify the scour and deposition changes.
in bed level during measurement periods to help assess gully behaviour (deepening or stabilisation), and sediment redistribution. Lengthening of the horizontal exposed section of the chain over the wet season was indicative of erosion (scour), burial of the chain was indicative of deposition. It was possible for a chain to experience both scour (lengthening) and burial in one wet season.

Figure 14. Gully cross section erosion pins, Virginia Park.

The erosion measurements were conducted before and after each wet season, or only after each wet season in some cases. The number of wet seasons monitored varied between gullies (Figure 16). Monitored gullies were labelled by two letters representing the study catchment (e.g; VP for Weany Creek on Virginia Park, MV for Wheel Creek on Meadowvale, MC for Main Creek, TC for Thorton Creek, LC for Lassie’s Creek), then G for gully, then gully number (for VP gullies XG denotes extra gullies where monitoring was established in 2004/05). In this section on gully erosion processes, we consider only data from Weany Creek and Wheel Creek gullies (VP and MV, respectively), which had multi-year monitoring of gully erosion at

Figure 15. Typical setout of gully erosion and deposition monitoring, shown for gully VPXG5.
multiple sites within each gully. Comparisons of headcut retreat between the study catchments with different grazing land management practices and land condition, are made in Section 5.

Figure 16. Water years over which gully erosion and deposition were measured at each gully, using headcut surveys, and erosion pin cross sections.

Erosion and deposition calculation

The soil volume lost from each gully headcut over the wet season was calculated by multiplying the change in location of the gully edge as a planimetric area, $A_{HC}$, by mean gully depth at the head cross section, $D_H$. In early years erosion pins were also used to measure headcut retreat; if pins were completely exhumed by erosion over the wet season, erosion was assumed equal to the buried length of the pin measured previously.

For each gully section, the soil volume loss or gain was calculated by multiplying the change in cross section area, $\Delta A_i$, by the length of each gully section, $L_i$, where $\Delta A_i$ was the sum of the product of the change in exposed length of each pin over the wet season by the pin spacing (0.5 m). Where pins are missing or bent, zero change was assumed. Negative change in volume implied net deposition. Net change in gully volume was then the sum of volume changes over the headcut and head, middle and valley ($H, M, V$) cross sections:

$$\Delta V = A_{HC}D_H + \sum_{i=H,M,V} (L_i\Delta A_i)$$

These volume changes represented total soil loss (all particle sizes), and changes in particle size between erosion and deposition on gully walls were assumed negligible relative to the change in area.

The volumes derived from cross sectional area and headcut retreat were then converted into mass by applying a soil bulk density of 1.54 tonnes per cubic metre.
4.2.3 RAINFALL AND RUNOFF

The dependence of gully cross section erosion and total sediment yield on annual rainfall and runoff. Surface runoff was measured at the VP Flumes (Figure 2), as reported by Bartley et al. (2010). Catchment area upslope of gully heads was also used as an indicator of runoff differences between gullies.

4.3 Results

4.3.1 GULLY GEOMETRY

Of the hillslope gully sites, the most complete gully geometry data were available for the Weany Creek and Wheel Creek catchments, where the density of gully erosion was 4.5 and 8.3 km km$^{-2}$, respectively (Heine, 2002).

The gully walls were generally steep (~55°), rilled and non-vegetated in the head cross sections, and of lower gradient and thinly grassed in middle (~36°) and valley (~15°) sections (Figure 17, Figure 18, Figure 19). Bedrock exposure was evident in some head cross sections. The channel bed was partly vegetated in the valley sections of some Weany Creek and Wheel Creek gullies. The Thorton Creek and Main Creek gullies tended to have dense vegetation cover in the gully beds, even within the head sections (Figure 20).

Figure 17. Weany Creek gully VPG0; clockwise from top left showing headcut, head cross section, middle cross section looking downstream, valley cross section. Photos taken in July 2010. Grass on the gully bed and walls is the stoloniferous (runner) grass Indian couch (Bothriochloa pertusa).
Figure 18. Weany Creek gully VPXG5; clockwise from top left showing headcut, head cross section looking upstream, middle cross section looking upstream, valley cross section looking upstream. Photos taken in May 2009 after 3 wetter than average wet seasons. Grass on the gully bed and walls is the stoloniferous (runner) grass Indian couch (*Bothriochloa pertusa*).

Figure 19. (a) Meadowvale Gully 1, July 2009. (b) Meadowvale Gully 2, Dec 2009.
In the Weany Creek gully head sections, the cross section widths (< 8 m) and depths (< 4 m) were small compared with some other studied gullied regions with deeper and finer or less textured soil. However, the gully lengths followed drainage lines for considerable distances in this dissected granodiorite terrain, with the monitored Weany Creek gullies ranging 200–900 m in length, being typical of that catchment (Figure 21). Across the Weany and Wheel Creek gullies, the defined head, middle and valley sections occupied 18%, 29% and 52% of total gully length, respectively (Figure 22). The longitudinal slopes were similar between Weany Creek and Meadowvale gullies (Figure 23). The co-ordinates, catchment areas and slopes and other gully site details are tabulated in Appendix A.

Figure 21. (a) Widths and depths of the cross sections below gully heads, and (b) overall lengths of the Weany Creek monitored gullies. The lengths of monitored gullies are compared against a length histogram of 30 other Weany Creek gullies mapped from air photos.
Figure 22. Lengths (m) of the sections monitored in each of the Weany and Wheel Creek gullies, used for calculating erosion volumes and tonnes from the erosion pin cross sections. The head section length shown for gully VPG0 is the longest of 5 head sections monitored.

Figure 23. Gully longitudinal profiles, showing the location of head, middle and valley erosion pin cross sections. The top of the headcuts (shown at 0 m) were also monitored with erosion pins.

4.3.2 LOCATIONS OF EROSION AND DEPOSITION WITHIN GULLIES

The Weany Creek and Wheel Creek gullies had sufficient years of data to robustly indicate variations in erosion rate between headcuts, and head, middle and valley cross sections (Figure 16). The headcut and head cross sections experienced larger rates of erosion than further downstream (Figure 24). Overall, gully middle cross sections experienced small rates of erosion, and valley sections experienced net deposition, which is consistent with their definitions as transport and deposition zones, respectively. There were significant differences in erosion rates between gullies, illustrating the benefit of monitoring multiple gullies (Figure 25). The valley sections were a net sink in 6 of the 8 gullies.
Figure 24. Mean-annual erosion or deposition at headcuts and gully cross sections, averaged across 8 gullies in the Weany Creek and Wheel Creek catchments.

Figure 25. Mean-annual erosion or deposition at headcuts and gully cross sections for each monitored gully in the Weany Creek and Wheel Creek catchments.
After converting the erosion and deposition depths for each section into tonnes and accounting for the length of each section, the head sections were a slightly larger source than the headcuts overall (Figure 26). Across the Weany Creek monitored gully network, deposition in valley sections reduced overall sediment loss by 55% from what it would have been from headcut, head and middle sections alone. Deposition in valley sections was most influential in reducing net yield in drier years (Figure 29).

Six of the 8 gullies had a positive net sediment yield over the monitoring period. The net storage estimated in gullies VPXG2 and MVG1 resulted from large net storage in the valley sections. Given the low wall slopes of valley sections in those gullies, and the larger magnitudes of deposition in dry years, the net storage was probably derived more from erosion from the adjacent slopes lateral to the gully, rather than delivered through the gully from the catchment upslope of the gully heads. It is also likely that the mass deposited was slightly over-estimated by applying the same bulk density to deposited material as to eroded gully wall material ($1.54 \text{ t m}^{-3}$). Previous measurements indicate that deposited material in the gully bed has bulk density 10% lower than gully wall material (Bartley et al., 2007). In addition, the estimates for individual gullies have broader confidence intervals than aggregated across gullies, and the spatial sampling of the valley sections of these two gullies is poorer than other sections due to their longer length.

Bed level change as estimated from the scour chains was neglected when calculating total gully sediment yield. The channel bed scour chains indicated cumulative changes in bed level in the valley section over 8 years of <80 mm, except VPXG2 which degraded by 290 mm (Figure 27). The channel bed widths ranged 1–2 m. Also, the channel bed material had a coarser particle size distribution (~25% fine sediment) than the gully head and walls, (~36% fines) (Bartley et al., 2007).
4.3.3 RELATIONSHIPS WITH RAINFALL AND RUNOFF

Annual gully yield averaged across the six Weany Creek gullies was strongly dependent on annual runoff ($R^2 = 0.60$), with the positive gradient being significant at $p<0.05$ (Figure 28). Catchment area upstream of the gully heads (influencing runoff volume) was also a good predictor of mean-annual gully yield, particularly above 0.5 ha (Figure 28). Previous studies have also found dependence between gully erosion rate and runoff (Wijdenes and Bryan, 2001; Marzolff et al., 2011). Annual gully sediment yield was also significantly dependent on annual rainfall ($R^2 = 0.62$).
Figure 28. Relationships between (left) sediment yield in each year averaged across Weany Creek monitored gullies relative to annual runoff, and (right) mean-annual sediment yield over 8 years for each gully relative to the catchment area upslope of each gully head.

The timing of gully sediment yield also helps to indicate drivers of erosion. The annual net yields averaged across Weany Creek gullies were variable over the monitoring period (Figure 29). Net gully yields were negative during the first two years of monitoring, when rainfall was <470 mm. In the last 6 years of monitoring, net gully yields alternately increased, then decreased; giving a sawtooth pattern. These large increases in yield often, but not always, coincided with increases in rainfall and runoff.

The measured fluctuations in gully yield are consistent with a similar sawtooth pattern in annual Weany Creek TSS loads reported by Bartley et al. (2010c; In review). Variations in gully net sediment yield explained 84% of variations in Weany Creek annual TSS load (R-squared=0.84). Consistency in patterns of gully and catchment yield variation is not surprising given that gully erosion is the largest source of fine sediment in the Weany Creek catchment (Bartley et al., 2007). Sediment tracing also confirms that Weany Creek TSS is dominated by sub-surface soil (Wilkinson et al., 2013c). Thus, the consistency with Weany Creek TSS load validates the capacity of gully erosion pin monitoring to reliably detect differences between years, supporting the robustness of measured differences in erosion between gullies and between gully sections. It cannot be concluded from the regression R-squared value that gullies contributed 84% of TSS load, since other catchment sources such as hillslope scald erosion may also display similar temporal patterns.
Figure 29. Annual time series of net sediment yield averaged over the monitored Weany Creek gullies, and also the net yield for headcuts, head and middle sections only, neglecting valley sections. Gully yields are compared against rainfall, and also the runoff and TSS loads measured at the Weany Creek catchment outlet (Bartley et al., 2010c).

The erosion rates of gully head cross sections, as the largest source area in the gully network (Figure 26), were significantly dependent on annual runoff at p<0.05 (R-squared of 0.62; Figure 30). Head section erosion was less dependent on rainfall (R-squared of 0.31), indicating that upslope runoff was more important in driving widening of the head section than local rainsplash on gully walls. The magnitude of sediment storage in valley sections was also dependent on annual runoff (Figure 30). Valley sections were a net sediment sink in 7 of the 8 years.

Surprisingly, headcut erosion was not dependent on annual runoff than the gully cross sections (R-squared = 0.12; Figure 30). There was also no significant relationship between headcut retreat rate and the catchment area supplying runoff to each headcut. A larger but still modest dependence on rainfall was observed (R-squared = 0.32). This variability may indicate sensitivity to the sequence of rainfall, and patterns in the mass failure processes operating across the headcut faces, keeping in mind that monitoring was around the upper lip only. The magnitude of headcut retreat rates (< 5 mm yr⁻¹) was also much smaller than observed in previous studies of younger gully networks in less-textured soils (Wijdenes and Bryan, 2001; Marzolff et al., 2011; Rieke-Zapp and Nichols, 2011; Frankl et al., 2012), which probably contributed to the headcut retreat rates being relatively variable in time. Erosion or deposition in middle sections was less dependent on runoff, which is consistent with their field definition as transport zones, between erosional head sections and depositional valley sections.
4.3.4 RELATIONSHIPS WITH COVER

Cross section erosion rates were generally lower, and net deposition was more likely, at higher cover levels (Figure 31). This does not indicate that cover controls gully cross section erosion, indeed the opposite may be the case because high erosion rates may prevent vegetation from becoming established. However, association between gully wall cover and erosion rate is useful in a field monitoring context. Further, the association supports assumptions made by Thorburn and Wilkinson (2013) that gully erosion rates are lower at higher ground cover levels.
Outcomes

The hillslope gully geometries are consistent with a relatively mature gully network, in the latter stages of extension and deepening, and the middle states of widening and infill. Erosion occurs primarily as a result of overland flow over the gully head, widening of the head section by toe scour and sheetwash and rill erosion of the middle and valley sections. Mass failure was evident in some gully headcuts at some times. Despite erosion pins being a sparse sampling method, the consistent results across gullies and with changes in catchment sediment yields indicates that the number of gullies monitored was sufficient.

The large and significant dependence of head section erosion and gully yield on runoff is consistent with experience elsewhere (Figure 1). Consequently, it can be expected that reducing runoff into gullies is an effective way to reduce gully sediment yield.

The large contribution of deposition in valley sections to reducing overall sediment loss from the monitored gully network, and the decline in wall erosion at higher cover levels, illustrates the potential for reducing gully yield by improving vegetation cover within gullies (Figure 1). The channel bed level in valley sections of monitored gullies was also generally stable, indicating that vegetation would not be destabilised by undercutting. That the magnitude of deposition was largest during drier years indicates the importance of holding grazing pressure at consistently low levels during dry periods to enhance sediment trapping within gully networks.
5 Responses to grazing practice change

5.1 Objectives

The principles of gully erosion management are well known in a general sense (Section 1.2). However, the principles have not been tailored to, or tested within, the climates, landscapes and grazing systems of the Burdekin basin. This objective of this research component was to measure the impact on gully sediment yields of (i) reducing the runoff into gullies, which could be achieved by improving land condition, and (ii) increasing the vegetation cover within gully channels. These interventions are relatively cheaper and more practical in extensive grazing systems than reshaping gully features using earthworks or engineered drop structures.

5.2 Methods

5.2.1 EXPERIMENTAL DESIGN OF GRAZING PRACTICE TREATMENTS

The three principles identified in Section 1.2 by which grazing land management practices can influence gully erosion rates were represented in the experimental design; namely reducing runoff, increasing vegetation cover on gully walls, and increasing vegetation cover in gully channel beds.

The experimental design had two components. The first component was to apply grazing practice changes (treatments) to some Weany Creek monitored gullies. This component implemented a Before-after-control-impact (BACI) experimental design, building on the gully monitoring network in the Weany Creek catchment which had 6 years of monitoring data prior to treatment application. Non-treated controls were included with the intent to enable the possible separation of treatment responses from climate-induced inter-annual variability. In the second component of the experimental design, gully erosion rates were compared between study catchments with different grazing practices, land condition and runoff.

Grazing practice treatments applied to Weany Creek gullies

Reducing hillslope runoff

Three treatments were applied to Weany Creek gullies VPXG2 and VPXG5 to influence hillslope runoff into the gullies (it can be expected that reductions in runoff should lead to lower erosion rates of headcuts and head cross sections. Table 4). Firstly, pasture renovation was undertaken by the landholder early in the dry season in 2010, across part of the property including adjacent to gully VPXG5. This involved ripping approximately 30% of the gully catchment to approximately 10–15 cm depth and sowing seed at high application rates, being buffel grass (Cenchrus ciliaris), Urochloa (Urochloa mosambicensis) and shrubby stylo (Stylosanthes scabra). The ripping was relatively light and many existing Indian Couch (Bothriochloa pertusa) plants remained (Figure 32).

Secondly, the paddocks containing the two treated gullies (VPXG2 and VPXG5) were spelled in the 2010 dry season, the 2010/11 wet season and the 2011/12 wet season, with grazing re-introduced in early 2012. Thus there may be some change in the within gully cover as well as in catchment cover.

Thirdly, in 2011 a contour bank was installed to divert hillslope runoff away from the headcut of VPXG2. This technique may not be practical to install above all gully heads, but provides an opportunity to measure the end-member response to reducing hillslope runoff through improving land condition. The contour bank means that erosion rates within the head section of the gully system will be driven by local rainfall only rather than by upslope runoff. The diverted runoff bypassed the gully head via the adjacent drainage line.
which was well-grassed, and rejoined the gully channel in the valley section, 200 m downstream of the gully head.

It can be expected that reductions in runoff should lead to lower erosion rates of headcuts and head cross sections.

Table 4. Commencement dates of different treatments for hillslope gully sites, all of which continued until 2012. The monitoring period is shown in the right-hand column. Blank cells indicate that no change was made for those treatments at those gullies.

<table>
<thead>
<tr>
<th>CATCHMENT</th>
<th>GULLY</th>
<th>ALTERNATE WET-SEASON SPELLING</th>
<th>CATTLE EXCLUSION</th>
<th>RIP AND SEED</th>
<th>UPSLOPE CONTOUR BANK</th>
<th>GULLY CHECK-DAMS</th>
<th>MONITORING COMMENCED</th>
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<tr>
<td>Weany Creek</td>
<td>VPG0</td>
<td>2002</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>Thorton Creek</td>
<td>TCG1</td>
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<td></td>
<td></td>
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<td>2011</td>
</tr>
<tr>
<td></td>
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<td>2001</td>
<td></td>
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<td></td>
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</tr>
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<td>TCG3</td>
<td>2001</td>
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<td>2001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2011</td>
</tr>
</tbody>
</table>

^ Gully check-dams in VPG2 were installed over two years; the 3 valley section check-dams were installed in 2010 and the 3 middle section check-dams in 2011.
Figure 32. After ripping and seeding above gully VPXG5 on Virginia Park in 2010. (a) Ripping and seeding occurred over a large proportion of the catchment. The track on the right marks the upslope extent of the gully catchment. (b) Some of the existing Indian Couch was retained following ripping. (c) The Buffel grass seed germinated by July 2010.

Gully revegetation

Revegetation comprised two treatments. Firstly, an electric fence was installed to continually exclude grazing from ~10 m around gullies VPXG2 and VPXG5. Based on runoff monitoring, it is unlikely that the resulting increase in ground cover and biomass significantly impacted runoff volumes into the gully (Bartley et al., 2010a).

Secondly, revegetation within the gully channel beds of VPXG2 and VPXG5 was encouraged by installing 6 permeable check-dam structures in each gully, 3 in the middle sections and 3 in the valley sections. The
The purpose of these structures was to increase the proportion of fine sediment in the gully channel, allowing germination of available seeds from perennial grasses, shrubs and trees. The gully floor sediment deposits had typically only 10% by weight of silt and clay particles (Bartley 2007), making them too dry, unstable and nutrient poor to sustain much vegetation except from thin layers of Indian couch which tended to die off during droughts. The long-term aim was that this vegetation would enhance fine sediment trapping within the gully channel, increasing the carbon and nitrogen in the gully floor material (Garzon-Garcia et al., 2013). This should then sustain revegetation of the gully floor to continue the sediment trapping function, while the check dam timber would decompose over time.

These structures comprised fallen timber dragged to the site from within 100 m of the gully (mainly Ironbark spp.), stacked onto 100 mm mesh in a loose bundle spanning the gully channel. The sides of the mesh were gathered up and wired together forming a structure of ~0.5m round cross section (Figure 33). Star pickets were used to secure the structures into the gully floor. The check-dams were located in the middle and valley sections of the gullies, where scour chain monitoring indicated that the bed level was stable in the long term (Figure 27). The check-dams were spaced along the gully such that the crest height of each structure was approximately equal to the gully bed elevation at the next upstream structure (Figure 34, Figure 35).

It can be expected that gully revegetation should lead to reductions in gully sidewall erosion rates.

Figure 33. Installation of permeable timber check-dam structures in gully VPXG5.

Figure 34. Longitudinal profile of gully VPXG2, showing the location of check-dam structures S1–S6, erosion pin cross sections and the Gauge measuring runoff and water quality.
Differences between study catchments

The second component of the experimental design quantified the differences in land condition resulting from differences in land management practices between study catchments. It also quantified how those differences in land condition impacted on gully erosion rates. The Weany Creek catchment has had wet season spelling in alternate years and reduced pasture utilisation since 2002 (Bartley et al., 2010a). This change in grazing land management practices was not implemented in the Wheel Creek catchment, as described in Table 2. Thorton Creek and Main Creek catchments together represent a third type of grazing practice, with negligible or very light livestock grazing pressure but higher fire frequency since 2001, during which time they have been managed for military training. The wet-season spelling and grazing exclusion treatments are listed for each monitored gully in It can be expected that reductions in runoff should lead to lower erosion rates of headcuts and head cross sections (Table 4).

5.2.2 MONITORING METHODS

Weany Creek gullies

Monitoring the effect of treatments applied at Weany Creek gullies on vegetation, runoff and sediment yield involved the following methods:

Vegetation and hydrologic function

- The effect of pasture renovation and stock exclusion at VPXG2 and VPXG5 was monitored using Landscape Function Analysis (Tongway and Hindley, 2004b). This method provided indices describing soil stability, infiltration and nutrient cycling along 50 m transects upslope from the gully heads, bisected by the fenceline around the gullies.
- Within all Weany Creek gullies, ground cover and functional group was monitored annually, within a circle of radius 0.25 m around each gully cross section erosion pin.
- Photo-points were also established at each gully check-dam structure to monitor vegetation changes over time.

Surface runoff

The water discharge during runoff events was estimated at the upstream end of the valley section of the gully channels of VPXG2 and VPXG5 by monitoring event runoff depth at 1 minute intervals with a Greenspan PS700 pressure sensor connected to a Campbell CR10X data logger. The instrumentation was installed downstream of where the runoff diverted around the head of gully VPXG2 re-entered the main gully channel. Discharge rating curves were constructed against depth using HEC-RAS version 4.1 (January 2010), based on approximately 25 cross sections surveyed along each gully with a Sokkia total station. HEC-RAS assumptions included Steady Flow, a Critical Depth boundary function, and a Manning roughness of 0.04. The resulting discharge rating curves were of polynomial form (Table 5).
Table 5. Discharge-depth rating curves for instrumentation in VPXG2 and VPXG5 gullies

<table>
<thead>
<tr>
<th>GULLY</th>
<th>DEPTH RANGE</th>
<th>DISCHARGE (Q, M³/S) RATING EQUATION AGAINST DEPTH (Y, MM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPXG2</td>
<td>All</td>
<td>Q=2(E-9)y³ + 8(E-7)y² + 5(E-5)y + 0.0032</td>
</tr>
<tr>
<td>VPXG5</td>
<td>&lt;200 mm depth, low-flow channel</td>
<td>Q=2(E-6)y² – 0.0001y + 0.0037</td>
</tr>
<tr>
<td></td>
<td>&gt;200 mm depth</td>
<td>Q=1(E-5)y² – 0.0046y + 0.4736</td>
</tr>
</tbody>
</table>

Gully erosion and sediment yield

Cross sections of erosion pins were used to indicate rates of erosion and deposition at the gully headcut and in head, middle and valley sections (Section 4.2). Within the treated Weany Creek gullies (VPXG2 and VPXG5), cross sections were also surveyed with a Sokkia 510 electronic total station, upstream, across the crest and downstream of each check-dam following check-dam installation, and annually thereafter, to quantify the deposition upstream of each structure through time. Permanent benchmarks were used to enable survey repeatability over time. Deposition volumes upstream of each check-dam were calculated from survey data using Surfer software (V11, Golden Software; Figure 36). Deposition mass was calculated assuming a dry bulk density of 1.38 t m⁻³, based on measurements of Bartley et al., (2007). The annual sediment yields of treated gullies were compared before and after treatment, considering differences in annual runoff. To further identify treatment effects within the inter-annual variability in rainfall the relative differences in annual yield before and after treatment were compared between treated and untreated (control) gullies.

Figure 36. Looking upstream from the most upstream structure in VPXG5, showing the depositional surface overlayed across the reference gully profile.

The effect of gully check-dams on gully bed particle size distribution was quantified by sieving bed sediment samples to determine the proportion of the silt / clay component (<63 µm), relative to untreated gullies, gully walls. These data were combined with prior data on the particle size distribution of gully walls (Bartley et al., 2007), and also from several soil cores taken in the Weany Creek and Wheel Creek catchments by DNRM staff as part of the P2R program.

Within these two gullies, the runoff TSS, TN and TP concentrations were monitored by taking 1L water samples during runoff events using an ISCO 3700 24 bottle sampler. The sampling interval was every 2 minutes during runoff initially, adjusted to 10 minute intervals later in the season to better sample the full duration of events. Turbidity was recorded every two minutes during runoff events using a McVann Analite NEP395 probe.

From the runoff and TSS data, three methods were used to estimate TSS yield from treated gullies:

a. Turbidity-TSS relationship: For periods where turbidity records were available, the TSS concentration was estimated using a regression fitted between the TSS concentration of each sample and field turbidity (NTU). Discharge was multiplied by TSS concentration to estimate the
suspended sediment load for each time period (at VPXG2 turbidity data were unavailable after 30 Nov 2010 and method (c) was applied after this date).

b. Mean Annual Concentration (MAC): Discharge for each 1 minute period was multiplied by the annual mean concentration of suspended sediment obtained from water samples.

c. Mean Period Concentration (MPC): Discharge for each 1 minute period was multiplied by the mean concentration of suspended sediment measured from each of the three main periods of flow Nov-Dec, Jan-Feb and Mar-Apr.

These TSS yield estimates also provided validation of erosion pin measurements of gully sediment yield (Section 4.3).

Differences between study catchments

For the comparison of gully erosion rates between study catchments, the hillslope ground-layer vegetation was surveyed to determine its biomass and functional group composition, including native and exotic perennial grasses, and annual grasses. For this component, gully erosion data were limited to monitoring which was consistent across all study catchments, being headcut retreat during 2011/12 (Figure 16).

5.3 Results

5.3.1 TREATMENT EFFECTS AT WEANY CREEK

Summary

Responses to the gully treatments are qualitatively summarised by measurement metric in Table 6. The basis for these assessments and the magnitudes of the treatment impacts are described below.

Table 6. Summary of treatment effects in 2011 and 2012. Significant effects are shown in bold.

<table>
<thead>
<tr>
<th>TREATMENT</th>
<th>METRIC</th>
<th>GULLY VPXG2</th>
<th>GULLY VPXG5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rip and seed, fence around gully</td>
<td>Hillslope vegetation cover</td>
<td>NS(^a)</td>
<td>NS</td>
</tr>
<tr>
<td>Rip and seed, fence around gully</td>
<td>Hillslope soil infiltration capacity</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Hillslope contour bank</td>
<td>Gully headcut erosion rate</td>
<td>NS(^b)</td>
<td>Not applied</td>
</tr>
<tr>
<td>Fence around gully</td>
<td>Vegetation cover at erosion pin cross sections</td>
<td>Slight increase</td>
<td>Slight increase</td>
</tr>
<tr>
<td>Fence around gully</td>
<td>Erosion at erosion pin cross sections</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Gully check-dams</td>
<td>Vegetation cover at check-dams</td>
<td>Slight increase</td>
<td>Large increase</td>
</tr>
<tr>
<td>Gully check-dams</td>
<td>Deposition at check-dams</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td>Gully check-dams</td>
<td>Deposition of fine sediment at check-dams</td>
<td>NS</td>
<td>Significant</td>
</tr>
<tr>
<td>All</td>
<td>Reduction in total sediment yield</td>
<td>NS</td>
<td>Significant in 2(^{nd}) post-treatment yr.</td>
</tr>
</tbody>
</table>

\(^a\) Not Significant

\(^b\) Based on only one year of post-treatment monitoring
Vegetation responses

Hillslopes

Because the whole paddock containing the treated gullies was spelled in the 2010/11 and 2011/12 wet seasons, the effectiveness of the fence around the gullies could not be tested, and there was no obvious difference across the fence in landscape function at either treated gully.

Both hillslopes remained generally in stable, functional states with little or no signs of soil erosion. There was a general improvement in condition. On the VPXG2 hillslope, Stylostanthes legume spp became more prevalent during the monitoring period (Figure 37). On the VPXG5 hillslope where pasture renovation occurred in 2010, the sown *Cenchrus ciliaris* (Buffel Grass) and *Stylosanthes spp*. (legumes) were the dominant plant species found in these bands. The LFA stability, infiltration and nutrient cycling indices in the ‘Rip and Seed’ bands increased over the two post-treatment years but remained significantly lower than the other vegetated patches despite the above average rainfall in both wet seasons (Figure 38). This response indicates that this treatment takes a substantial time to affect hydrologic function. Given that the LFA infiltration index is correlated with measured soil infiltration capacity (Bartley *et al.*, 2006), the pasture renovation treatment cannot be expected to have reduced hillslope runoff in the monitoring period. The infiltration and nutrient cycling indices were highest under trees.

![Figure 37. VPXG2 facing down slope towards gully head in 2011 (left) and 2012 (right) showing the increase in *Stylosanthes spp.*]
Erosion pin cross sections

Within the treated gullies, cover in treated gullies increased at all cross sections over both of the post-treatment years, with the exception of VPXG5 head cross section in 2010/11 (Figure 42). The magnitude of increase in cover was generally above the average of the control gullies. The contrast between treated and control gullies was particularly noticeable in the middle and valley gully sections during the first post-treatment wet season, which was wetter than average.

Figure 39. Changes in mean cover at erosion pin cross section for treated and control gullies.

Gully check-dams

The check-dams were effective in slowing the passage of runoff through the gully, providing opportunity for finer sediment to deposit, without creating a large difference in head across the structures, and there were impressive changes in vegetation cover at some of the check-dams (Figure 40). In fact large increases in vegetation cover occurred on the gully bed adjacent to most of the gully check-dams, with 3 in gully VPXG5 having full grass coverage and two also including shrub recruitment by 2012 (Figure 41). In gully VPXG2 vegetation responses were less evident, particularly in the valley section.
Looking across both treated gullies as a group, the annual cross-section erosion rates, and the total gully sediment yields estimated from erosion pin cross sections, were within the range of yields in pre-treatment years. Considering the annual variations in post-treatment sediment yields of control gullies, a treatment effect was not strongly evident (Figure 42). Therefore, it is concluded that the stock exclusion and hillslope treatments did not impact significantly on sediment yield, which is not surprising given the modest effects of those treatments on vegetation.
Check-dam deposition reduced the mean gully sediment yield of the treated gully group from that estimated by erosion pin cross sections alone, although again this was not significant considering the decline in sediment yield of control gullies that occurred in the years following treatment (Figure 42).

Figure 42. Mean yield per gully for treated gullies (VPXG2 and VPXG5), and control gullies in the Weany Creek catchment, as estimated from the erosion pin cross sections. The dashed line indicates the timing of treatment. The treated gully mean yields are also shown including deposition upstream of the check-dams.

However, the two treated gullies had contrasting responses. The check-dams appeared to significantly reduce sediment yield for gully VPXG5. The VPXG5 sediment yield in 2011/12 was much lower than in any pre-treatment year including years of comparable runoff, and the first year with a negative estimated yield in the 8 year record (Figure 43a). The runoff in that year was modest (133 mm), and the hydraulic effect of check-dams is relatively more effective against smaller runoff. The additional vegetation growth in the gully channel in the second post-treatment year may also have enhanced deposition in 2011/12 (Figure 40). The control gullies had mean sediment yields in the post-treatment years that were below the regression of pre-treatment years, perhaps due to the run of wetter than average years, but within the range of previous yields (Figure 43c).

In contrast to VPXG5, the VPXG2 sediment yields in both post-treatment years were similar to those in the pre-treatment period for comparable runoff depths (Figure 43b). The check-dams in VPXG2 were installed...
over 2 years and so only one post-treatment year was monitored for the most upstream 3 check-dams, although the total volume of sediment deposition was similar between the two treated gullies (5.9 t and 5.3 t for VPXG2 and VPXG5, respectively). A more likely explanation is that the catchment area upstream of the checkdams in VPXG2 was larger than in VPXG5, leading to a greater volume of runoff, as indicated by the lack of revegetation around the checkdams (Figure 41).

The VPXG2 headcut retreat rate following installation of the contour bank was within the range of pre-treatment years, as were headcut retreat rates in control gullies (data not shown). Therefore

**Particle size of deposited sediment**

The particle size distribution of the deposited sediment was an indicator of the moisture and nutrient status of the gully bed for supporting natural revegetation. For gully VPXG5, the sediment deposited upstream of check-dams had much more fines (silt and clay) than did sediment on the bed of control gullies, and for 4 of the 6 check-dams it had more fines than subsoil (Figure 44). In contrast, check-dam sediment in VPXG2 (average 2.3% fines) was only slightly higher than that in control gullies. The control gully sediment was 0.7% fines on average (n=18), with the maximum fine sediment composition being 1.7%.

By comparison, soil cores in the Weany Creek catchment were on average 25% clay and 10% silt (35% fines; n=12), similar to previous sampling of gully walls in Weany Creek which recorded 36% fine sediment composition (Bartley et al., 2007).

![Figure 44. Proportion of silt and clay (<63 µm) in sediment deposited upstream of gully check-dams (sampled in March 2013), relative to control gully bed sediment and to soil cores.](image)

The contrast in check-dams effectiveness between VPXG2 and VPXG5, in terms of the significance of deposition volume, proportion of deposited silt and clay, and bed vegetation cover, is the difference in catchment area upstream of check-dams, and consequently runoff volumes. The catchment area for the most-upstream check-dam in VPXG2 was 3.3 ha, while the most-downstream check-dam in VPXG5 had catchment area of 1.6 ha.

**Gully runoff and fine sediment yield**

The runoff total estimated at the gully instruments were similar to those measured at the hillslope flume as a percentage of rainfall (Table 8). This provided some confidence about derived TSS loads, but suggested that the VPXG5 runoff may be under-estimated. Diverting runoff around the VPXG2 gully head and middle sections in 2010 had minimal effect on subsequent runoff as measured at the instruments, downstream of where that runoff re-entered the gully.

The absolute magnitudes, and relative changes in, sediment export estimated from the erosion pins were also similar to, or smaller than, those estimated from the in-gully instrumentation of runoff and TSS.
concentration (Table 8). This provides verification that a significant reduction in sediment yield occurred in VPXG5, and suggests that the reduction in yield estimated in VPXG2 was larger than estimated by the erosion pins.

Table 7. Runoff estimates from instrumentation in VPXG2 and VPXG5 gullies, relative to other estimates.

<table>
<thead>
<tr>
<th>SITE</th>
<th>WET SEASON</th>
<th>CATCHMENT AREA (HA)</th>
<th>RAINFALL (MM)</th>
<th>RUNOFF (MM)</th>
<th>RUNOFF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VPXG2</td>
<td>2010/11</td>
<td>16</td>
<td>1006</td>
<td>203</td>
<td>20</td>
</tr>
<tr>
<td>VPXG2</td>
<td>2011/12</td>
<td>16</td>
<td>787</td>
<td>201</td>
<td>26</td>
</tr>
<tr>
<td>VPXG5</td>
<td>2010/11</td>
<td>1.5</td>
<td>1186</td>
<td>106</td>
<td>9</td>
</tr>
<tr>
<td>VPXG5</td>
<td>2011/12</td>
<td>1.5</td>
<td>871</td>
<td>99</td>
<td>11</td>
</tr>
<tr>
<td>Flume 1^A</td>
<td>2010/11</td>
<td>1.2</td>
<td>1060</td>
<td>229</td>
<td>22</td>
</tr>
<tr>
<td>Flume 1^A</td>
<td>2011/12</td>
<td>1.2</td>
<td>787</td>
<td>134</td>
<td>17</td>
</tr>
</tbody>
</table>

^Source Bartley et al., (In review).

Table 8. Sediment load estimates from instrumentation in VPXG2 and VPXG5 gullies, relative to other estimates.

<table>
<thead>
<tr>
<th>GULLY</th>
<th>WET SEASON</th>
<th>TSS LOAD (TONNES) TURBIDITY METHOD</th>
<th>TSS LOAD (TONNES) MAC METHOD^A</th>
<th>TSS LOAD (TONNES) MPC METHOD^B</th>
<th>RELATIVE CHANGE (INSTRUM'TS)</th>
<th>GULLY YIELD (TONNES) PIN METHOD^C</th>
<th>RELATIVE CHANGE (EROSION PINS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2010/11</td>
<td>32.5</td>
<td>59.4</td>
<td>37.7</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2011/12</td>
<td>5.8</td>
<td>6.4</td>
<td>NA</td>
<td>-82%</td>
<td>13</td>
<td>-35%</td>
</tr>
<tr>
<td>5</td>
<td>2010/11</td>
<td>6.8</td>
<td>9.7</td>
<td>9.8</td>
<td>8.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2011/12</td>
<td>1.7</td>
<td>2.1</td>
<td>NA</td>
<td>-75%</td>
<td>1.3</td>
<td>-84%</td>
</tr>
</tbody>
</table>

^A Mean-annual concentration method
^B Mean period concentration method
^C For gully sections and check-dams upstream of instruments only

5.3.2 LAND CONDITION IMPACTS ON GULLY HEADCUT RATES

Vegetation cover and composition

We found significant differences in vegetation cover, biomass and composition between the study catchments. This indicates that some catchments can be expected to retain rainfall more efficiently and thus deliver less runoff into gullies than other catchments, potentially leading to lower gully erosion rates.

In particular, there were significant differences in the dry season ground cover index (GCI) between the study catchments. During the three drought periods represented in the data (1987, 1996 and 2003), when the GCI represents the persistence of perennial vegetation (Bastin et al., 2012), Main Creek and Thorton Creek, both within the Townsville Field Training Area, had similar relatively high cover levels, then Weany Creek had relatively lower cover levels, with Wheel Creek being relatively lower again (Figure 45).

The biomass and native perennial composition of ground layer vegetation was also higher in Main Creek and Thorton Creek than in Weany Creek or Wheel Creek (Figure 46). The remainder of the biomass was predominantly exotic Indian couch at Wheel Creek and Weany Creek, which has relatively limited root mass to enable infiltration of rainfall and reduce runoff, while in Thorton Creek and Main Creek the remainder of biomass was a mixture including deep-rooted legumes and grasses.
Figure 45. Annual dry season ground cover index for the properties containing each study catchment (or TFTA sectors in the case of Main Creek and Thornton Creek).

Figure 46. Standing biomass and native perennial grass percentage of ground layer vegetation in the 2011 dry season. Data for Main Creek and Thornton Creek are derived from Wilkinson et al. (2012). Data for Weany Creek are derived from Bartley et al. (In review).

Catchment runoff data are also consistent with TFTA catchments having better land condition and rainfall infiltration than grazed catchments. For daily rainfall totals of <100 mm, regressions across all runoff events indicated that Main Creek tended to have lower runoff than Weany Creek (Figure 47), despite these catchments having similar area, slope and soil type (Table 1). This is consistent with a previous study in Chromosol soils, which found that runoff decreases with increasing vegetation cover particularly on days with <50 mm rainfall (McIvor et al., 1995b). There is considerable scatter in the catchment runoff data, which can be attributed to variations in antecedent soil moisture and rainfall intensity. However, across 9 years of monitoring 2002–2011, more than half of the long-term runoff from the Weany Creek catchment occurred on days of <50 mm rainfall, and across those days, the overall runoff yields were 10% for Weany Creek and 3% for Main Creek. If Weany Creek instead had Main Creek runoff yields for those days, the long-term Weany Creek runoff would have been more than 30% lower. That land condition has a large impact on runoff from Chromosol catchments is also supported by runoff comparisons between grazed and non-
grazed hillslope plots on Meadowvale, which indicate 60% less runoff from the grazing exclosure (Hawdon et al., 2008).

![Figure 47. Main Creek and Weany Creek daily totals of rainfall and catchment runoff for days with non-zero runoff, over the period 2002–2011.](image)

Comparison of gully headcuts between TFTA and grazed catchments also indicates there may be some potential for reducing gully sediment yields by improving land condition. Headcut retreat rates were of similar magnitude across all catchments, but gullies in Thorton Creek had much larger upslope catchment areas (Figure 48). This suggests lower specific runoff volumes in Thorton Creek catchment (L/ha). The rainfall was higher in Main Creek and Thorton Creek catchments (947 mm and 888 mm compared with 786 mm in Wheel Creek and 866 mm in Weany Creek), and cannot explain why headcut catchment areas are larger in TFTA catchments.

Additional years of monitoring will better identify differences in headcut retreat rate between catchments, as will measuring erosion at cross sections within all gullies.
Weany Creek gully erosion rates were of similar order to those at Wheel Creek (Figure 25). This is not surprising given that hillslope runoff volumes in the Weany Creek catchment have not declined appreciably in the period since wet season spelling and reduced forage utilisation was introduced (Bartley et al., 2010a). More complete recovery of land condition, including dominance of native perennial tussock grasses, is required before hillslope runoff may reduce in the Weany Creek catchment.

5.4 Outcomes

This study demonstrates that when gully stick trap check-dams are sized appropriate to the catchment area and expected runoff volumes (catchment area <2 ha) they were effective at trapping fine sediment, and increasing vegetation cover on the gully channel bed. They were relatively ineffective where the catchment area was >2 ha, at least within 2 years of above-average rainfall. These findings are consistent with previous studies, in terms of the importance of sizing check-dams appropriately to the catchment area and expected runoff volumes for them to be effective (e.g., Armstrong and McKenzie, 2002), for their effectiveness in initiating revegetation of gully beds (Heede, 1979; Thorburn and Wilkinson, 2013), and for their effectiveness in reducing gully sediment yields (Heede, 1979; Rustomji et al., 2008; Thorburn and Wilkinson, 2013).

We found that renovation of Indian couch pastures on Chromosol soil requires more than 2 years to return to the pre-treatment levels of stability and infiltration capacity, and is not effective in reducing hillslope runoff within that period.

The treatment responses to date over two years are encouraging. Further monitoring is required to enable quantitative estimates of the sediment yield reductions resulting from these treatments, to allow vegetation responses to continue and to represent a wider range of climatic conditions.

Comparison of two catchments indicates that long-term catchment runoff may be >30% higher from degraded catchments relative to those in good condition, with differences occurring especially at rainfall totals <50 mm per day. Gully heads in good condition grazing land can have similar levels of stability to those in degraded condition at much larger catchment areas. Further analysis is required to assess whether these observations are broadly indicative. The processes involved in reducing runoff from degraded catchments are investigated in Section 6.
6 Process changes for reducing landscape runoff

6.1 Objectives

Sections 3, 4 and 5 support the proposition made in Section 1.2 that reducing runoff volumes from rangeland hillslopes may be expected to reduce gully sediment yields. Annual gully sediment yields in the Weany Creek catchment are dependent on differences in catchment area above each gully head, and on annual variations in runoff volumes (Figure 28). We also see that where runoff as a proportion of rainfall is lower, gully heads tend to have larger catchment areas, positioning them further downslope, and so reducing the present-day gully volume (Figure 48). In recent decades the headcut rate of gullies in TFTA catchments, particularly Main Creek, has been slower than in more heavily-grazed catchments (Figure 6), and so gully sediment yield will also have been lower. This section investigates the processes by which surface runoff can be reduced, and the time-scales of change.

As noted in Section 1.2, the runoff response to reduced stocking and increased vegetation cover appears to be dependent on pasture type and the degree of land degradation in past droughts. In degraded areas, pasture biomass is now dominated by Indian couch (Bothriochloa pertusa), which has a small basal area and root mass. Wet-season spelling and reduced forage utilisation has seen a steady recovery in the native perennial proportion of forage biomass in degraded pasture (Bartley et al., 2010a), which may lead to substantial hydrologic change if the recovery continues. However, reduction in annual runoff has not been observed over 10 years (Bartley et al., 2013). Modelling is a useful approach to investigating the long-term impacts of grazing management on runoff. Field data are typically too few to estimate changes in runoff with practice change, since rainfall is highly variable (Petheram et al., 2008), and the vegetation responses to practice change can have long time-lags (Wilcox et al., 2008b).

The objectives of this Section are to:

1. Describe a conceptual model for runoff from grazed hillslopes
2. Undertake a preliminary calibration and evaluation of the model using runoff data from Weany Creek
3. Using published values, investigate the possible ranges of hillslope model parameters controlling runoff, that would simulate runoff reductions of 20% and 50%
4. Compare (3) with published observations of runoff reductions due to grazing management actions and recovery processes
5. With guidance from published studies of landscape recovery, discuss the likely timeframes for recovery, and the management actions that might lead to them.

We discuss the findings from above and some broad implications for grazing management.

6.2 A conceptual framework

This section describes a conceptual framework for hillslope runoff and uses it to derive a simple water balance model for preliminary investigation of the effect of management actions. Models for describing surface hydrology are many and have been applied to grazing lands in the Burdekin catchment at broad scales (catchment to sub catchment) to estimate erosion and sediment export e.g. (Prosser et al., 2002), (Kinsey-Henderson et al., 2007b) and (Kinsey-Henderson et al., 2003). Hillslope runoff and erosion models have also been applied, with useful results, to dry tropical grazing lands by (Silburn et al., 2011b), who include a comprehensive review of other similar studies. Previous modelling studies have been relatively sophisticated, apart from the simple empirical model of (Scanlan et al., 1996b) that requires rainfall at the event time scale, and soil water deficit. For this preliminary modelling study, we have developed a simpler
approach that requires daily meteorological data and soil and vegetation data that can be estimated easily on site, from the literature, or from National data bases.

A savannah landscape typically comprises trees, shrubs, grass, litter and bare soil, which we have represented pictorially for an idealised hillslope (Figure 49). The “water balance” accounts for the redistribution of water fluxes (arrows with labels in italics) through stores (bold font) in the soil, the terrain and the vegetation.

Interaction between stores and fluxes are as follows: The input flux of rainfall ($P$) directly enters the canopy, soil surface and litter stores ($C$, $SS$ and $L$) and, once these stores are full, via infiltration ($I$) to the root zone store ($RZ$ – notionally bounded by the dashed line). Rainfall can also indirectly enter $SS$ and $L$ via throughfall ($TF$ – rain falling directly through, or dripping off, foliage) and stem flow ($SF$ – water running down the outside of stems) that, subsequently, become $I$. Water is lost from $C$ via interception loss ($IL$ - direct evaporation from foliage) and via evaporation ($Es$) from surface soil $SS$ and $EL$ from litter $L$ and from $RZ$ via evapotranspiration ($ET$) and drainage ($D$) below $RZ$. $D$ eventually enters the groundwater (not shown) or stream flow ($Q$). The residual flux is runoff ($R$ – sometimes called overland flow); it begins as sheet flow and is concentrated by hillslope geometry and other features like stock tracks ($ST$). It then enters gullies ($G$) and finally contributes to $Q$. Although, under certain circumstances, there can be sub surface lateral flow within, and from, the root zone, we assume it to be negligible. Streams drain the catchment and can also contribute to groundwater via lateral flow into stream banks and drainage via the stream bed but these processes are beyond the scope of this study.

Figure 49 The major water fluxes and stores in an idealised savannah hillslope comprising vegetation, bare soil and litter. The stores are labelled with bold symbols, and fluxes are represented as arrows with italic labels. Labels are defined in the text above.

Land use and management can influence the capacity of the stores and the processes that govern the rates and timing of some fluxes, for example, by altering: tree canopy cover (via clearing), pasture canopy (via grazing); litter (because of less biomass and litter fall); and infiltrability, via soil structural damage and disruption of soil ecology from animal traffic (Mclvor et al., 1995a; Holt et al., 1996). These changes have flow-on effects that influence the magnitude of stores $C$, $SS$, $L$ and $RZ$ and directly the flux $I$. The main flux of interest for this report is runoff ($R$) and is a result of the interactions between the stores and other fluxes.
and any changes in these due to grazing – any change in $R$ can, therefore, be considered to be an indirect result of grazing practices.

A schematic representation of the stores (depth, mm) and fluxes (mm d$^{-1}$) can be constructed as a “bucket” model (i.e. the stores are assumed to be either bounded or leaky buckets) for degraded and recovered hillslopes (Figure 50). To represent the fluxes and stores and their interactions requires theoretical descriptions of the underlying processes, and significant data to parameterise the representative processes. The appropriate timescale (e.g. rainfall event, daily, monthly, annual) best represented is dependent on the scientific questions to be asked and, in turn, determines the physical processes that must be represented. While sub daily processes (e.g. infiltration) are important and provide information directly relevant to management, many additional data are required to describe them. On the other hand, annual or decadal timescales often do not provide sufficient information to interpret seasonal or management effects.

![Figure 50 Schematic representations of the relative magnitudes and interaction stores and fluxes shown in Figure 49 for degraded and recovered grazing hillslopes. Changes in the area representing the stores are indicative of changes in storage capacity (mm); changes in arrow width are indicative of the increase or reduction in flux. Subsurface horizontal flow (or interflow) of water from the root zone is assumed to be negligible.](image)

There is typically an optimum level of model complexity between simplistic and highly descriptive where uncertainty is neither dominated by poor process representation (simplistic) nor unknowable parameters (complex) (Grayson et al., 2002; Silberstein, 2006). To represent all the stores and fluxes in Figure 50 requires a relatively complex model and properties and processes that are difficult to determine (e.g. $L$ and $E_L$).

Some of the above processes also occur at sub daily time scales. For example, infiltrability of soil changes at the temporal scale of a rainfall event (minutes to hours) and therefore influences Hortonian (infiltration excess) runoff (Horton, 1933) i.e. where $(P - IL) > I$. Interception loss ($IL$) can also vary rapidly as canopies wet up to capacity and then dry following rain events but representing this level of detail (Rutter et al., 1971; Gash, 1979) is unlikely to better inform management decisions e.g. (Dunin et al., 1978). Rainfall, potential evaporation $PET$ (used to estimate $E_S$, $E_L$ and $ET$) are typically widely available as daily totals, and daily runoff, although a coarse descriptor, can be sufficient for comparison of different runoff regimes in the first instance. For these reasons, we have chosen here a daily rainfall-runoff time step to help characterise hillslope hydrology and to investigate possible responses to changes in management.
6.3 Methods

6.3.1 A SIMPLE WATER BALANCE MODEL

To simplify the modelling of stores and fluxes, we preserved their behaviour at a daily scale, without describing their complex underlying physics. In particular we simplified the above schematic representation (Figure 50) by (i) not partitioning $P$ between $P$, $TF$ and $SF$, (ii) by combining the canopy, litter and soil surface into a single store (CLS) and (iii) combining evaporation from litter $E_l$ and soil surface $E_s$ with interception loss ($IL$), as shown in Figure 51.

![Figure 51 A simplified schematic of water stores and fluxes, where rectangles represent stores and arrows represent fluxes. The changes in the area of the rectangles representing the storages and the width of the arrows representing the fluxes give an indication of expected changes between degraded and recovered states.](image)

In this simplified water balance, evapotranspiration ($ET$) is sourced from the RZ store as is runoff ($R$), which remains disconnected from the soil surface component of CLS for simplicity. Infiltration ($I$) occurs only after CLS has reached maximum capacity. Evaporation comprises two phases delineated by a threshold of soil water storage $S^*$, defined as a proportion of $RZ$. For $S/RZ > S^*$, soil water is freely available and ET is maximum; for $S/RZ < S^*$, soil water is limiting and ET decreases monotonically to zero at $S/RZ = 0$. There is no restriction in infiltrability and therefore the root zone store (RZ) is simply an “open bucket” that is filled by $I$ and overflows when full, to produce runoff ($R$) as overland flow. $R$ can result only from saturation excess (Dunne and Black, 1970). Infiltration-excess (Hortonian) runoff is not represented in our preliminary model. We later show that for our site the opportunities for significant Hortonian flow are substantially fewer than those for saturation excess, and address the ramifications of omitting this process in the discussion. Interception loss ($IL$) occurs equally from all components of CLS and evapotranspiration ($ET$) is sourced from RZ. It is assumed there is no horizontal subsurface flux from the root zone. $S$ is the water stored in RZ at any time.

CLS is set to a constant maximum amount for each rain day, depending on canopy cover and is set to zero after each rainfall event. Effective rainfall events (i.e. they are sufficient to cause infiltration into the soil), therefore, must be larger than CLS and, in which case will equal $P - CLS$; for $P \leq CLS$, effective rainfall is zero.

Drainage ($D$) can occur as two main processes: i) saturated flow, which occurs when the soil is saturated and is in the order of millimetres per day, depending on the soil texture and macroporosity (Horton and Hawkins, 1965; Minasny and McBratney, 2000); or ii) unsaturated flow, which is orders of magnitude smaller than (i), and can be ignored for the purposes of simplification (Campbell, 1974). Other processes, such as by-pass and preferential pathway flows can occur in highly structured soils or where drying can lead...
to extensive cracking. These processes are spatially very heterogeneous, non-uniform or episodic and, because of the difficulties in measuring, describing and predicting them, are typically not represented (Booltink and Bouma, 1991; Morris and Mooney, 2004). However, evidence for their existence can sometimes be suggested by comparison of measured and modelled results.

A mathematical description of this daily model is given in Appendix B.

### 6.3.2 MODELLING THE EFFECTS OF GRAZING AND GRAZING MANAGEMENT

For a given climate series, our model partitions rainfall between the various fluxes (e.g. runoff $R$) depending on the capacity of the interception store ($CLS$), the root zone store ($RZ$) and the drainage flux ($D$). These are the three ‘fitting’ parameters. In this section, we look at evidence for the physical effects on these following the introduction of grazing systems and grazing management strategies. Although grazing effects on infiltrability (and hence the infiltration flux) are noted here, they are not included in the model.

Interception loss can be up to 30% of rainfall and, among other things, is dependent on the storage capacity of tree and pasture canopies, litter and soil surfaces.

Trees are critical players in savannah hydrology (Joffre and Rambal, 1993; Weltzin and McPherson, 1997; Williams et al., 1997; Hutley et al., 2000; Eamus et al., 2001) and clearing of grazing lands can affect runoff (Wilcox, 2007; WILCOX et al., 2008a; Pena-Arancibia et al., 2012a). The causal mechanisms for this are multiple and include changes in interception storage capacity, evapotranspiration flux and soil water storage capacity (see next section). Grazing also reduces pasture and shrub biomass by herbivory or treading (Lusby, 1970; McIvor et al., 1995a; Scanlan et al., 1996a; Mwendera et al., 1997; Greenwood and McKenzie, 2001; Taddese et al., 2002; Roth, 2004; Drewry et al., 2008; Teague et al., 2010; Teague et al., 2011). This reduces interception storage capacity of savannah vegetation and litter (Dunin et al., 1978; Thurow et al., 1987; Joffre and Rambal, 1993) illustrates the dependence of interception loss on canopy storage capacity of Australian forests.

(Thurow et al., 1987) have provided a useful conceptual diagram for the partitioning of rainfall between canopy, litter and soil storages, depending on the rainfall amount (Figure 52) for oak woodlands in North America. The diagram illustrates how small rainfall events $\leq$ canopy + litter storage capacity are entirely evaporated from leaf and litter surfaces. Where soil cover is incomplete, there will also be loss directly from the soil surface layer and we have proposed that surface soil will also comprise a component of $CLS$.

Rainfall in excess of $CLS$ will therefore enter the root zone store ($RZ$) if there are no infiltrability restrictions i.e. infiltration rate $\geq$ rain rate, which we assume to always be the case for the purposes of our model.
A range of pasture, rangeland or savannah studies have quantified either interception as a proportion of rainfall, canopy storage capacity, litter storage capacity or all of these (Appendix B, Table 10). Interception loss can represent up to 58% of rainfall reported by (Llorens and Domingo, 2007) for trees and shrubs in a Mediterranean environment. Lower values are reported for tree canopies and litter in grassy savannah (24 and 20%, respectively) (Thurow et al., 1987); it is not clear, however, what value the authors estimate for the whole plant community. Interestingly, they report that up to 222% of rainfall reached mineral, soil close to the tree stems (presumably augmented by stem flow) but it is difficult to determine, from the document, an average interception value for the ecosystem. More relevant for our study are the reported values of interception capacity which range between 0.5 and 2.8 mm for pasture (Marriam, 1961, cited by (Rutter et al., 1975) and 1.0 to 1.8 mm for savannah oak canopy (Thurow et al., 1987). While these studies do not provide definitive values, we have used them to advise our modelling and therefore assigned maxima for $\text{CLS} = 1.0$ mm during drought and 3.0 mm during non-drought years.

Soil water storage capacity (in our case, $RZ$), in simple terms, is determined by root depth and soil porosity and both are likely to be altered by plant and soil faunal activity. Above ground herbivory interacts complexly with below ground biomass and biota in natural systems. (Bardgett and Ward, 2003) and (McNaughton et al., 1998) reported no reduction in below ground biomass on an annual timescale due to ‘natural’ grazing on the African Serengeti. However, heavy grazing by sheep in Mongolia reduced below ground biomass (Zhao et al., 2005) and other authors reported similar biomass interactions and reduced fauna activity (Gross et al., 1991; Holt et al., 1996; Bardgett et al., 1998). We have found no reports on the effect of grazing on the rooting depth of pastures. Basal area and biomass of perennial pasture species have been used to develop soil infiltration indices in rangeland (Roth, 2004; Tongway and Hindley, 2004a) and was used as a surrogate for improved water entry and storage. We have reviewed soil bulk density values (Appendix B, Table 11), from which porosity ($\gamma$) can be estimated:

$$\gamma = 1 - \frac{\rho_b}{\rho_s} - \theta_{wp}$$

where $\rho$ is density (mass/volume) and the subscripts $b$ and $s$ refer to “bulk” and “soil particles”, respectively and $\rho_s = 2.65 \text{ g cm}^{-3}$. $\theta_{wp}$ is the volumetric water content at wilting point. Applying this to Table 11 gives a range of porosity between about 0.4 and 0.5, assuming a modest $\theta_{wp}$ of about 0.2. The review of (Greenwood and McKenzie, 2001) cites nine studies including the changes in soil bulk density from cattle grazing from 5 mths to 38 years in duration and all reported increase in bulk density for a range of soils rang of soils.

Amongst the studies we reviewed, we found no reports of root depth in Australian savannah and only one report (Snyman, 2005) of measured root depth (900 mm) from South African savannah. (Canadell et al.,...
1996), however, in a global review of maximum root depth of vegetation types, cites reports for temperate grassland of maximum root depths between about 1.2 and 6 m, with a median of about 2.5 m. Reports of grassland/savannah, maximum root depths range between about 1.5 m (presumably the grass components) and > 60 m (presumably the tree component).

The bulk density values reported above are unlikely to be measured at depths greater than about 1 m. Using a conservative root depth of 1 m and porosity of 0.4 gives an approximate value for pasture $R_Z = 400$ mm. In their study of deep drainage from savannah in the Upper Burdekin, (Williams et al., 1997) estimated PAWC (analogous to but smaller than $R_Z$) between 140 (grass) and 380 mm (trees).

The model does not seek to describe changes in infiltrability or underlying processes causing that, although the likely ramifications for the results are discussed later. These changes and processes are summarised as follows: During rainfall, litter and biological crusts can protect soil structure from raindrop impact and compaction (Moss, 1991a; Moss, 1991b; Belnap et al., 2005; Belnap, 2006). During overland flow, litter can form micro terraces and the increased surface hydraulic roughness produces deeper overland flow that allows longer durations for infiltration (Ellis et al., 2006a). Grazing affects surface soil structure, biological crusts and micro topography by either treading or reduction in litter and soil fauna (Lusby, 1970; Bridge et al., 1983a; Williams and Bonell, 1988; McIvor et al., 1995a; Holt et al., 1996; Mwendera and Saleem, 1997; Greenwood and McKenzie, 2001; Roth, 2004; Belnap, 2006; Drewry et al., 2008). These effects lead, inevitably, to reduced infiltrability and soil water storage. Table 11 lists relevant soil physical and hydraulic parameters and gives a clear indication of the tendency for grazing land management practices to reduce saturated hydraulic conductivity ($K_{sat}$) by up to >90%. Most notable is a relationship between bulk density and infiltration rate (Bartley et al., 2010b) shows that the low bulk densities associated with light grazing (10 years) and no grazing (16 years) were correlated with infiltration rates up to 1000 mm/hr, about 10 times that of normal grazing. These effects can have potentially large consequences for the partitioning of high intensity rainfall that can lead to infiltration excess (Hortonian overland flow). As indicated by Figure 53, this was an important consideration for representing many small events. This was less so for the larger events which tended to occur during the rainy season and, presumably, on wet soil that would have higher infiltrability.

Long term average deep drainage under native open forest in water-limited environments in Australia is typically small, although most data reported are for southern Australian regions, with a winter dominant and less episodic rainfall regime compared to Weany Creek (Allison et al., 1990; Walker et al., 1991; Walker et al., 2002). Table 11 gives values for $K_{sat}$ for seven relevant studies but measurements typically represent surface soil hydraulic properties. The exception is the study of (Williams et al., 1997) who used estimates of $K_{sat}$ for depth intervals between 0-0.15 m (720 to 960 mm d$^{-1}$) to 2.5-4.5 m (24 to 72 mm d$^{-1}$). The description of the drainage process in our model is an approximation only, allowing a fixed $D$ (mm d$^{-1}$) x 1 (d) for each day that $R_Z$ was full and we assumed that $D$ could be approximated by $K_{sat}$. For calibration we set $D = 20$ mm d$^{-1}$.

The main parameters in our model that reflect grazing management actions are in CLS and $R_Z$. After model calibration (described below), these parameters were adjusted to simulate pre-defined target reductions in runoff. Two runoff targets were simulated; 20% and 50% reductions, being potentially representative of best management grazing practices, and total grazing exclusion, respectively. These targets were defined based on the >30% difference in long-term runoff between Weany Creek and Main Creek (Section 5.3.2), the >60% difference in long-term runoff between grazed and non-grazed exclosures on Chromosol soil (Hawdon et al., 2008), and the ~50% difference between grazed hillslopes and brigalow vegetation (Thornton et al., 2007). The management actions and likelihood of achieving the runoff targets, and the likely timeframes, are discussed in Section 6.4 with reference to published data.

The scenario simulation procedures were as follows:

1. Calibration
   - Set $D$
   - Set $ET_{max}$ and $S^*$
• Determine by trial and error the wet/dry threshold that roughly distinguished drought years from non-drought years
• Set CLS for drought and non-drought years, to reflect higher biomass outside droughts
• Adjust $RZ_{\text{drought}}$ and $RZ_{\text{non-drought}}$ such that modelled runoff for the whole period = measured runoff and the correlation coefficient (Figure 53) was maximised

2. 20% runoff reduction – best grazing management practice (BMP)
• Adjust $RZ_{\text{non-drought}}$ such that 20% runoff reduction was achieved
• All other settings were unaltered

3. 50% runoff reduction (~ ungrazed)
• Set $CLS_{\text{drought}} = CLS_{\text{non-drought}}$ to reflect no grazing and therefore reasonable pasture biomass during drought and non-drought
• Adjust $RZ_{\text{non-drought}}$ such that 50% runoff reduction was achieved
• All other settings were unaltered.

6.3.3 APPLICATION OF THE WATER BALANCE MODEL AT WEANY CREEK

Data used for parameterising and calibrating the model were collected in the Weany Creek catchment, which was is dominated by eucalypt woodland on a cattle grazing property. The site is described in detail at the hillslope scale by Bartley et al. (2010b) and placed in a catchment context by Bartley et al. (2010d). The soils are predominantly red chromosols with a surface slope of about 3 to 4% with significant gullyling on the lower slopes (see Section 2.1). Native perennial pastures and soil surfaces was degraded, exotic annual grasses had colonised most areas and there existed a small number of bare surface scalds. Bartley et al. (2010b) describe grazing treatments and the monitoring during 2001–2007. Monitoring at the sites has continued to the present day and we have evaluated data up to and including 2010.

Model inputs were daily $P$, measured on-site, and PET (Potential EvapoTranspiration) obtained from the Silo Patched Point Data source (Jeffrey et al., 2001) for nearby weather station at Bluff Downs (19.60° S, 145.88° E). It was assumed that the vegetation was perennial, so the $ET$ “loss function” of the form (Figure 54; Appendix B) was active throughout the year, with $E_{\text{max}}$ and $S^*$ equal to 0.9 and 0.3, respectively, estimated from (Dunin et al., 2001). $D$ was estimated from the literature (Table 11; Appendix B) and set to 20 mm for each day that $S/RZ = 1$, where $S$ is the water store in $RZ$ (Figure 51). As large differences were observed in vegetative growth between the drought and non-drought periods, we made a distinction between “drought” years (<250 mm annual rainfall) and “non-drought” years (≥250mm annual rainfall). CLS was estimated from the literature (Table 12) with a maximum of 3 mm for “non-drought” years and 1 mm for “drought” years and this was applied by screening daily rainfall events $\leq CLS$.

For calibration, a Microsoft Excel spreadsheet was used to perform the algorithms of the water balance model described in Equations (1 to 6b). Hillslope runoff data for the period 24 January 2001 to 17 February 2010 were obtained from hydrological flumes draining three hillslopes (~0.2 to 1.1 ha) (Bartley et al., 2010a). $RZ$ was adjusted to maximise the correlation between measured and modelled $R$ (Figure 53) and aiming to represent well significant runoff events (at the daily time step) and resulted in $RZ_{\text{dry}} = 103$ mm and $RZ_{\text{wet}} = 161$ mm. If $RZ$ can be estimated as soil porosity x rooting depth, these values are within realistic boundaries, however we acknowledge this is a simplification of soil physical properties.

6.4 Results

6.4.1 SCENARIO MODEL OUTPUTS

The modelled water balance components (Table 9) show that interception loss over the modelled period was 19% of rainfall and this value is within reasonable bounds for Australia (Table 10). The maximum
measured daily runoff was 96 mm compared to the modelled value of 114 mm. Increases in CLS from 0 to 1, 2 and 3 mm during non-drought periods reduced runoff by 7, 17 and 27%, respectively.

Table 9. Water balance model parameters, field measurements and model results for the calibration and the 20% (BMP = Best Management Practice) and 50% (ungrazed) runoff reduction scenarios for the period 24 January 2001 to 17 February 2010 at Weany Creek. Wet/dry threshold is the annual rainfall upper bound where a particular year was deemed to be “drought”. Years with annual rainfall greater than this were deemed to be “non-drought”. RC indicates runoff the coefficient.

<table>
<thead>
<tr>
<th>MODEL PARAMETER</th>
<th>CALIBRATION</th>
<th>20% REDUCTION BMP</th>
<th>50% REDUCTION UNGRAZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drought threshold (mm yr(^{-1}))(^A)</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>(RZ_{\text{non-drought}}) (mm)</td>
<td>161</td>
<td>210</td>
<td>310</td>
</tr>
<tr>
<td>(RZ_{\text{drought}}) (mm)</td>
<td>103</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>CLS(_{\text{non-drought}}) (mm)</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>CLS(_{\text{drought}}) (mm)</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>(D) (mm d(^{-1}))</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>(E_{\text{max}})</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>(S)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Water balance component (mm)

<table>
<thead>
<tr>
<th>Water balance component (mm)</th>
<th>CALIBRATION</th>
<th>20% REDUCTION BMP</th>
<th>50% REDUCTION UNGRAZED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured rainfall (P)</td>
<td>4393</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Measured runoff (R)</td>
<td>667</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max measured daily runoff</td>
<td>96</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Measured RC</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Modelled runoff</td>
<td>667</td>
<td>533</td>
<td>332</td>
</tr>
<tr>
<td>Max modelled daily runoff</td>
<td>114</td>
<td>83</td>
<td>83</td>
</tr>
<tr>
<td>Modelled drainage</td>
<td>360</td>
<td>300</td>
<td>180</td>
</tr>
<tr>
<td>Modelled interception</td>
<td>832</td>
<td>832</td>
<td>908</td>
</tr>
<tr>
<td>Modelled evapotranspiration</td>
<td>2534</td>
<td>2727</td>
<td>2972</td>
</tr>
<tr>
<td>Modelled RC</td>
<td>0.15</td>
<td>0.12</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\(^A\)(Williams et al., 1997)
\(^B\)(Dunin et al., 2001)

Because of the simplifications used for the model, Hortonian runoff events (Horton, 1933) were not represented and appear as zero modelled runoff (Figure 53). The model was better able to represent events during the rainy season that resulted from saturation excess and this tended to be the larger events. An obvious anomaly was a runoff on the 27 February, 2007 that was recorded as 60 mm but modelled as 113 mm. One possible explanation is that deep cracking in the soil following drought allowed water to enter the deeper soil more than under normal conditions.
Simulating increased cover/biomass during drought for the ungrazed scenario increased interception loss by a further 9% over the modelling period. Increasing $RZ$ reduced drainage and increased evapotranspiration, as would be expected. $RZ$ values agreed well with those used by (Williams et al., 1997) and runoff was insensitive to changes in $RZ_{\text{drought}}$ for the two runoff reduction scenarios. The size of maximum daily runoff was reduced from 114 to 83 mm for the 20% runoff reduction scenario and this remained unchanged for the 50% reduction scenario. Table 9 lists the relevant model parameters and resulting water balance components for the calibration and the two runoff scenarios.

### 6.4.2 PROCESSES AND TIMEFRAMES OF RECOVERY

**Comparison with other studies in the Upper Burdekin catchment**

The 20% reduction in long-term runoff required a $RZ$ 30% larger than the Weany Creek baseline scenario, while the 50% reduction in runoff required a $RZ$ 90% larger (Table 9). These relative differences are consistent with the differences between Weany Creek and Main Creek catchments estimated by catchment-scale conceptual runoff modelling using the SIMHYD model (Chiew et al., 2002) (data not shown).

If it were assumed that $RZ$ responded in proportion with long-term changes in above-ground biomass, then it appears likely that a 20% reduction is achievable by continuing grazing at lower rates of forage utilisation. This is based on the fact that native perennial or Indian couch pastures on Chromosol soil in good land condition carried more than 3,000 kg/ha of forage biomass in 2011 (Wilkinson et al., 2013a), while Indian couch pastures in degraded condition such as Weany Creek carried less than 2,000 kg/ha (Figure 46).

It can be estimated that such large changes in biomass and $RZ$ will most probably require several decades of improved grazing management for degraded pastures. After 10 years of reduced forage utilisation Weany Creek pasture is still approximately 1,000 kg/ha, and annual runoff has not declined appreciably (Bartley et al., 2010a; Bartley et al., In review). Based on linearly extrapolating the increase in native perennial biomass which has occurred in Weany Creek over the past 10 years into the future, it will take another 20–30 years into the future before levels characteristic of pastures in good condition will be realised.

The potential magnitude and timescale of increases in $RZ$ resulting from reduced grazing pasture utilisation of degraded Indian couch pastures on Chromosol soils is not yet known in practice. Large differences in...
Comparison with studies elsewhere

We have reviewed 12 studies elsewhere reporting recovery of soil structure, hydrological characteristics or biota activity, and the time periods over which observations were made, ranging from three months to 40 years (Table 12). Although we could not find a definitive study, our review indicated that the level of soil structural recovery was roughly dependent on the level of soil degradation, the soil type and the climate wetness. There are numerous other factors including endemic and invasive vegetation, soil flora and fauna.

One notable example of vegetation influencing recovery outcomes is the rapid recovery of native perennial forage biomass following exclusion of grazing (Silburn et al., 2011a), in contrast to the long time-lines for recovery of forage biomass in degraded Indian couch pastures. In that case, the above-average rainfall, and good soil nutrient status, would also have been key factors to the rapid recovery. Colloff et al. (2010) measured soil macropore density and infiltration rates on revegetation plantings in south eastern Australia up to 20 years of age. They concluded there was little or no increase in infiltration rate for plantings 3-5 and 6-10 years old, but infiltration doubled for plantings 11-20 years old.

Time-Controlled (TC) grazing has become popular in parts of Queensland and limits the period that pastures are stocked, typically requiring divide paddocks to allow rotations with time. Both the vegetation and the soil are therefore subject to less damage. A five year study of time-controlled grazing by Sanjari et al. (2008) and Sanjari et al. (2009) found improvements in soil physical and chemical health, little effect on runoff, but increased ground cover and reduced sediment yield – similar findings to (Bartley et al., 2006).

We also reviewed six studies of the effects of grazing by sheep with durations ranging from 6 months to 5 years. Three studies reported with no change in bulk density with one reduction due to improved pasture, despite increased stocking rates on E. Camaldulensis savannah with a meadow podzol (Russell, 1960). The remaining two studies reported increases in bulk density with grazing. (Braunack and Walker, 1985) showed there was little difference between 16 years and 8 years of recovery on a duplex and a gradational solodic soil. Soil surface resistance decreased by about 40% and porosity, in some cases doubled to a depth of 12cm over this time. The deleterious effects of grazing were greatest on the gradational soil. Organic carbon levels increase by up to 5% after 16 years of reduced or removed grazing but little or no increase was observed before 8 years. The authors observed that the grazing-induced increases soil strength were bad for seedling recruitments.

The soil degradation influences from pasture grazing (as opposed to recovery) were reviewed by Drewry et al. (Drewry et al., 2008). Their work was not restricted to rangeland and includes limited information on recovery. The review of Greenwood and McKenzie (2001) illustrated that treading by stock decreases habitable soil pore space and reduces soil fauna populations and diversity. From the 12 studies we reviewed, half reported that grazing caused reduced aggregate stability. Eight studies reported on the effects of grazing on soil biology; grazing and soil biology including earthworms, earthworm larvae, termites and fungal hyphae. The majority reported deleterious effects and the remainder reported no correlation – grazing increased pests such as scarab beetles.

6.5 Outcomes

We developed a simple conceptual model of runoff from a hillslope and described this mathematically at a daily time step, with the root zone and soil-surface/interception storages being the main parameters sensitive to grazing management. The model was evaluated against measured runoff on a savannah landscape and found to indicate realistic storage values when calibrated to runoff monitoring data.

Considering the conceptual modelling scenarios, and the range in grazing impact and forage biomass which currently exists across the Upper Burdekin catchment, we find that reductions in long-term runoff of the
order of 20% are likely to be achievable in the long-term if pasture composition and biomass can be restored to levels typical of grazing properties at the upper end of ground cover levels.

Reviews of the recovery processes governing reduced runoff from improved grazing management practices, and the likely time frames to be expected for this recovery, show great variation in response (years to decades), depending on the degree of degradation, soil type, pasture composition, and other biophysical factors. For Australian conditions, significant recovery of soil and root zone conditions have been documented to be as long as 20 years, and are likely to be longer in areas of the Upper Burdekin catchment where pasture composition is now dominated by Indian couch. Even where recovery times are long, increases in above ground pasture biomass can increase vegetation interception capacity, resulting in some reduction in runoff within several years.
7 Conclusions

This study has investigated processes of gully erosion in the Upper Burdekin catchment and their response to grazing land management practices. It used air photos to track the growth of hillslope and alluvial gully networks over the past 65 years, monitoring of annual erosion and deposition processes throughout individual gully features over several years, a controlled trial of improved grazing land management practices including check-dams and pasture renovation, and conceptual modelling of the link between grazing practices and the volumes of hillslope runoff driving gully erosion.

From this study it is concluded that hillslope and alluvial gully networks in the catchment were predominantly initiated prior to 1945, and most likely around 1900. Today these mature features are eroding at approximately 50% of the rate over the entire life since their initiation, in grazed landscapes of the Upper Burdekin catchment. Some younger gully features within the networks have continued to erode rapidly in recent years of above average rainfall. Contemporary activity is lower in areas of good land condition. Air photo studies of gully activity are required at a larger number of sites to represent spatial variations in activity across the Burdekin basin.

It is concluded that reducing runoff volumes by reducing forage utilisation and improving land condition would be an effective method for reducing sediment yields from hillslope gullies, which are derived predominantly from the most upstream head sections of these features.

Reducing grazing pressure and improving land condition, to include perennial pastures having large basal area and deep root systems, should reduce runoff in the long term according to the physics of runoff generation. In particular, runoff can be reduced by increasing the size and availability of moisture stores in above-ground biomass, on the soil surface and in the root zone.

Increasing vegetation cover in gullied areas is also an effective method for reducing gully sediment yield, by enhancing deposition in downstream sections. Porous check-dams constructed of local fallen timber have been demonstrated as an effective way to trap fine sediment on the gully bed and so initiate revegetation of gully channels. They are effective at assisting revegetation of gully channels if runoff volumes are not so excessive as to wash all fine sediment further downstream (i.e. catchment area <2 ha). Further monitoring is required to quantify the effect on gully sediment yield.

These principles of reducing gully sediment yields, and of assessing practice effectiveness, may be expected to be transferable to other areas within the GBR catchments. It is recommended that the knowledge of gully erosion processes developed here can be used to investigate spatial variations in the responsiveness of gully networks to management practice change across GBR catchments. Guidelines for design of gully remediation treatments are also required to ensure reliable return on investment in practice change.
### Appendix A – Gully monitoring sites and instrumentation.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>GULLY</th>
<th>INSTRUMENTATION</th>
<th>EASTING</th>
<th>NORTHING</th>
<th>CATCHMENT AREA (HA)</th>
<th>CATCHMENT LENGTH (M)</th>
<th>CATCHMENT WIDTH (M)</th>
<th>CATCHMENT SLOPE (%)</th>
<th>CATCHMENT PROFILE</th>
<th>MONITORING COMMENCED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virginia Park</td>
<td>VPG0</td>
<td>LFA, erosion, veg cover, photos</td>
<td>449356</td>
<td>7799215</td>
<td>4.1</td>
<td>210</td>
<td>196</td>
<td>3.6</td>
<td>Convex</td>
<td>2001</td>
</tr>
<tr>
<td>Virginia Park</td>
<td>VPXG1</td>
<td>LFA, erosion, veg cover, photos</td>
<td>451975</td>
<td>7800173</td>
<td>0.8</td>
<td>75</td>
<td>102</td>
<td>3.6</td>
<td>Convex</td>
<td>2003</td>
</tr>
<tr>
<td>Virginia Park</td>
<td>VPXG2</td>
<td>LFA, erosion, veg cover, photos, runoff, autosampler</td>
<td>453562</td>
<td>7800432</td>
<td>0.4</td>
<td>243</td>
<td>17</td>
<td>2.4</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>Virginia Park</td>
<td>VPXG3</td>
<td>LFA, erosion, veg cover, photos</td>
<td>452654</td>
<td>7801614</td>
<td>6.7</td>
<td>262</td>
<td>257</td>
<td>2.9</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>Virginia Park</td>
<td>VPXG4</td>
<td>LFA, erosion, veg cover, photos</td>
<td>451920</td>
<td>7800395</td>
<td>1.4</td>
<td>241</td>
<td>58</td>
<td>2.0</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>Virginia Park</td>
<td>VPXG5</td>
<td>LFA, erosion, veg cover, photos, runoff, autosampler</td>
<td>448994</td>
<td>7800429</td>
<td>0.5</td>
<td>182</td>
<td>29</td>
<td>3.3</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>Meadowvale</td>
<td>MVG1</td>
<td>LFA, erosion, veg cover, photos</td>
<td>0.5</td>
<td>125</td>
<td>41</td>
<td>25</td>
<td>41</td>
<td>2.8</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>Meadowvale</td>
<td>MVG2</td>
<td>LFA, erosion, veg cover, photos</td>
<td>1.2</td>
<td>135</td>
<td>91</td>
<td>25</td>
<td>91</td>
<td>3.9</td>
<td>Concave</td>
<td>2003</td>
</tr>
<tr>
<td>TFTA</td>
<td>TCGA</td>
<td>Erosion, photos</td>
<td>415033</td>
<td>7834718</td>
<td>9.3</td>
<td>541</td>
<td>172</td>
<td>10.9</td>
<td>n/a</td>
<td>2009</td>
</tr>
<tr>
<td>TFTA</td>
<td>TCGB</td>
<td>Erosion, photos</td>
<td>414747</td>
<td>7834926</td>
<td>6.5</td>
<td>493</td>
<td>132</td>
<td>10.3</td>
<td>n/a</td>
<td>2009</td>
</tr>
<tr>
<td>TFTA</td>
<td>TCGC</td>
<td>Erosion, photos</td>
<td>414732</td>
<td>7834865</td>
<td>0.1</td>
<td>25</td>
<td>25</td>
<td>8.0</td>
<td>n/a</td>
<td>2009</td>
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<tr>
<td>TFTA</td>
<td>TCGD</td>
<td>Erosion, photos</td>
<td>414516</td>
<td>7834866</td>
<td>1.5</td>
<td>271</td>
<td>55</td>
<td>10.4</td>
<td>n/a</td>
<td>2009</td>
</tr>
<tr>
<td>TFTA</td>
<td>TCGE</td>
<td>Erosion, photos</td>
<td>414436</td>
<td>7834880</td>
<td>15</td>
<td>733</td>
<td>205</td>
<td>5.1</td>
<td>n/a</td>
<td>2009</td>
</tr>
<tr>
<td>TFTA</td>
<td>MCG1</td>
<td>Erosion, photos</td>
<td>0.2</td>
<td>64</td>
<td>29</td>
<td>3.6</td>
<td>29</td>
<td>3.6</td>
<td>n/a</td>
<td>2011</td>
</tr>
<tr>
<td>TFTA</td>
<td>MCG2</td>
<td>Erosion, photos</td>
<td>1.3</td>
<td>273</td>
<td>46</td>
<td>2.7</td>
<td>46</td>
<td>2.7</td>
<td>n/a</td>
<td>2011</td>
</tr>
<tr>
<td>Lassie’s Creek</td>
<td>LCG1</td>
<td>LFA, erosion, veg cover, photos</td>
<td>373794</td>
<td>7872037</td>
<td>3.9</td>
<td>63</td>
<td>53</td>
<td>2.8</td>
<td>Concave</td>
<td>2011</td>
</tr>
<tr>
<td>PROPERTY</td>
<td>GULLY</td>
<td>INSTRUMENTATION</td>
<td>EASTING</td>
<td>NORTHING</td>
<td>CATCHMENT AREA (HA)</td>
<td>CATCHMENT LENGTH (M)</td>
<td>CATCHMENT WIDTH (M)</td>
<td>CATCHMENT SLOPE (%)</td>
<td>CATCHMENT PROFILE</td>
<td>MONITORING COMMENCED</td>
</tr>
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</tr>
</tbody>
</table>

A Universal Transverse Mercator Zone 55S
B Catchment upslope of the gully head
C Measured along the drainage line of the catchment measured from the 25 m digital elevation model.
D Width derived as area divided by length
E Townsville Field Training Area
F Landscape Function Analysis (Tongway and Hindley, 2004b)
Appendix B – A simple water balance model

We have proposed a daily time step “bucket” model as a framework for the initial investigation of hillslope water balance, aligned with readily available inputs rainfall \((P)\) and potential evaporation \((PET)\). The two stores \(CLS\) and \(RZ\) are assumed to act as a bucket, and a leaky bucket, respectively, that overflow when full: when \(CLS\) is full, any excess water can become infiltration \((I)\) if \(RZ\) has not reached maximum capacity; and when \(RZ\) is full excess water become runoff \(R\). Owing to the absence of essential data to estimate Hortonian runoff (i.e. rainfall rate; \(\text{mm d}^{-1}\)), we have chosen not to represent it, at this stage, and infiltration is simply equal to the depth of the rainfall event or the remaining capacity of \(RZ\); whichever is the smaller. This limits the descriptive power of the model, as we demonstrate in the calibration stage and must be taken into account when interpreting results. Maximum capacity of \(RZ\) is a surrogate for Plant Available Water Capacity (PAWC) and represents the maximum soil water (mm) at field capacity (maximum water held in freely drained soil) minus the water held at wilting point, below which plants cannot access the water (Dunne and Willmott, 1996; Walker and Langridge, 1997). Plant available water content (PAWC = drained upper limit minus wilting point) is therefore less than maximum \(RZ\). We qualify the above by noting that we use water content as a surrogate for soil water tension (expressed in units of pressure), to which plants respond, rather than soil water content. Relations between soil water content and soil water tension vary between soil types and are dependent on soil texture i.e. the distribution of soil particle sizes (Minasny and McBratney, 2000; McKenzie et al., 2002; Harold and Hwat Bing, 2007).

The rate at which plants transpire depends on the atmospheric demand \((PET\), or potential evapotranspiration\) but can also be limited by supply - the amount of water \(S\) held in \(RZ\) (Federer, 1979; Chiew et al., 1995; Jung et al., 2010). Plants have a range of responses to this depending on their perenniality (either annual or perennial) and the soil water regime under which they have evolved. For example, an arid zone perennial has evolved to survive protracted dry periods and therefore uses less water as the soil dries out to survive until the next rainfall event (Eagleson, 1982; Rodriguez-Iturbe, 2000; Eagleson, 2002). Annual species have a short life cycle and therefore tend to use water available to them until senescence. Perennials that have evolved in humid environments are typically profligate water-users and do not cope well with dry periods. They respond to atmospheric demand by continuing to use water down to low levels, or wilting point, for which they are not physiologically adapted, and grow poorly or die (Harper et al., 2000).

Ritchie (1981) proposed a simple representation of water use characteristics of plants as having ‘stressed’ and ‘non-stressed’ water use domains (Figure 54). For convenience, we will refer to the plant water use characteristic as the plant ‘loss function’ from here on. A more general version of this the ‘loss function’, as defined by Rodríguez-Iturbe et al. (1999); it includes more conservative behaviour close to wilting point and incorporation of drainage into the loss function. Figure 54 shows \(ET/PET\) (\(ET\) normalised with \(PET\)) as it relates to relative soil water storage \((S)\) normalised with \(RZ\) for three types of vegetation with different water use strategies. \(E_{\text{max}}\) represents the maximum \(ET/PET\) (we use 0.6 for drought-adapted vegetation; 1.0 for a “high” water user) and \(S^*\) represents the threshold relative soil water storage between the non-stressed and the stressed (or more conservative) water use domains. Drainage in the model will occur when the soil profile is saturated \((S/RZ = 1)\) and until field capacity (FC) is reached and we simplify this by representing drainage as a “saturated flow event” – approximated by a fixed amount (mm) on each day that \(S/RZ\) reaches unity.
The relations of the water balance for the conceptual diagram in Figure 51 are listed below, where \( t \) signifies the daily time step, stores (bold) are in millimetres and fluxes (italic) are in millimetres per day. The subscript \( (t) \) indicates the relevant time step and \( \min[...] \) indicates the minimum of the terms within the brackets.

\[
I_L(t) = \min[P(t), CLS],
\]

\[
I(t) = \min[P(t) - CLS(t), RZ - S(t-1)]
\]

\[
R(t) =
\begin{cases} 
0 & \text{if } (P(t) - CLS(t)) \leq (RZ - S(t)) \\
(P(t) - CLS(t)) - (RZ - S(t)) & \text{if } (P(t) - CLS(t)) > (RZ - S(t))
\end{cases}
\]

\[
S(t) = S(t-1) + I(t) - ET(t) - D,
\]

where \( D = \)

\[
\begin{cases} 
0 & \text{if } S(t)/RZ < 1 \\
\text{constant} & \text{if } S(t)/RZ = 1
\end{cases}
\]

and where \( ET \) takes the discontinuous form of Figure 54

\[
ET(t) =
\begin{cases} 
PET(t) \left( \frac{E_{max}}{S^*} \right) \left( \frac{S(t)}{RZ} \right) & \text{for } 0 \leq \frac{S(t)}{RZ} < S^* \\
PET(t)E_{max} & \text{for } 0 \leq \frac{S(t)}{RZ} < 1
\end{cases}
\]

and \( PET(t) \) is the potential evaporation for day \( t \) and \( E_{max} \) and \( S^* \) are indicated in Figure 54 but will be specified for examples used here. The following tables review previous studies to determine...
appropriate parameter values for applying the model in the Weany Creek catchment, and for interpreting the magnitudes of change in runoff indicated by the model outputs, and for estimating the processes and time-lines over which changes in runoff may be expected occur.
### Table 10. Interception and canopy storage values for trees, shrubs, grass and litter in low rainfall environments

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site</th>
<th>Landscape/vegetation</th>
<th>Mean annual rainfall (mm)</th>
<th>Climate</th>
<th>Interception % rainfall</th>
<th>Maximum canopy storage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Crouse et al., 1966)</td>
<td>California USA</td>
<td>Grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Dunin et al., 1978)</td>
<td>Southern Tablelands NSW Australia</td>
<td>Themeda australis (kangaroo grassa) grassland</td>
<td>~600</td>
<td>Mediterranean</td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>(Llorens and Domingo, 2007)</td>
<td>Various in Europe</td>
<td>Trees and shrubs</td>
<td></td>
<td>Mediterranean</td>
<td>7 to 58</td>
<td>Not recorded</td>
</tr>
<tr>
<td>(Paco et al., 2009)</td>
<td>Portugal</td>
<td>Oak woodlands (savannah-type). Trees only considered.</td>
<td>669</td>
<td>Mediterranean</td>
<td>24</td>
<td>1.16</td>
</tr>
<tr>
<td>(Thurow et al., 1987) – see also Figure 52</td>
<td>Sonora Texas USA</td>
<td>Canopy Litter</td>
<td>609</td>
<td>Semarid savannah</td>
<td>25.4 20.7</td>
<td>1 to 1.8</td>
</tr>
<tr>
<td>Burg and Pomeroy (1958), cited by (Rutter et al., 1975; David et al., 2006)</td>
<td></td>
<td>Mixed grasses and legumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marriam (1961), cited by (Rutter et al., 1975)</td>
<td></td>
<td>Lolium perenne (perennial ryegrass)</td>
<td></td>
<td></td>
<td></td>
<td>0.5 to 2.8</td>
</tr>
</tbody>
</table>
Table 11. Sites and parameters for relevant soil hydraulic and soil physical properties in rangeland experiments

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site</th>
<th>Measured</th>
<th>Method</th>
<th>Treatments</th>
<th>Other results</th>
<th>Bulk density</th>
<th>Kunsat (mm/hr)</th>
<th>Ksat (various)</th>
<th>PAWC (mm m⁻¹)</th>
<th>Root depth (mm)</th>
<th>Soil depth (mm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Hawdon et al., 2008)</td>
<td>Meadowvale</td>
<td>Infiltration, hydraulic conductivity</td>
<td>Ring and hood infiltrometer, disc permeameter Tongway</td>
<td>Non Grazing (NG), Light Grazing (LG) and Heavy Grazing (HG)</td>
<td>Non- 1.333 Light – 1.516 Heavy – 1.569</td>
<td>Disc zero tension 54.59 11.11 3.96</td>
<td>Mostly opposite trend on no grazing but not clear. Generally NG&gt;LG&gt;HG with sig diff. Large values in NG.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(Alewine, 2003)</td>
<td>Kirk River</td>
<td></td>
<td>See above</td>
<td>NG – 1.455 LG – 1.421 HG - 1.462</td>
<td>Disc zero tension 25.01 9.12 5.84</td>
<td>Ditto Specific observations on and off tussocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Bartley et al., 2010b)</td>
<td>Weany Creek Meadowvale etc</td>
<td>etc</td>
<td>Grazing Light grazing No grazing</td>
<td>Etc.</td>
<td>~1.70 ~1.50 ~1.38</td>
<td>~50 ~400 ~1000</td>
<td>~</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Bridge et al., 1983c)</td>
<td>Katherine 14.6S 132.2E</td>
<td>Ksat Sorptivity</td>
<td>Single ring infiltrometers</td>
<td>Grassland Burn Burn Burn + clip Bare</td>
<td>cm/min 0.12 0.028 0.041 0.031 0.057</td>
<td>Macro pore space</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Bridge et al., 1983b)</td>
<td>Katherine 14.6S 132.2E</td>
<td>Single ring infiltrometers</td>
<td>Different pastures</td>
<td>0.029-0.182</td>
<td>1.4-1.6</td>
<td>mm/hr 10-50 15-85</td>
<td></td>
<td></td>
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<tr>
<td>(Colloff et al., 2010b)</td>
<td>Northern Victoria Bendigo Heathcote Charlton St Arnaud</td>
<td>Macropores Infiltration Age classes: 3-5, 6-10 and 11-20 years</td>
<td>Rainfall simulator</td>
<td>Vegetation paddock</td>
<td>1.35 (surface) 1.75 – little difference between trees and pasture</td>
<td>Pasture – 31.2-36.5 Trees 45.3-50.4</td>
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<tr>
<td>(Ellis et al., 2006b)</td>
<td>Booroowa NSW</td>
<td>Runoff Infiltration</td>
<td>Rainfall simulator</td>
<td>Trees and pasture,</td>
<td>1.35 (surface) 1.75 – little difference between trees and pasture</td>
<td>Pasture – 31.2-36.5 Trees 45.3-50.4</td>
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<tr>
<td>Reference</td>
<td>Site</td>
<td>Measured</td>
<td>Method</td>
<td>Treatments</td>
<td>Other results</td>
<td>Bulk density</td>
<td>Kunsat (mm/hr)</td>
<td>Ksat (various)</td>
<td>PAWC (mm m⁻¹)</td>
<td>Root depth (mm)</td>
<td>Soil depth (mm)</td>
<td>Comments</td>
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<td>------------------------------------------------</td>
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<tr>
<td>(Hawdon et al., 2008)</td>
<td>Meadowvale</td>
<td>Runoff from Scanlan (1996) plots</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(Holt et al., 1996)</td>
<td>80 km for Charters Towers Hillgrove Cardigan</td>
<td>Infiltration</td>
<td>Disc. 20 and 40 mm suction</td>
<td>Low GP</td>
<td>High GP</td>
<td>Hillgrove 0.91, 0.93 Cardigan 1.46, 1.41</td>
<td>Hillgrove mm/hr 9.6, 30.6; 6.2, 13.8 Cardigan 7.4, 27.4; 3.7, 19.3</td>
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<tr>
<td>(Kinsey-Henderson et al., 2005)</td>
<td>Weany Ck</td>
<td>Modelled runoff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Importance of hillslope shape regarding concentrating flow etc.</td>
</tr>
<tr>
<td>(McIvor et al., 1995b)</td>
<td>Cardigan Charters Towers</td>
<td>Runoff infiltration</td>
<td>4 pasture systems (with and without trees) with 2 stocking rates. Sown pastures</td>
<td>Runoff vs cover</td>
<td>Runoff vs sediment</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Recommendations on minimum cover (&gt;40%) if runoff and sediment yield was to be reduced by 20% from maximum</td>
</tr>
<tr>
<td>(Roth et al., 2003)</td>
<td>Weany and Wheel Rain sim: Thalanga Pinnacle transect Simpson’s dam High range Meadowvale Wambiana</td>
<td>Runoff Sediment Modelling Gully monitoring Infiltration vs cover Review (Ch 8 M Webb) of landscape remediation techniques.</td>
<td>‘Scanlon plots’ Micro plots Profile meter Rainfall simulation</td>
<td>Different results – in line with Scanlon, that low intensity events – runoff declined as cover increased. But no obvious relationship with high intensity – see p47</td>
<td>1.53-1.90 1.51-1.72 1.46-1.67 1.36-1.57 1.43-1.61 1.48-1.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Maps of gully head migration figs 5.25 and 5.26 Ch 7 for runoff. Table 7.4 brings a lot of it together.</td>
</tr>
<tr>
<td>Reference</td>
<td>Site</td>
<td>Measured</td>
<td>Method</td>
<td>Treatments</td>
<td>Other results</td>
<td>Bulk density</td>
<td>Kunsat (mm/hr)</td>
<td>Ksat (various)</td>
<td>PAWC (mm m(^{-1}))</td>
<td>Root depth (mm)</td>
<td>Soil depth (mm)</td>
<td>Comments</td>
</tr>
<tr>
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</tr>
<tr>
<td>(Mwendera and Saleem, 1997)</td>
<td>Ethiopian Highlands</td>
<td>Infiltration runoff</td>
<td>Runoff plots Ponded double ring infiltrometer – read when steady</td>
<td>Natural pasture 3 grazing regimes + control. Some with ploughing first</td>
<td></td>
<td>5.3 to 17.6</td>
<td></td>
<td></td>
<td>220-295</td>
<td></td>
<td></td>
<td>Grazing pressure increased runoff from combined effects of trampling and cover removal</td>
</tr>
<tr>
<td>(Owens et al., 2003)</td>
<td>Springvale Qld</td>
<td>Modelling soil water balance and runoff Curve number and pasture growth CN better than Scanlan empirical model – 4 soil layers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>116.5 74.4 101.1 64.7 37.5 82.5 122.6 50.7 108.4 119.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Snyman 2005)</td>
<td>South Africa</td>
<td>Roots Biomass runoff</td>
<td>Good moderate poor condition</td>
<td>Runoff 1.6% good 4.8% fair 10% poor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Measured to 900</td>
</tr>
<tr>
<td>(Pena-Arancibia et al., 2012b)</td>
<td>Comet and Burdekin</td>
<td>Tree cover Stream flow</td>
<td>Remote sensing</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Clearing seems to have had a smaller impact on streamflow than estimated by others</td>
</tr>
<tr>
<td>(Scanlon et al., 1996)</td>
<td>Upper Burdekin</td>
<td>Runoff Sediment Bedload Rainfall</td>
<td>Runoff plots Empirical runoff model</td>
<td>Grazed ungrazed</td>
<td>Strong relationship showing reduction in sediment with cover</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Influence of cover, rainfall event, intensity and water deficit – very interesting</td>
</tr>
<tr>
<td>(Silburn et al., 2011a)</td>
<td>Springvale</td>
<td>Rainfall Runoff, sediment bedload</td>
<td>Review of runoff research Runoff plots</td>
<td></td>
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</tbody>
</table>

Gully erosion and its response to grazing practices in the Upper Burdekin catchment
### Table 12. Australian pasture/rangeland studies and recovery times for soil structure and hydrology

<table>
<thead>
<tr>
<th>Reference</th>
<th>Site</th>
<th>MAR (mm)</th>
<th>Climate</th>
<th>Landscape</th>
<th>Soils</th>
<th>Treatment</th>
<th>Relevant measurements</th>
<th>Results</th>
<th>Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Bartley et al., 2010b; Bartley et al., 2010d)</td>
<td>Weany Creek</td>
<td>584</td>
<td>Dry tropical</td>
<td>Rangeland savannah</td>
<td>Red Chromosol, Yellow to brown texture contrast, some dispersive B horizons.</td>
<td>Wet season spelling</td>
<td>Runoff, vegetative biomass, sediment yield and concentration</td>
<td>Little impact on runoff except for early season small events, increased biomass, significantly reduced sediment yield</td>
<td>6 years</td>
</tr>
<tr>
<td>(Russell, 1960)</td>
<td>Kybyolite southeast South Australia – native grasses</td>
<td>549</td>
<td>Mediterranean</td>
<td>Undulating sheep grazing - originally E. Camaldulensis savannah</td>
<td>Solonetzic Podzol</td>
<td>Fertilizer treatments x 8</td>
<td>Bulk density reduction from 1.43-1.61 to 1.15-1.52</td>
<td>Improved carrying capacity</td>
<td>40 years</td>
</tr>
<tr>
<td>(Braunack and Walker, 1985)</td>
<td>Wycanna Queensland</td>
<td></td>
<td></td>
<td>Grazed poplar box savannah</td>
<td>Duplex (Paleusalf)</td>
<td>Grazing exclusion</td>
<td>Infiltration, $K_{sat}$, soil surface resistance. porosity</td>
<td>30 to 50% bulk density reduction. ~40% reduction in penetration resistance. Improved $K_{sat}$ depending on soil type.</td>
<td>16 years</td>
</tr>
<tr>
<td>Reference</td>
<td>Site</td>
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</tr>
<tr>
<td>(Greenwood and McKenzie, 2001)</td>
<td>Exhaustive international review</td>
<td>multiple</td>
<td>multiple</td>
<td>Sheep and cattle grazing</td>
<td>Multiple</td>
<td>Grazing pressure/exclusion</td>
<td>Bulk density, penetration resistance, water content, aggregate stability</td>
<td>General decrease in bulk density and penetration resistance. Negative or no relationship between stocking rate and aggregate stability. Typically negative relationship between stocking rate and soil water.</td>
<td>3 months to 50 years</td>
</tr>
<tr>
<td>(Stephenson and Veigel, 1987)</td>
<td>Reynolds Creek, Idaho, USA</td>
<td>239 to 1124 see (Nayak et al., 2010)</td>
<td>Varied</td>
<td>Rangeland to alpine</td>
<td>Not given</td>
<td>Stocking rates, up to 10 head per ha.</td>
<td>Bulk density</td>
<td>Bulk density reduction form 1.48-1.57 to 1.37-1.38. 92% recovery</td>
<td>16 months. Two growing seasons.</td>
</tr>
<tr>
<td>(McIvor et al., 1995a)</td>
<td>Cardigan, Charters Towers, Queensland</td>
<td>650</td>
<td>Monsoonal</td>
<td>Semiarid savanna</td>
<td>Red neutral duplex Dr2.12 Northcote 1979</td>
<td>Fertilizer, grazing pressure and tree density, fire</td>
<td>Infiltration, K&lt;sub&gt;sat&lt;/sub&gt; and soil macrobiota, bulk density</td>
<td>Influence of groundcover depended on size of rainfall event. Managers should maintain &gt;40% cover.</td>
<td>14 years</td>
</tr>
<tr>
<td>(Holt et al., 1996)</td>
<td>Cardigan, Charters Towers, Queensland</td>
<td>650</td>
<td>Monsoonal</td>
<td>Semiarid savannah</td>
<td>Red neutral duplex Dr2.12 Northcote 1979</td>
<td>Fertilizer, grazing pressure and tree density, fire</td>
<td>Loss of soil fauna activity and trampling and associated higher bulk density and lower infiltration and K&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>years</td>
<td></td>
</tr>
<tr>
<td>(Colloff et al., 2010a)</td>
<td>23 sites – northern Victoria</td>
<td>431 to 569</td>
<td>Mediterranean</td>
<td>Undulating grazing</td>
<td>Solodized solonetz</td>
<td>Revegetation – ecological tree plantings and fencing</td>
<td>Rainfall simulation, infiltration, macro pore density, macro fauna species</td>
<td>Increases in infiltration (up to 2.5 times) and macropore density (&gt;10 times) due to action of macrofauna</td>
<td>11 to 20 years</td>
</tr>
<tr>
<td>(Connolly et al., 1997)</td>
<td>Springvale, Queensland</td>
<td>690</td>
<td>Highly variable summer-dominant rainfall</td>
<td>1 to 14 % slope on sandstone, siltstone or mudstone base</td>
<td>Moderately herding-setting sandy loams – solodised solonetz-solodic Great Soils Group</td>
<td>Cover increase from 20 to 60-70%</td>
<td>Data collection and modelling. Runoff and infiltration. Reduction in runoff from 20% to 0 to &lt;10% rainfall following stock exclusion and revegetation</td>
<td>Reduction in runoff from 20% to 0 to &lt;10% rainfall following stock exclusion and revegetation</td>
<td>6 years</td>
</tr>
<tr>
<td>(Ellis et al., 2006a)</td>
<td>Boorowa New South Wales</td>
<td>~650</td>
<td>Mediterranean</td>
<td>Undulating grazing 6% slope</td>
<td>Chromic Luvisol or Red Chromosol</td>
<td>Fenced farm shelter belt</td>
<td>Rainfall simulation – runoff and infiltration, bulk density</td>
<td>Runoff reduced by 100, 63 and 14%, respectively, for events with, 2, 10 and 50 year return period, in rapid succession</td>
<td>15 years</td>
</tr>
<tr>
<td>Reference</td>
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</tr>
<tr>
<td>(Sanjari et al., 2008)</td>
<td>40 km west of Stanthorpe Qld</td>
<td>645</td>
<td>Dominant summer rainfall</td>
<td>Semi arid grazing</td>
<td>Clay to clay-loam mostly</td>
<td>Time-controlled grazing</td>
<td>Bulk density, cover, litter, soil organic carbon and nitrogen</td>
<td>No reduction in bulk density from time controlled grazing</td>
<td>5 years</td>
</tr>
<tr>
<td>(Sanjari et al., 2009)</td>
<td>40 km west of Stanthorpe Qld</td>
<td>645</td>
<td>Dominant summer rainfall</td>
<td>Semi arid grazing</td>
<td>Clay to clay-loam mostly</td>
<td>Time-controlled grazing</td>
<td>Cover, runoff and sediment loss</td>
<td>Runoff decreased only for small events – little change overall; significant reduction with increase in cover</td>
<td>5 years</td>
</tr>
</tbody>
</table>
References

Bergonse RV, Reis EJ. 2011. Theoretical constraints to gully erosion research: time for a re-evaluation of concepts and assumptions? Earth Surface Processes and Landforms, 36: 1554-1557. 10.1002/esp.2188.


