Alluvial Gully Erosion Rates and Processes Across the Mitchell River Fluvial Megafan in Northern Queensland, Australia

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Abstract

Gully erosion is the process by which running water cuts new unstable channels into erodible regolith. It causes severe land degradation, is a major component of contemporary sediment budgets, and is a major source of sediment pollution to aquatic ecosystems. In northern Australia, there is widespread gully erosion into unconfined alluvial deposits on active and abandoned floodplains – here defined as *alluvial gully erosion*. In catchments draining to the Gulf of Carpentaria, alluvial gullies can cover 0.2% to 1.0 % of the total catchment area and locally >10% of the floodplain area. Alluvial gully erosion has been poorly documented and differs substantially from colluvial or hillslope gullying in south-eastern or northern Australia. The objectives of this research were to investigate and quantify alluvial gully erosion processes and rates at a variety of spatial and temporal scales across a pilot study area, which encompasses the Mitchell River fluvial megafan on the Cape York Peninsula in northern Queensland.

Along the Mitchell megafan, alluvial gullies are concentrated along main drainage channels. Their scarp heights and potential energy are highly correlated to the local relief between the floodplain and river thalweg, which is a result of river incision into the megafan since the Pleistocene. Other factors such as floodplain hydrology, soil texture and chemistry, vegetation cover, and land-use disturbance also influence the distribution and propagation of gullies, via changes in the driving and resisting forces. The frequency of river flood inundation of alluvial gullies on the floodplain changes longitudinally according to river incision and confinement. Near the top of the megafan, flood water is contained in the macro-channel up to the 100-yr recurrence interval (RI) but still backwaters adjacent alluvial gullies. In downstream Holocene floodplains, complete inundation of alluvial gullies occurs beyond the 3- to 5-yr RI and can contribute significantly to total annual erosion. However, a majority of gully scarp retreat is still driven by direct rainfall and infiltration-excess runoff, with the 24-hr rainfall total being the most predictive variable. This direct erosion is enhanced by inherent soil dispersibility and the lack of vegetative cover, with the later if present having the potential to dissipate the effective kinetic energy of rainfall and promote infiltration.

Sediment production estimates from alluvial gullies across the Mitchell megafan suggest that ~ 6.3 Mt/yr were eroded historically, compared to ~3.9 Mt/yr recently. These sediment sources dominate the suspended sediment budget for the Mitchell River, when compared to empirical load estimates from main river and tributary gauges up- and down-stream. At a 33 ha gully, empirical water and sediment yield measurements document high suspended sediment concentrations (10,000 to >100,000 mg/L) and sediment yields (80 to 350 t/ha/yr), which are high by both Australian and world standards. Theoretical modelling of both suspended

sediment- and wash-load transport suggests that sediment concentrations are near the ‘transport limit’, which can be modelled using transport-limited equations. Additional field gauge data and modelling efforts should continue to investigate the event, seasonal and annual variability in sediment yield, internal erosion processes, and gully morphology evolution at distributed gully sites.

Trees that have survived or re-colonized after the passage of a gully head cut have the potential to define the timing and rates of gully erosion, through ring counting and age dating. Radium-226/228 and carbon-14 radionuclide dating of *Eucalyptus microtheca* trees demonstrates that ring production rates vary between 0.3 and 0.9 rings/yr, depending on local growing conditions. These rates can be used to estimate tree ages from ring counts. Tree age and position along the gully outlet channel can be used to estimate tree colonization rates. Independent erosion rate estimates from historic air photos suggest that time lags and disequilibrium exist between scarp retreat, gully inset-floodplain development, and tree colonization. Thus, tree ages on gully inset-floodplains can only define the minimum time of gully initiation, whereas tree colonization rates can only estimate maximum rates of gully expansion.

Alluvial gully scarp retreat rates are quantified at 18 sites across the Mitchell megafan using recent GPS surveys and historic air photos, which demonstrate rapid increases in gully area of 1.25 to 10 times their initial 1949 area. Extrapolation of gully area growth trends backward in time suggests that the current unprecedented phase of extensive gullying initiated between 1880 and 1950, post-European settlement. This is supported by young optically stimulated luminescence (OSL) dates of gully inset-floodplain deposits, LiDAR terrain analysis, historic explorer accounts of earlier gully types, and archival records of cattle numbers and land management. It is hypothesized that intense cattle grazing concentrated in the riparian zones during the dry season increased the potential for gully erosion initiation in the wet season along steep banks, hollows and precursor gullies. This is a result of reduced native grass cover, increased physical disturbance of soils, and the concentration of runoff along cattle tracks, which were possibly coupled with fire regime modifications, episodic drought, and the invasion of exotic weed and grass species. Thus, land-use change pushed the landscape across a threshold towards instability, which it was intrinsically close to as a result of the evolution of the fluvial megafan over geomorphic time. A conceptual model of the evolution of these alluvial gullies has been developed that describes their initiation, development, and potential stabilization over time. Spatial and temporal projections of gully area growth into the future until stabilization suggest that they will continue to be chronic erosion features on the landscape for several hundred to several thousand years, growing 10 to 50 times their initial 1949 size, unless mitigated by land management intervention.

A paradigm shift in land management and cattle grazing practices is needed to reduce chronic soil erosion across northern Australian floodplains. Cattle should be managed more cautiously in or excluded from the riparian zones and steep banks of river, streams, and other water bodies across large areas of floodplain landscape. This will reduce the initiation of new alluvial gullies, slow gully erosion rates where already initiated, and aid in passive or proactive rehabilitation efforts. Australian and international gully literature indicates that many different biological, chemical, and physical tools and passive or direct management actions are available to rehabilitate gully erosion. However, the failure of many rehabilitation projects is common due to a lack of initial rigorous experimentation and adaptive management. A trial rehabilitation program could determine the most cost-effective, practical, and sustainable land management activities needed to reduce alluvial gully erosion, and prevent future initiation, by targeting the process-based causes of gully erosion rather than the symptoms. Outcomes could be synthesized into best management practices (BMP) guidelines for alluvial gullies that could be utilized by the regional pastoral community for rehabilitation and soil conservation actions.

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Declaration of Originality

I declare that this work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself and as outlined below in the contributions detail.

Jeff Shellberg

Jeffrey Gray Shellberg

November 2011

Contributions By Co-Authors

Chapter 1

This chapter was written by Jeff Shellberg.

Chapter 2

This chapter was published as:

Brooks, A.P., Shellberg, J.G., Spencer, J. and Knight, J., 2009. Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia. *Earth Surface Processes and Landforms*, 34: 1951-1969. With 2010 Erratum, *Earth Surface Processes and Landforms*, 35: 242–245.

This chapter was initated from earlier funded work to Dr. Andrew Brooks as principle investigator, with initial project conceptual/technical support by John Spencer, Dr. Jon Knight, and Jeff Shellberg. Dr. Andrew Brooks orchestrated the overall project from initiation to data analysis to write-up, contributing 25% to the overall final product. Jeff Shellberg conducted the literature review for the paper, synthesized the available data, conducted the analysis of the megafan and gully profiles, modelled the variation in gully scarp height, created a majority of the figures, provided the hydrological analysis, helped create the conceptual model of alluvial gully evolution, and wrote a majority of the paper, contributing 25% to the overall final product. John Spencer provided detailed analysis of the gully distribution data, collected and analysed the GPS erosion rate data at the local and catchment scale, assisted in the classification of alluvial gullies, and created several figures, contributing 25% to the overall final product. Dr. Jon Knight conceived and implemented the idea for mapping alluvial gullies using satellite data, assisted in the classification of alluvial gullies, and provided feedback in the final paper write-up, contributing 25% to the overall final product.

Chapter 3

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Jeff Shellberg conceived and implemented the project, collected and analysed the data, and wrote the chapter, contributing 75% to the overall final product. Dr. Andrew Brooks provided theoretical and technical input during project conception, implementation, data analysis, and write-up, contributing 10% to the overall final product. John Spencer provided field support during surveying and support during GIS analysis of LiDAR and air photo data, contributing 10% to the overall final product. Dr. Doug Ward provided MODIS satellite data and analysis support on the inundation frequency of the lower Mitchell River, contributing 5% to the overall final product.

Chapter 4

This chapter will be modified and submitted to be published likely as two separate chapters:

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Rose, C.W., Shellberg, J.G., and Brooks, A.P., 2012 forthcoming. Suspended sediment production and yield from an alluvial gully: modelling approaches. *Target Submission: Journal of Hydrology*.

Jeff Shellberg and Professor Calvin Rose co-conceived the project. Jeff Shellberg implemented the project, collected and analysed the empirical data, modelled sediment transport, and wrote the chapter, contributing 70% to the overall final product. Professor Calvin Rose provided the initial theory and background to modelling sediment transport at the transport limit, in addition to the encouragement to apply this theory to the alluvial gully field situation. Prof. Rose provided detailed feedback on model setup and output, in addition to the written chapter, contributing 20% to the overall final product. Dr. Andrew Brooks provided overall advice and guidance during project conception, implementation, data analysis, and write-up, contributing 10% to the overall final product.

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Jeff Shellberg and Dr. Andrew Brooks co-conceived the project, in terms of the potential for Eucalyptus trees to serve as geomorphic indicators and age markers of erosion processes within alluvial gullies. Jeff Shellberg designed and implemented the project, collected and analysed the data, and wrote the chapter, contributing 75% to the overall final product. Dr. Quan Hua provided detailed guidance and training for Carbon-14 analysis, as well as overall theory in chapter/paper, contributing 10% to the overall final product. Atun Zawadski provided detailed guidance and training for radium analysis, as well as overall theory in chapter/paper, contributing 10% to the overall final product. Dr. Andrew Brooks provided overall advice and guidance during project conception, data analysis, and write-up, contributing 5% to the overall final product.

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Jeff Shellberg, John Spencer, and Dr. Andrew Brooks co-conceived the project based on earlier work (Chapter 2). Jeff Shellberg designed and implemented the project, collected most of the field data, analysed the data from the field and laboratory, and wrote the chapter, contributing 70% to the overall final product. John Spencer initiated the original GPS surveys of gully scarps, assisted in field data collection, provided advice and support with the analysis of LiDAR and air photograph data, and gave feedback into the data interpretation and write-up, contributing 15% to the overall final product. Dr. Andrew Brooks provided detailed guidance and input during project conception, data analysis, and write-up, contributing 10% to the overall final product. Dr. Tim Pietsch provided advice, guidance, assistance and technical support in OSL dating of gully sediments contributing 5% to the overall final product.

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Jeff Shellberg and Dr. Andrew Brooks co-conceived the chapter based on initial discussions about gully rehabilitation in the field. Jeff Shellberg conducted the literature review and wrote the chapter, observed and collated the existing rehabilitation work in the Mitchell, and co-developed the proposal for experimental gully manipulation and best management practice development, contributing 85% to the overall final product. Dr. Andrew Brooks co-developed the proposal for experimental gully manipulation and best management practice development, and provided input into the state of the science and art of gully rehabilitation in Australia and around the world, contributing 15% to the overall final product.

Chapter 8

This chapter was written by Jeff Shellberg.

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"*Science has given the world at least one great contribution, the scientific attitude or spirit; a desire for the truth for truth's sake, a willingness to experiment to that end, and the effort to give as unbiased judgement as possible which must be based on sound evidence*". C.W. Gray 1925. A minimum or maximum course in chemistry. Journal of Chemical Education, 2(4): 235-240.

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Chapter 3

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Chapter 6

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Chapter 7

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Chapter One: Introduction

1.1 Thesis Background

Gully erosion is the process by which running water cuts new unstable channels > 30cm into erodible regolith that typically has not been previously incised or dissected before. Gully erosion is a global phenomenon, a major cause of severe land degradation, and an important source of sediment pollution that reduces water quality and degrades aquatic ecosystems (Oldeman et al. 1990; Lal 1992; Poesen et al. 2003; Valentin et al. 2005). In northern Australia, there is widespread gully erosion into unconfined alluvial deposits on active and abandoned floodplains – here defined as *alluvial gully erosion* – which were known to locals as "breakaways" and described by several earlier researchers (Simpson and Doutch 1977; Condon 1986; Brooks et al. 2006; Brooks et al. 2007; Knight et al. 2007; McCloskey 2010). Recent research by Brooks et al. (2006; 2007) and Knight et al. (2007) used aerial reconnaissance and satellite remote sensing to map areas of active alluvial gullying across catchments draining into the Gulf of Carpentaria. They found extensive areas degraded by active alluvial gully erosion [Mitchell (16,700 ha), Gilbert (10,100 ha), Leichhardt (29,100 ha), Gregory/Nicholson (12,300 ha)], which covered 0.2% to 1.0 % of the total catchment area and locally >10% of the floodplain area. Similar *alluvial* gully erosion extents have been estimated in the Victoria River catchment in the Northern Territory (10,400 ha, 0.22% of catchment, Condon 1986). Alluvial gullies also exist along the floodplains of the Fitzroy River in Western Australia (Payne et al. 1979), the Daly River in the Northern Territory (Sattar 2011), and several rivers draining into the Great Barrier Reef (GBR) in Queensland such as the Normanby (Brooks and Spencer 2011) and Burdekin Rivers (Rebecca Bartley, personal communication).

To date in northern Australia, only a handful of reports and studies have analysed *alluvial* gully erosion in terms of erosion processes, rates, causal mechanisms, and rehabilitation potential. These studies have been concentrated in the Victoria and Ord catchments in the Northern Territory and Western Australia (Medcalf 1944; Condon 1986; Tongway and Ludwig 2002; Wasson et al. 2002; Payne et al. 2004; McCloskey 2010). Additionally, some of these studies did not emphasize the large differences in form and process between alluvial gullies along floodplains and the more commonly understood colluvial gullies on hillslopes, which can both coexist across regional landscapes. However more importantly for the river floodplains draining into the Gulf of Carpentaria in northern Queensland mentioned above, there was a dearth of quantitative information on alluvial gully form, process, and rates before this current study commenced. This is despite the much larger extent and diversity of alluvial gullies and floodplains in the Gulf region than elsewhere in northern Australia (Brooks et al. 2006; Ward et al. 2011).

The lack of scientific knowledge and data on *alluvial* gully erosion into unconfined floodplains in northern Australia is especially evident when compared to the wealth of gully erosion research from south-eastern Australia in both partially confined valley-fills (Eyles, 1977a; 1977b; 1977c; Prosser et al. 1994; Prosser and Slade 1994; Fryirs and Brierley 1998), colluvial hillslopes (Prosser and Abernathy 1996; Beavis, 2000) or both (Olley et al. 1993; Prosser and Winchester 1996; Wasson et al. 1998; Olley and Wasson 2003; Whitford et al. 2010). In south-eastern Australia, soil and gully erosion post-European settlement have accelerated following widespread introduction of hard-hoofed cattle and sheep grazing, in addition to tree clearing (Eyles 1977a; Prosser et al. 1994; Prosser and Slade 1994; Prosser and Winchester 1996; Wasson et al. 1998; Olley and Wasson, 2003; Rustomji and Pietsch 2007). Rangeland degradation leading to extensive gully erosion and increased sediment yields also has been well documented in more remote arid regions of Australia (Condon et al. 1969a-d; Wasson and Galloway 1986; Pickup 1991; Fanning et al. 1999; McKeon et al. 2004; Pringle et al. 2006; Stafford Smith et al. 2007).

In northern Australia, there is a growing body of literature on colluvial or hillslope gullying (Bartley et al. 2007; 2010a; 2010b; Hancock and Evans 2006a; 2006b; 2010), with mixed interpretations of the influence of European grazing and fire regime changes. However, this knowledge on colluvial or hillslopes gully erosion in proximal or distant regions is likely not directly applicable to alluvial gullying in northern Australia due to major differences in landscape setting, hydrology, erosion processes, soil texture and chemistry, lateral confinement, and land use and management history. Therefore, the objective of this research was to investigate and quantify alluvial gully erosion processes and rates across a pilot study area in northern Australia, which encompasses the lower Mitchell River catchment and Mitchell River fluvial megafan on the Cape York Peninsula in northern Queensland.

Understanding erosion processes, rates, causal mechanisms, and rehabilitation potential of alluvial gullies is important from both fundamental science and land management perspectives. For the later, alluvial gully erosion in savannah landscapes of northern Australia poses a major threat to productive pasture land for cattle production, future agricultural development, human infrastructure (e.g., roads, fences, buildings, and water points), the long-term sustainability of the landscape, and provision of ecosystem services to support human land uses (e.g., McKeon et al. 2004; Pimentel 2006; Montgomery 2007; Stafford Smith et al. 2007). Since alluvial gully erosion is often concentrated along the riparian margins of major river channels, this degradation likely has major implications for health of associated native flora and fauna. The proximity of alluvial gullies to main river channels and floodplain waterbodies (e.g., lagoons) results in highly effective sediment delivery and sedimentation impacts. Accelerated soil erosion and sediment pollution of waterways are serious off-site and downstream concerns in terms of water quality (e.g., excess suspended sediment and nutrients), impacts to freshwater and marine aquatic ecology (e.g., fish production), and indigenous cultural uses of the landscape (e.g., subsistence use of waterholes; degradation of ceremonial sites). The future impacts of alluvial gully erosion locally and off-site partially depend on the development outcomes of future planning scenarios for the northern Australia region (i.e., Woinarski et al. 2007).

1.2 Research Questions

From this background information regarding the extent of alluvial gully erosion in northern Australia, the lack of quantitative information on alluvial gully erosion rates and processes, and the understanding of gully erosion rates and processes in southern Australia, several over-arching research questions were developed to help guide specific research objectives for investigating and quantifying alluvial gully erosion in northern Australia.

1. What are the basic factors and processes that drive and resist unconfined *alluvial gullies*, compared to those operating in partially or fully confined hillslope or colluvial gullies elsewhere in Australia?
2. Have alluvial gully erosion rates changed over different time scales? Near-term (3-5 yrs); past contemporary (1940-present); post-European (1880-present); pre-European (<1880); and geologic (Quaternary: 1.8 million-yrs).
3. Have land-use changes associated with European settlement influenced the rate or extent of alluvial gully erosion? If so, what are the main land-use factors?
4. What is the rehabilitation potential for reducing alluvial gully erosion based on the gained understanding of the driving and resisting factors associated erosion processes?

1.3 Thesis Objectives

The objective of this research was to investigate and quantify alluvial gully erosion processes, rates, and rehabilitation potential across a pilot study area in northern Australia. The objectives were chosen to help support or refute the hypotheses outlined above. The pilot study area encompasses the lower Mitchell River catchment and Mitchell River fluvial megafan on the Cape York Peninsula in Queensland. This area was chosen because it is a hotspot for alluvial gully erosion in northern Australia as identified from earlier research (Brooks et al. 2006; Brooks et al. 2007; Knight et al. 2007). Coupling process and rate data is essential to understanding both natural erosion cycles and accelerated erosion due to human land use. Effective land management to reduce human induced erosion can only be accomplished once a detailed understanding is available to define the processes that may be driving or resisting erosion, how erosion rates have changed over time with or without land management, and how future erosion may affect both the natural landscape and the good and services it provides to humans.

The specific objective of this research have been categorized and grouped by chapter as follows:

Chapter 2: Alluvial Gully Erosion: An Example from the Mitchell Fluvial Megafan

- Describe the continuum of gully form-process models described within the international literature and where unconfined alluvial gully erosion fits within this continuum.
- Define the unique form of alluvial gully erosion that is widespread across floodplain landscapes in the tropical savannas of northern Australia.
- Identify the spatial distribution of alluvial gullies within the Mitchell catchment (based on earlier work by Brooks et al. 2006; Knight et al. 2007; Brooks et al. 2007).
- Develop a preliminary conceptual model of the hydrogeomorphic, soil geochemical and vegetative processes that are driving or resisting alluvial gully erosion.

Chapter 3: The Hydrogeomorphic Influences on Alluvial Gully Erosion along the Mitchell River Fluvial Megafan

- Quantify longitudinal changes in inundation hydrology and river connectivity with adjacent floodplains and alluvial gully complexes.
- Quantify the complex intra-annual hydrology of alluvial gully complexes as influenced by local rainfall-runoff and floodplain inundation processes.
- Update conceptual models of the hydrogeomorphic factors driving alluvial gully erosion and the influence of floodplain water source mixing (perirheic zone) on the initiation or propagation of alluvial gullies.

Chapter 4: Determining Suspended Sediment Production and Yield from an Alluvial Gully: Empirical and Theoretical Approaches

- Empirically measure erosion and sediment yield from an alluvial gully over various time scales.
- Utilize theoretical models of erosion and sediment transport to highlight some of the physical processes influencing sediment transport and yield.
- Compare empirical and theoretical estimates of suspended sediment yield to suggest the best approach to future measurement and modelling of alluvial gully erosion at the landscape scale.

Chapter 5: Quantification of Alluvial Gully Erosion Rates Using Radium-226/228 and Carbon-14 Radionuclide Dating of *Eucalyptus microtheca* Tree Ages

- Investigate patterns of Eucalyptus tree location, size, and ring counts in relation to geomorphic patterns and processes within an alluvial gully.
- Quantify average annual ring production of Eucalyptus tree from independent dating techniques such as C-14 and Ra-226/228.
- Assess the potential for trees to quantify rates of gully head scarp advance and the initiation of gully erosion in time from Eucalyptus tree location, size and age.

Chapter 6: Alluvial Gully Erosion Rates Across the Mitchell River Fluvial Megafan

- Quantify alluvial gully erosion rates (linear and volumetric) over different time scales:
    - Near-term (5 yrs), past contemporary (1940-present), post-European (1880-present), pre-European (pre-1880).
    - Trial different tools to quantify erosion rates and timing over different time scales: GPS, air photos, LiDAR, OSL, U/Th/Ra, tree ring dating.
- Assess the potential influence of cattle introduction and European settlement on alluvial gully erosion rates and processes?
- Refine the earlier conceptual model on the evolution of alluvial gully erosion based on synthesized knowledge from erosion rate data, historical observations, and a process-based understanding of the threshold stability of landforms.

Chapter 7: Rehabilitation of Alluvial Gullies in the Lower Mitchell Catchment

- Review scientific and management literature on gully and sodic soil rehabilitation.
- Discuss lessons learned to date from ad-hoc gully stabilization efforts in the Mitchell catchment and beyond from the literature review.
- Propose controlled rehabilitation trials for experimental gully catchments in the Mitchell catchment and beyond.
- Outline the development of Best Management Practice (BMP) guidelines for alluvial gully erosion reduction and rehabilitation**.**

1.4 Thesis Study Design

The study area is located in the Mitchell River catchment (71,630 km^2) in tropical northern Queensland, Australia and is concentrated in the lower half of the catchment where the Mitchell River fluvial megafan (i.e., vast fan shaped alluvial floodplains) covers 31,000 km^2 (Figure 1-1, also see Chapter Two). A nested hierarchical approach was taken that addressed both uniqueness in space but also the major geomorphic structures and hydrodynamics at multiple spatial and temporal scales (Poole 2002), from the entire fluvial megafan, to river segments, to large gully complexes, and the individual head cuts within a gully complex. A representative subset of alluvial gullies (Figure 1-1) was selected based on the overall population of gullies distributed across the Mitchell River megafan (Brooks et al. 2006; 2007; Knight et al. 2007) and detailed ground reconnaissance surveys in 2006. These sites were used to quantify erosion rates and processes contributing to erosion. It is important to note that none of the selected gully sites was initiated or heavily influenced by roads. Road induced gullying and rilling is an additional land-use issue that was not the focus of this thesis.

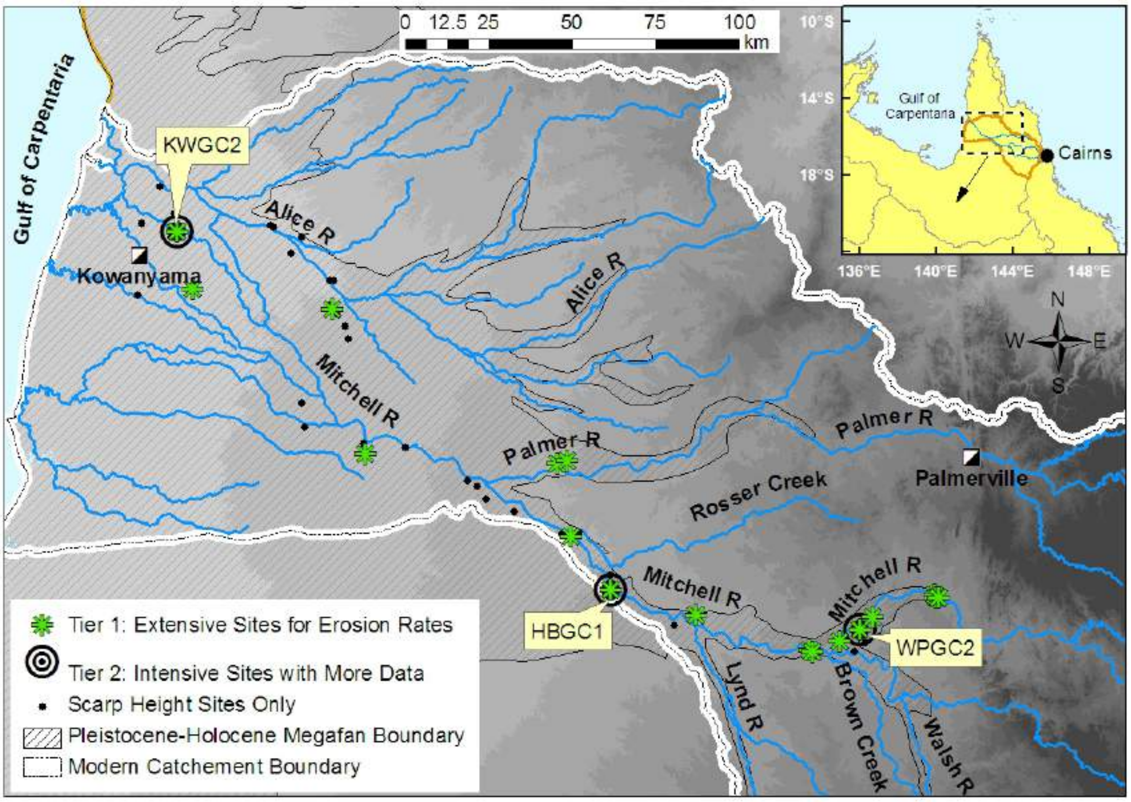


Figure 1-1 Study area and site locations along the Mitchell River fluvial megafan.

A hierarchical site selection and data analysis process was used to investigate gully erosion at two levels of detail spatially and quantitatively (Tier 1 and 2 sites). Extensive (Tier 2) sites consisted of eighteen (18) gully complexes distributed along the river longitudinal profile, spanning a wide range of geomorphic positions and forms. Only a basic suite of data was collected at these sites, such as erosion rate data from GPS surveys and historic air photos (Figure 1-1; Table 1-1). Nested within these sites, three (3) intensive (Tier 1) gully complexes received a larger suite of quantitative data collection (Figure 1-1; Table 1-1). These three intensive sites were situated at major zones of local relative relief between the gully head and river channel thalweg. In addition to these sites, field measurements during reconnaissance trip stops at a wider range of gullies were used to estimate gully scarp heights at the catchment scale (Figure 1-1).

Table 1-1 Data parameters at Tier 1 (Intensive) and Tier 2 (Extensive) gully complexes.

Data Use	Data Parameter	Extensive Tier 2 Gully Complexes	Intensive Tier 1 Gully Complexes
Rate	Recent Scarp Erosion: GPS	++	++
Rate	Historic Scarp Erosion: Air Photos	++	++
Rate / Timing	OSL Stratigraphic Dating		++
Rate / Timing	Tree Ring Dating		++
Rate / Process	Time-Lapse Photography		++
Property / Process	Continuous Stream Gauging		++
Property / Process	Rainfall		++
Property / Process	Soil Moisture / Pore Water Pressure		++
Property	LiDAR Topography		++
Property	Gully Morphology Metrics		++
Property	Soil Characteristics		++

Chapter Two: Alluvial Gully Erosion: An Example from the Mitchell Fluvial Megafan, Queensland, Australia

Brooks, A.P., **Shellberg, J.G.,** Spencer, J. and Knight, J., 2009. Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia. *Earth Surface Processes and Landforms*, 34: 1951-1969. With 2010 Erratum, *Earth Surface Processes and Landforms*, 35: 242–245.

2.1 Introduction

Considerable interest has been expressed towards increasing land and water resource development (e.g., irrigated agriculture, inter-basin water transfers, mining, intensive grazing) in the tropical savanna landscapes of northern Australia (e.g., Davidson 1965; Woinarski and Dawson 1997; Yeates, 2001; Camkin et al. 2007 Ghassemi and White 2007). This interest has continued despite severe economic and technical challenges (e.g., Davidson 1965, 1969; Bauer, 1978; Basinski et al. 1985; Woinarski and Dawson 1997), which are a partial result of the significant limitations imposed by the natural climate, hydrology, geomorphology, soils, and location of the region (e.g., Davidson 1965, 1969; Smith et al. 1983; Petheram et al. 2008). To date, this region has experienced relatively low levels of agricultural and urban development compared with temperate and sub-tropical regions of Australia, notwithstanding the existing land uses: Aboriginal land use and cultural management, cattle grazing, alluvial and hard rock mining, commercial and recreation fishing, tourism, biodiversity conservation. As a consequence, there has been limited scientific research into the sustainable carrying capacity of the landscape to support both human and ecosystem demands.

In northern Australia, the extent to which current and past land use has impacted erosion rates and sediment loads within the regions extensive river systems has not been fully analysed, unlike the extensive research on southern Australian sediment loads over time (e.g., gully and valley fill incision: Eyles 1977; Fryirs and Brierley 1998; Fanning 1999; Prosser et al. 2001; Olley and Wasson 2003). In southern Australia, gully erosion has been identified as a dominant sediment source in many regions (Olley and Wasson 2003; Prosser et al. 2001), locally contributing up to 90% of the total sediment yield and demonstrating major increased rates of activity (order of magnitude or more) in the post-European period (e.g., Olley and Wasson 2003). Recent sediment budget modelling in northern Australia predicted a dominance of hillslope surface erosion sources in savanna landscapes (Prosser et al. 2001). However, field based tracing and monitoring studies suggest relative contributions of subsurface gully and channel erosion are more akin to the situation in southern Australia (Wasson et al. 2002; Bartley et al. 2007). Given the close relationship between sediment and nutrient fluxes, and the role of soils in agricultural production, there is a pressing need to better understand current and past soil erosion processes across northern Australia before decisions are made regarding future land-use scenarios.

Recent reconnaissance surveys and remote sensing research in northern Australia (Brooks et al. 2006; Knight et al. 2007; Brooks et al. 2007) have revealed that gully erosion of alluvial floodplain, terrace, and megafan deposits is widespread across the tropical savanna catchments draining into the Gulf of Carpentaria (GoC), a major epicontinental sea in northern Australia. It has been estimated that active gullying covers up to 1% of the land area of the lower alluvial portions of these catchments, but represents a more substantial component of the total sediment budget (Brooks et al. 2008). Such gully erosion in alluvium is often concentrated along the riparian margins of major river channels, represents a highly connected sediment source, which degrades the most productive land for native flora and fauna, cattle grazing, and potentially agricultural development. It is clear that this type of gully erosion differs fundamentally from the typical hillslope or colluvial gullies found in southern or northern Australia.

Given the extent of gully erosion identified from reconnaissance survey work, the aim of this chapter is to: (1) to describe a form of gully erosion that is widespread across alluvial landscapes in the tropical savannas of northern Australia, and to place this within the continuum of gully form-process models described within the international literature; (2) to describe the spatial distribution of gullies within one large catchments in the GoC, the Mitchell River; (3) based on insights gained from the spatial pattern of gully distribution and ground observation, develop a conceptual model of the processes influencing gully erosion in the Australian tropical savanna.

The question of whether current gully erosion rates are indicative of natural background erosion rates and processes, or represent accelerated erosion from human activities, is fundamental to assessing the sustainability of this savanna landscape under current land-use scenarios, let alone under future planning scenario outcomes (e.g., Woinarski et al. 2007). However, it is not the purpose of this chapter to present evidence to address this question; this will be addressed by data in Chapter Five and Chapter Six. As a more preliminary step, alluvial gully forms and landscape positions will be described, and a *preliminary* conceptual model will be developed of the evolution of these landforms to provide insights into the processes initiating and perpetuating the gullying, including human land use.

2.1.1 Hillslope and colluvial gullies

Gully erosion has been described in a large variety of landscapes throughout the world (e.g., Poesen et al. 2003; Valentin et al. 2005) and indeed on other planets (Higgins 1982). The commonly accepted definition of gullies is that they are larger than rills, which can be ploughed or easily crossed (e.g., Poesen et al. 2003), but smaller than streams, creeks, arroyos, or river channels (e.g., Graf 1983; Wells 2004).

The most commonly described gullies on Earth tend to be those that could be described as 'hillslope gullies', which are present in the upland portions of catchments in northern Australia (e.g., Hancock and Evans 2006; Bartley et al. 2007), and are widespread in eastern Australia (e.g., Olley et al. 1993; Prosser and Abernethy 1996; Beavis 2000), and around the world (e.g., Graf 1979; Harvey 1992; Kennedy 2001; Li et al. 2003; Bacellar et al. 2005; Kheir et al. 2006). Hillslope gullies are those that erode into colluvium, aeolium, saprolite, weak sedimentary rock, or other weathered rock, and have also been defined as valley-side or valley-head gullies (Brice 1966; Schumm 1999). Hillslope gullies are generally located in low stream-order headwater settings, where they are tributary to other gullies or channels of low stream-order. In general, the length of hillslope gullies is much greater than their width. The erosion mechanism is typically overland flow in which excess shear stress exceeds resisting forces (e.g., Montgomery and Dietrich 1988; Prosser and Slade 1994; Knapen et al. 2007). Erosional forces and channel head location are dependent on the local slope and upstream catchment area (i.e., a discharge surrogate) (Montgomery and Dietrich 1988, 1989). The extension of the channel head highly depends on the available catchment area (Prosser and Abernethy 1996). Due to the relatively coarse sediment supply and headwater setting of hillslope gullies, their eroded sediment contributes to both bed and suspended loads (e.g., Rustomji 2006) and they have relatively low sediment delivery ratios due to ample opportunity for storage between the source and ultimate base level outlet (Walling 1983; Wilkinson and McElroy 2007).

2.1.2 Alluvial gullies

In contrast to the hillslope gully model, various researchers have described valley-bottom gullies (e.g., Brice 1966; Schumm 1999) and bank gullies (Poesen 1993; Poesen and Hooke 1997; Vandekerckhove et al. 2000), in which the gully is eroding entirely into alluvium. Gullying in alluvial plains has been documented as a major land degradation process by Pickup (1991) in central Australia, Pringle et al. (2006) in Western Australia, and Oostwoud Wijdenes and Bryan (2001) in Kenya. However, rarely has a clear distinction been made between these 'alluvial gullies' and the more commonly described colluvial or 'hillslope gullies'. It is our contention that a clear continuum exists between colluvial and alluvial gully forms and that the two end members of this continuum represent distinct landforms, which have different form–

process relationships. It is of critical importance to make this distinction when parameterizing sediment budget models, such as SedNet (Prosser et al. 2001), as the existing hillslope gully models (e.g., Rustomji et al. 2008) as yet do not adequately represent alluvial gullies. As such, a definition of an alluvial gully is presented along with a type example of this gully variant from the Mitchell River catchment in Northern Queensland, Australia.

Alluvial gullies are here defined as relatively young incisional features entrenched into alluvium not previously incised since initial deposition. Alluvial gully complexes (up to several km^2) are defined as actively eroding and expanding channel networks incised into and draining alluvial deposits. They often form a dense network of rills and small gullies nested hierarchically within larger macro-gully complexes (e.g., Figure 2-1). Alluvial gullies are variable in erosion process, form, landscape location, climate, relief, and texture of alluvium. However, they most often occur in vast deposits of alluvium along high stream-order main river channels or other large water bodies such as lagoons or lakes (e.g., Figure 2-1). Thus they have high sediment delivery ratios and are highly connected sources of predominantly fine suspended sediment. They are often as wide or wider than they are long, due to the lack of structural control on their lateral expansion (Figure 2-1).

By definition, alluvial gullies erode drainage networks into some form of alluvium, which is a time varying storage component of transported fluvial sediment. Therefore, alluvial gully erosion represents a secondary cycle of erosion, occurring sometime after initial storage but before physical or chemical conversion into sedimentary rock. Primary and secondary erosion cycles that differentiate production, transport, and sink zones have been discussed by Schumm and Hadley (1957) and Pickup (1985; 1991). Following initial deposition, sink zones can become sediment production zones during a secondary cycle following changes in intrinsic or extrinsic thresholds, such as the alteration of resisting forces due to vegetation reduction or changes in erosive forces due to base level change, or increased discharge.

Alluvial gully complexes differ from badlands, which are most often formed in soft rock terrain, such as marl or shale sedimentary rock (Gallart et al. 2002; Harvey 2004) often which has experienced some form of uplift or re-exposure due to base level change (Bryan and Yair 1982). It is acknowledged, however, that the term badland is poorly defined and some could view certain stages and scales of alluvial gully complexes as examples of badland erosion. We contend that describing alluvial gully complexes as ‘badland erosion’ does not help to explain the processes driving this form of erosion, and only serves to further cloud the literature on badland erosion. The features we describe clearly have much in common with the extensive literature on gullies and are best placed in the context of this literature.

Alluvial gullies also differ from the cut and fill incised landscapes that occur along pre-existing linear channels in partially confined valleys filled with a mixture of alluvium, colluvium, weathered rock and soil (e.g., Eyles 1977; Prosser et al. 1994; Prosser and Winchester 1996; Fryirs and Brierley 1998), including arroyo (stream) channels (e.g., Schumm and Hadley 1957; Cooke and Reeves 1976; Graf 1979). Fluvial processes along major stream channels that are structurally controlled by surrounding hillslopes and underlying bedrock differ significantly to the processes operating in smaller alluvial gully channels uninfluenced by these structural controls. While hillslope gullies and cut and fill channels in headwater areas can erode into linear patches of alluvium, they are closer to the hillslope end of the continuum between pure colluvial and pure alluvial deposits and processes.

In the following section, the landscape context of the study area is described where type examples of alluvial gullying are identified and the extent of active gullies is mapped in a large savanna catchment.

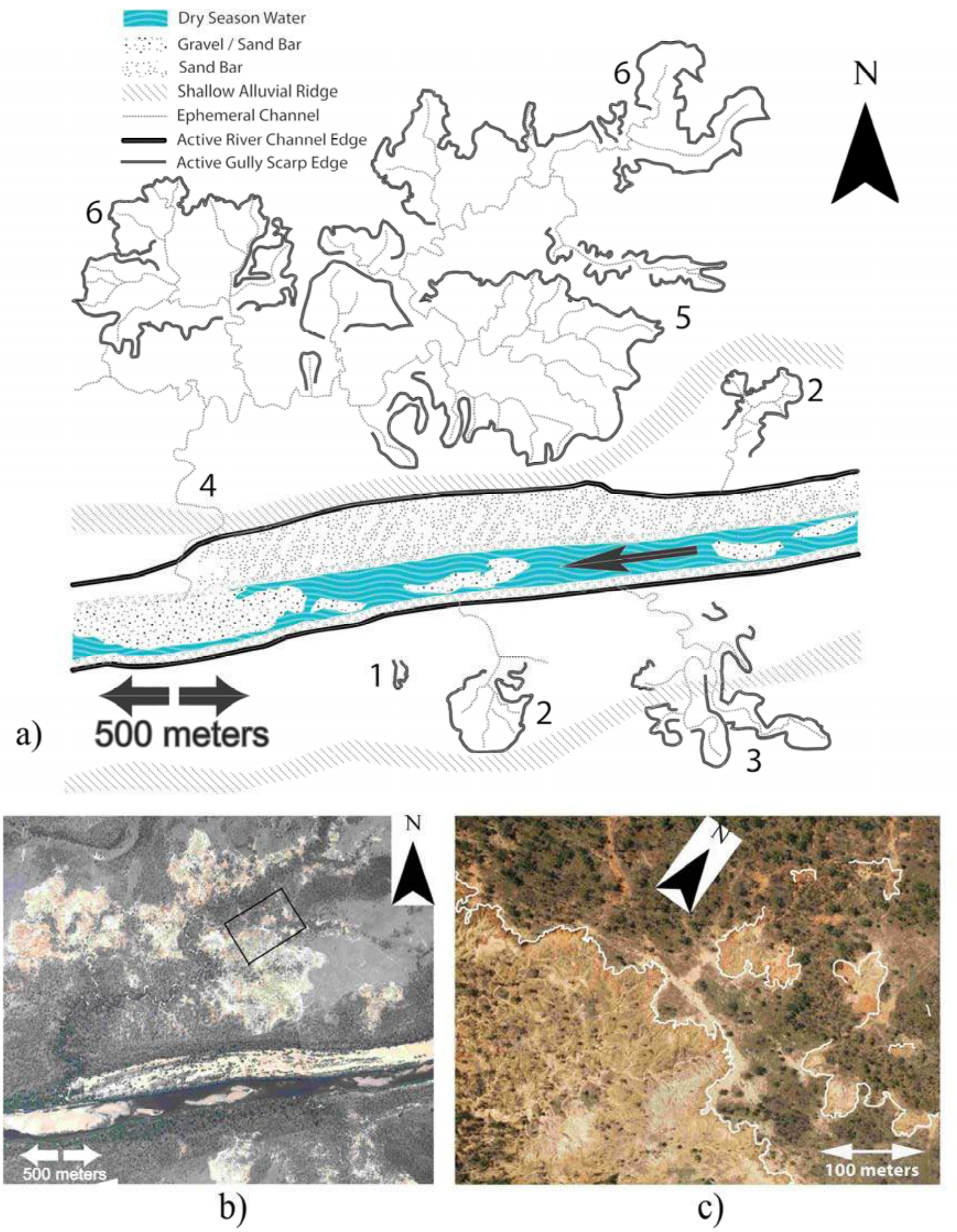


Figure 2-1 a) Schematic of numerous alluvial gully complexes draining both proximal and distal portions of the Mitchell River floodplain near the Lynd River, (b) aerial photograph of the same area as a) showing the white, bare portions of active alluvial gullies, (c) inset aerial photograph from b). Numbers in a) refer to gully location and evolutionary stage: 1) incipient proximal alluvial gullies, 2) bounded proximal alluvial gullies, 3) unbounded proximal alluvial gullies, 4) unbounded alluvial gully complexes, 5) bounded distal gullies and 6) unbounded distal gullies.

2.2 Landscape Setting

2.2.1 Monsoonal climate and hydrology

The study area is located in the Mitchell River catchment (71 630 km^2) in tropical northern Queensland, Australia and is concentrated in the lower half of the catchment where vast alluvial savanna plains (i.e., fluvial megafan deposits of alluvium, see later) cover 31 000 km^2 (Figure 2-2a; Figure 2-3). The Mitchell River catchment has one of the highest mean annual discharge volumes in Australia (>8 000 000 ML/y, excluding the Alice River: QDNRW 2008), despite being only the 13th largest by area. The tropical climate and resultant hydrology of the catchment is monsoonal and strongly seasonal (Hayden 1988; Stewart 1993; Petheram et al. 2008), with >80% of the mean annual rainfall (catchment mean 1015 mm; range 661 to 3396 mm) falling between the wet season months of December to March.

2.2.2 Geology

The upper half of the Mitchell catchment is dominated by rugged hillslope terrain with a maximum elevation of 1236 m and catchment mean of 245 m. The geology of the upper catchment is a heterogeneous mixture of metamorphic, igneous and sedimentary rock (Whitaker et al. 2006). The major structural control in the Mitchell catchment is the south-north striking, steeply dipping Palmerville fault (Vos et al. 2006), which is considered a reactivated Precambrian structure (see Vos et al. 2006 for review). This fault separates the adjacent Palaeozoic Hodgkinson Province to the east from Proterozoic metamorphic rocks to the west, which are overlain by fluvial megafan deposits (Figure 2-3).

The study area and lower half of the catchment below 200 m elevation are located on the largest fluvial megafan in Australia (*sensu* Horton and DeCelles 2001; Leier et al. 2005), with an alluvial extent of 31 000 km^2. The Mitchell fluvial megafan was originally described in detail by Grimes and Doutch (1978), who defined and delineated distinct fan units from the Pliocene to Holocene (Figure 2-2a). Over this period, sea level and climate change have resulted in at least five cycles of fan building, with nested fan-in-fan forms developed as megafan units coalesced and prograded toward the current estuarine delta in the Gulf of Carpentaria.

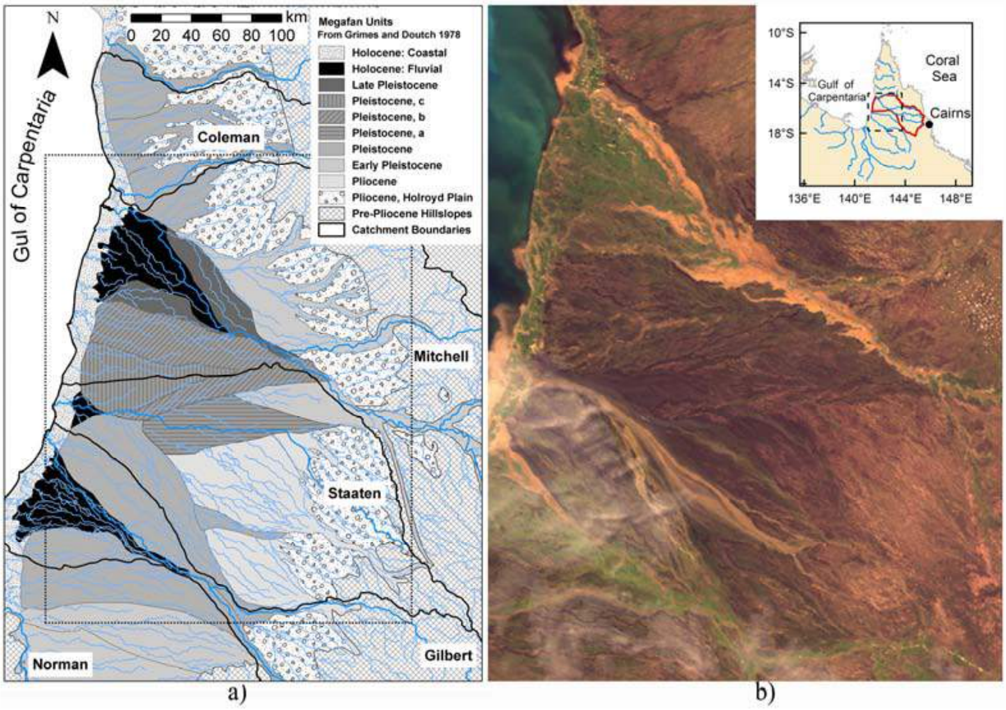


Figure 2-2 a) Location and evolution of the Mitchell and Gilbert megafans from the Pliocene to Holocene [modified from Grimes and Doutch (1978)], b) MODIS image of the Mitchell/Staaten/Gilbert River megafans during flood, representing the inset dashed rectangular area in a). Note partial cloud cover in lower left. Area represented in b) is indicated by the box in the inset location map.

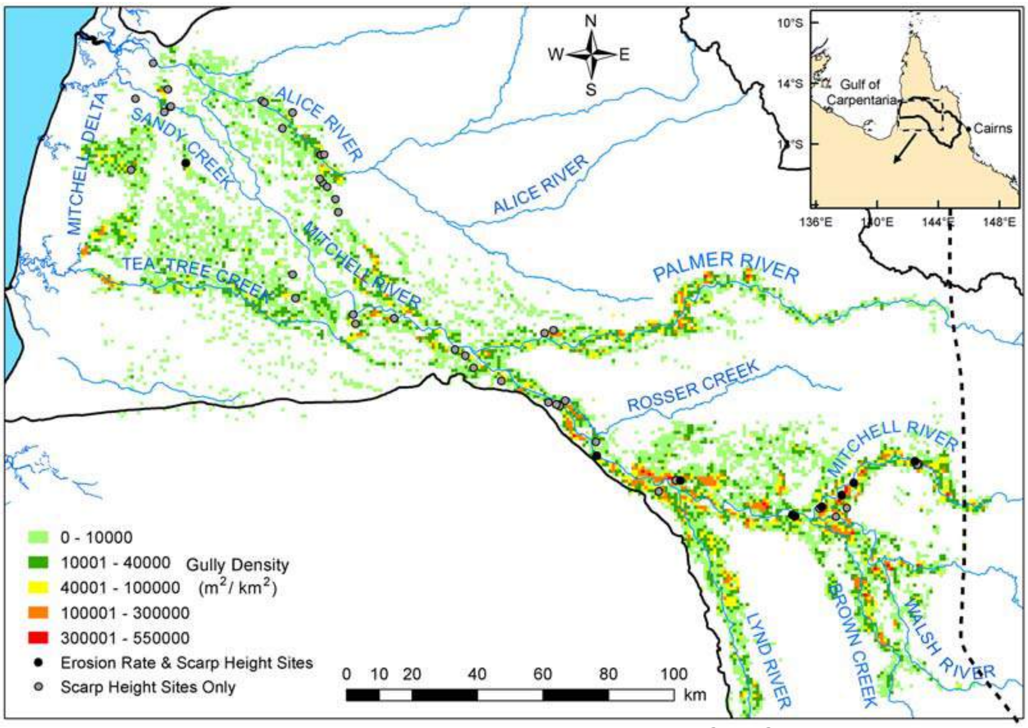


Figure 2-3 Alluvial gully distribution and density (in m^2/km^2) across the Mitchell fluvial megafan. The density grid resolution is 1 km^2 pixels. Dashed line is the Palmerville fault.

2.2.3 Megafan morphology

The morphological apex of the entire megafan is located near the confluence of the Lynd and Mitchell Rivers (Figure 2-2a; Figure 2-3), with narrower alluvial deposits backed up into the more confined river valleys upstream. Currently, the hydrologic apex of the Mitchell megafan is located below the confluence of the Palmer and Mitchell Rivers. The current Mitchell River delta and its interconnected distributary deltas (including the North, Middle, and South Mitchell Arms; Topsy Creek; Nassau River) are in combination the largest river delta in Australia in terms of total mangrove area (>112 km^2) and second largest in terms of total main channel length (>61 km) and perimeter (>300 km) (Heap et al. 2001).

Mitchell megafan units are dominated by alluvial silts and clays. Sand and some gravel are confined to the largest macro-channels (*sensu* van Niekerk et al. 1999) of the Mitchell and its main tributaries, which can span up to 2 km in width. The Mitchell River and it tributaries upstream of the Palmer River are incised into the megafan deposits due to megafan progradation into the Gulf of Carpentaria and possibly a reduction in catchment sediment supply over the Holocene (Nanson et al. 1992; Tooth and Nanson 1995).

Mitchell River channel morphology is dominated in the wet season by a relatively-straight, single-thread, macro-channel, which during the dry season contracts to a more sinuous low flow channel with multiple secondary channels separated in places by vegetated islands. The location of the low-flow channel (thalweg) is highly dynamic, resulting in a shifting habitat mosaic (*sensu* Stanford et al. 2005) of in-channel riparian vegetation communities. The connectivity of floodplains and channels across the megafan is highly dependent on river stage and discharge, when during flood stage (range 5 to 20 m above thalweg), water spreads across the megafan perirheic zone (*sensu* Mertes 1997) (Figure 2-2b). Interconnected networks of floodways, anabranches and distributaries result in the complex mixing of perirheic (surface) water from different sources (river water, emergent groundwater, infiltration-excess ponded surface water).

2.2.4 Soils

Across the megafan, soils have developed where alluvial sands, silts and clays have been relatively undisturbed physically, but not chemically, since initial deposition. These soils have been described by the BRS (1991), and vary depending on age, elevation, and river connectivity. Near main river channels, '*slightly elevated old filled channels and associated levees have sandy and loamy red earths, and occasionally lesser yellow earths*' (unit code Si14). Across most of the vast '*alluvial plains fringing major rivers, often traversed by old infilled stream channels and associated low levees, silty or loamy surfaced grey-brown duplex soils are dominant and are strongly alkaline at shallow depths. The A horizon depth ranges* *from 8 to 15 cm, and many areas have a scalded surface*’ (Si14), due to the removal of the A horizon. Further away from the main river, ‘*small swampy depressions and lower plains have grey cracking clays*’ (Si14) (BRS 1991).

The alluvial soils along the Mitchell River also appear to have a characteristic geochemistry, that to date has been poorly defined. Following the exposure of massive alluvial soils after gully erosion, nodules or pisoliths of ferricrete and calcrete readily form on the surface of exposed gullies (e.g., Pain and Ollier 1992). Gully floors appear to be preferential zones of accumulation of cations (e.g., iron, manganese, and calcium) through local pedogenic processes (relative accumulation; e.g., McFarlane 1991) and lateral groundwater input (absolute accumulation; e.g., McFarlane 1976) or both (Goudie 1973; 1984).

2.2.5 Catchment land use

Within the study area along the lower catchment megafan, land use is currently dominated by cattle grazing across savanna woodlands and unimproved grasslands (e.g., Neldner et al. 1997). These savanna vegetation communities are dynamic over space and time and strongly controlled by disturbance regimes (fire, flood, grazing, erosion), which have changed following European settlement (Crowley and Garnett 1998, 2000). The upper catchment is also dominated by hillslope grazing on unimproved pastures, with developed agriculture covering 2.6% of total catchment area in a relatively confined basaltic plain in the upper catchment. Locally significant areas of alluvial and hard rock mining occur throughout the catchment (McDonald and Dawson 2004), with hard rock mining expanding in recent years.

2.3 Methods

2.3.1 Alluvial gully distribution across the Mitchell megafan

Mapping of alluvial gully erosion in the Mitchell River catchment was undertaken using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes subset to extents covering the catchment. The remote sensing methods used to delineate active gully erosion area were described in detail in Brooks et al. (2008). In summary, a total of 10 ASTER scenes acquired across a five year period from 2000, and across both the wet and dry season, were processed individually using a standard remote sensing decision tree methodology to detect gully areas. To calibrate the method, the extent of gullies in subset areas was delineated with both LiDAR (light detection and ranging) generated DEMs (digital elevation models) and aerial photography, with parameter adjustment for individual ASTER scene differences. Validation involved using high resolution Quickbird imagery publicly available through Google Earth. Detection accuracy was estimated by comparing gully detection in 250 1-km cells randomly assigned and coincident with Quickbird coverage with the detection of gullies from the ASTER processing. Accuracy of gully delineation involved comparison of the aerial extent of gullies mapped from ASTER against manually digitized gully extent (bare, active gully areas) identified in 83 1-km grid cells with active gullies, randomly selected from the 250 cells used in the detection validation process. For the current purposes, the delineation of individual gullies as mapped from ASTER imagery included the bare, actively eroding sections within the gully. Thus, where the inset lower surface of a gully was (re)vegetated, it was not mapped as a gully area.

For alluvial gully analysis, the megafan limits were delineated from a surface geology data set that describes the extent of floodplain and channel alluvium at 1:1 000 000 (Whitaker et al. 2006), as well as the 1:2M soil landscapes data set (BRS 1991). Also, marine influenced areas and salt plains in the delta were delineated and excluded from the extent of the megafan, as they are controlled by a different set of process.

2.3.2 Gully position in relation to megafan geology and soils

Mapped gully areas were additionally compared to mapped megafan geologic units (Grimes and Doutch 1978) and soil units (BRS 1991). The frequency of mapped gully pixels (i.e., 15 m^2 pixels from the ASTER based mapping) in these units were analysed to gain insight into the units that were most sensitive to gully erosion.

2.3.3 Gully pixel proximity to main channels

The proximity of mapped alluvial gully areas to main channels across the Mitchell megafan was estimated by measuring the linear distance between the centroid of each gully pixel mapped with ASTER and the nearest linear drainage line mapped at the 1:2 500 000 scale. At this scale, only the major creeks and rivers are displayed (Figure 2-3). This metric does not provide a measure of thalweg channel distance to main channel. In addition in rare occasions, the direction of the distances measured might be different than the actual flow direction, which could be longer or shorter. However given the large data set (>500 000 gully pixels), it was determined that this error was infrequent and minimal.

Only pixels from within the bare, actively eroding areas of gullies were used for distance measures. Because the analysis was conducted at a pixel level, larger gullies, compared with smaller gullies, dominate in this type of approach. However at the catchment scale, this metric provides a method to assess overall gully proximity to channels.

2.3.4 Elevation at gully pixels

For each pixel of each mapped gully, elevation was extracted from a 30 m DEM rectified to Australian Height Datum (AHD) (SRTM DTED2, 2000). As vegetated sections of gullies were not delineated by the mapping, the pixels mapped as bare, actively eroding areas tend to be concentrated toward the higher elevations of a given gully complex, and thus are biased towards these higher elevations (potentially in the order of 1–2 m). Nevertheless, this bias should not unduly mask the pattern at the megafan scale, in which the elevation range is 180 m.

2.3.5 Gully position in relation to megafan relief

Relative relief was defined as the relative difference in elevation between the main channel thalweg and the relatively-flat, high-floodplain surface along the megafan. Relative relief was hypothesized to be a key control on gully activity and gully scarp height. Using the 1:250 000 drainage network and the 30 m SRTM DEM, channel to floodplain cross-sections were extracted at 20 km intervals down the longitudinal profile of the Mitchell River. From each cross-section, elevations of the thalweg (low point) and floodplain (i.e., the most frequent elevational highpoint) were determined as a pair and the relative difference (relief) between the two was calculated. In total, this provided a longitudinal profile of relative relief down the megafan.

2.3.6 Longitudinal gully profiles and scarp heights

Near vertical scarp heights at gully fronts were estimated using both field and remotely sensed data. Airborne LiDAR surveys of gullies were conducted in 2006 at four sites across the megafan. Within each LiDAR site, three longitudinal profiles of gully channels were measured, to calculate the height of the near vertical scarp and assess slopes above and below scarps. To supplement these data, measurements of scarp height were collected at field sites (Figure 2-3). In combination, these data were used to develop a distribution of gully scarp heights and form a basis for understanding patterns of gully distribution across the Mitchell megafan.

2.3.7 Erosion rates at gully fronts

Detailed surveys of selected alluvial gully fronts (scarps) in the Mitchell megafan were conducted using in situ differential global positioning system (GPS) with sub-meter accuracy (Trimble with Omnistar High Precision). Accuracy depended on signal strength and vegetation cover, but was typically within 0.5 m for repeat surveys. GPS surveys were conducted at nine sites across the alluvial megafan, totalling 25 485 m of gully front, surveyed repeatedly as shown in Table 2-1 and Figure 2-3. Gully expansion indicated by average scarp retreat rate was determined from annual surveys in 2005, 2006, and 2007, with the average rate equalling the total erosion area of change during any given year divided by the total common survey length, for each gully surveyed. Maximum linear rates were calculated for individual lobes, but only the average rate was applied across the entire length for budget purposes (see Brooks et al. 2008) (Table 2-1).

In Brooks et al. (2008), it was assumed the majority of new sediment contributed to the gully each year comes from primary vertical scarp retreat at the gully head. This is not to say that appreciable volumes of sediment are not coming from secondary erosion of incompletely eroded failed blocks, reworking of gully outwash deposits, or gully sidewall erosion. Indeed scarp retreat will slow if the deposited material is not reworked from the gully floor. Recent observations suggest, however, that due to the highly dispersible nature of the sediments and the fact that most of the sediment is going into suspension, material delivered from the head scarp is removed reasonably efficiently (Figure 2-12). The same observations, coupled with survey data, indicate that due to the high rates of head scarp retreat (Table 2-1; Figure 2-9) the majority of volumetric change in the gully void on an annual timescale is directly proportional to the head scarp retreat rate. Hence, head scarp retreat rate can provide an easily measurable indicator of minimum annual sediment supply from alluvial gullying when combined with gully scarp height data at individual gullies (Brooks et al. 2008).

2.3.8 Hydrologic monitoring

Initial insights into the key hydrologic drivers of gully erosion are being elucidated by measuring continuous water stage at several locations within different gully complexes. Local rainfall is also measured with automated tipping bucket rain gauges. The positioning of stage recorders within the gully floor as well as at the gully outlet channel allows us to distinguish between locally derived storm events and main stem river channel backwater and/or overbank events. The gauge network is also complemented with automatic time-lapse cameras that capture daily images of gully head scarp retreat throughout the wet season (November–April). Analysis of the time-lapse camera images coupled with the stage and rainfall records allows us to link the main hydrologic processes (rainsplash, surface runoff, groundwater sapping, gully backwater or overbank flooding) with the main periods of erosive activity. It is worth noting that the field area is completely inaccessible through the wet season, requiring all monitoring to be automated.

2.4 Results

2.4.1 Alluvial gully distribution across the Mitchell megafan

The detection accuracy of gullies varied between ASTER scenes because of acquisition time differences (both interannual and season) and variations in size and spectral responses of individual alluvial gullies. Based on the validation of gully detection from 250 randomly selected 1 km cells, the ASTER image detected 45 (18%) false positives and 18 (7%) false negatives. These results indicate that significant classification errors can occur when using remote sensing to detect alluvial gullies. False negatives were a result of lack of resolution in the ASTER and ability to detect small linear gullies in heavily vegetated areas. False positives represented the detection of either (1) bare surfaces stripped of their shallow A-horizon and grass vegetation, (2) the bed of small, dry seasonal wetlands, or (3) road surfaces. Overall however, the ASTER classification was successful in detecting the largest alluvial gully complexes between 1 ha and 1 km^2.

After the initial validation exercise, roads (false positives) across the entire megafan were manually removed from the dataset, representing a 28 km^2 reduction in ASTER detection area. The remaining error was corrected for via the Quickbird validation procedure, where gully area, gully perimeter, and scarp length adjustments were applied from the data derived from the 83 randomly selected 1 km cells manually digitized at high resolution (see Brooks et al. 2008, for more detail).

Mapped gully pixels and polygons were then amalgamated into 1 km^2 gully density grids for final distribution map displayed in Figure 2-3. In total, the analysis identified 129 km^2 of active alluvial gullies within the Mitchell megafan (31 000 km^2), which represents 0.4% of the land area. This should be treated as an absolute minimum area of alluvial gullies, as gullies masked by vegetation were not detected and delineated. The estimated active front length of alluvial gullies was 5567 km.

2.4.2 Gully position in relation to megafan geology and soils

Mapped gully pixels were most frequently located (56%) on megafan units described as Pleistocene by Grimes and Doutch (1978) (Figure 2-2a). Adjacent units mapped as Pliocene in age contained 41% of the mapped gully area, while Holocene units only contained 3% of the mapped gullies. These results indicate that older alluvium deposits in higher elevation areas of the megafan are most prone to erosion, while active Holocene aggradational areas are less prone to erosion. However, caution should be used when interpreting these results, due to the coarse nature of the original mapping exercise (Grimes and Doutch 1978; Figure 2-2a), and the lack of absolute dates for alluvium across the lower Mitchell catchment.

In relation to published alluvial soil descriptions (BRS 1991) across the Mitchell megafan, 50% of mapped gully pixel area had soils described as '*alluvial plains . . . with silty or loamy surfaced grey-brown duplex soils [that] are strongly alkaline at shallow depths*' (unit code Si14). A further 21% of the mapped gully pixel area was associated with '*gently undulating plains with . . . sandy to loamy yellow earths . . . grey duplex soils . . . and ironstone nodules at depth*' (unit code Mr11). While 13% of the mapped gully pixel area was associated with '*slightly elevated old stream terraces, levees, and infilled channels associated with sandy or loamy red earths and yellow earths . . . that are usually stratified at depth*' (unit code Mw40).

2.4.3 Gully pixel proximity to main channels

The proximity of gullies and mapped gully pixels to main channels is evident in the 1 km^2 density grid in Figure 2-3, where the largest concentrations of gullies parallels main channels. This relationship is quantified in Figure 2-4, where the modal distance of gullies to channels is less than 2 km and the distribution is skewed toward channel margins. However, not all gully pixels are immediately adjacent to main channels, as seen in the right tail of the distribution extending out beyond 10 km (Figure 2-4). These gully pixels represent gullies that either drain distally away from alluvial ridges and main channels, or represent channel adjacent gullies that drain into smaller water bodies not recorded within the 1:250 000 mapped drainage network. Field experience and high resolution air photograph interpretation indicates that all gullies are associated with drainage channels of variable size.

2.4.4 Elevation at gullies pixels

The distribution of gully pixel elevations across the Mitchell megafan is complex, but generally follows a bimodal distribution (Figure 2-5). The main mode of gully pixels occurs between 80 and 200 m elevation, which is coincident with the segments of the Mitchell River and its tributaries that are most incised into older alluvial deposits toward the top of the Mitchell megafan. A second major mode of gullying occurs between 10 and 50 m near the Mitchell delta. A distinct lack of gullying is evident between 50 and 80 m, which is coincident with the modern hydrologic apex of the Holocene megafan.

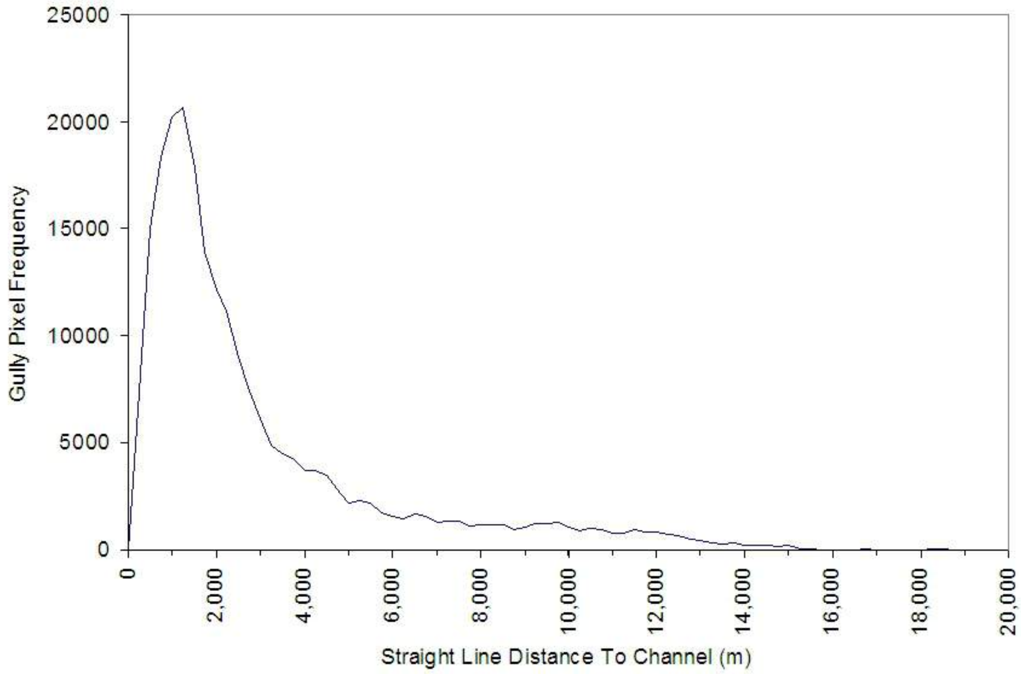


Figure 2-4 Gully pixel (15 × 15 m) frequency from ASTER delineation in relation to main channels.

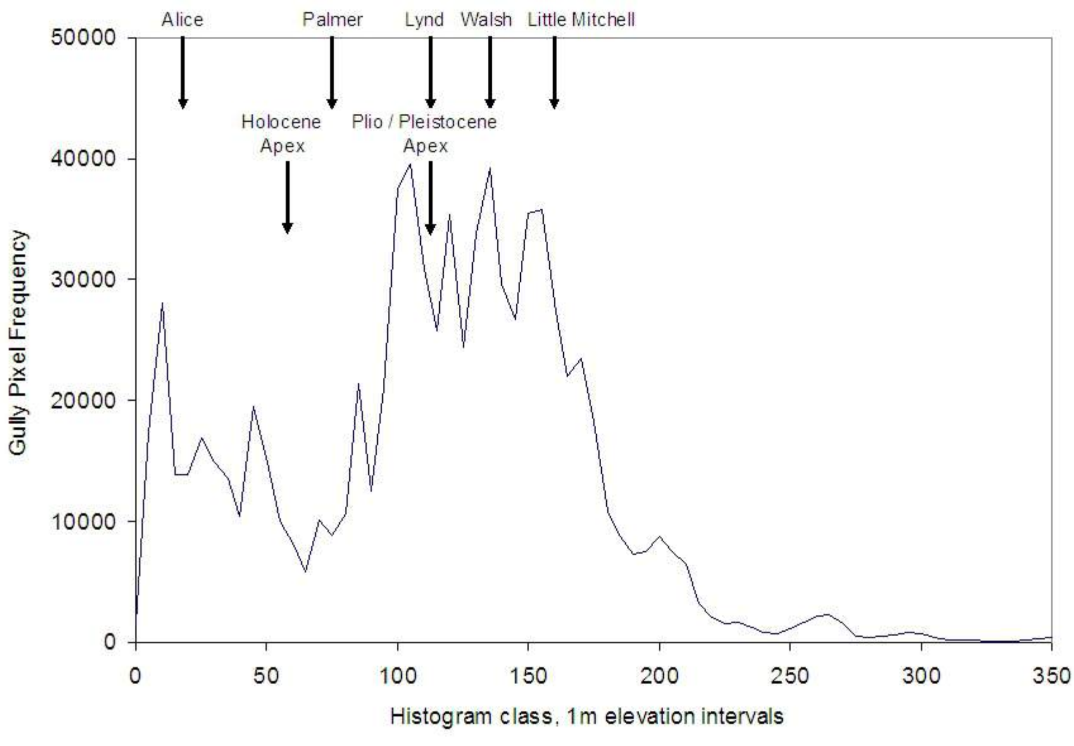


Figure 2-5 Gully pixel frequency from ASTER delineation in relation to pixel elevation determined from the 30 m SRTM DEM. Pixel elevation is closely correlated with distance from mouth, and hence this figure can be viewed as a type of longitudinal profile.

2.4.5 Gully position in relation to megafan relief

From the spatial distribution of gullies (Figure 2-3), the elevational distribution of gullies along the Mitchell River longitudinal profile (Figure 2-5) and the evolution of megafan units (Figure 2-2a), it appears that megafan elevation and river channel incision influence gully distribution across the lower catchment. This relationship is further supported by longitudinal profiles of the Mitchell thalweg and floodplain, along with their difference in relative relief (Figure 2-6). The Mitchell River thalweg upstream of river length (RL) 150 km (i.e., distance upstream of zero elevation on the 30 m SRTM DEM) has incised into surrounding alluvial deposits over the Quaternary, resulting in an increase in relative relief upstream of this point. Near the top of the megafan at RL 350 km, the relative relief is up to 20 m, which effectively confines all but the largest floods. Towards the Holocene hydrologic apex of the megafan at RL 150 km (Figure 2-2a and Figure 2-6), the relative relief is lowest and flood water readily distributes across the lower megafan into a series of distributaries. It is likely that both channel and floodplain accretion are most active in this area, resulting in few gullies (Figure 2-5) in this elevation band. Downstream of the Holocene apex, relative relief actually increases slightly. This small increase in relative relief is likely a factor controlling the second major mode of gullying between 10 and 50 m elevation (Figure 2-5).

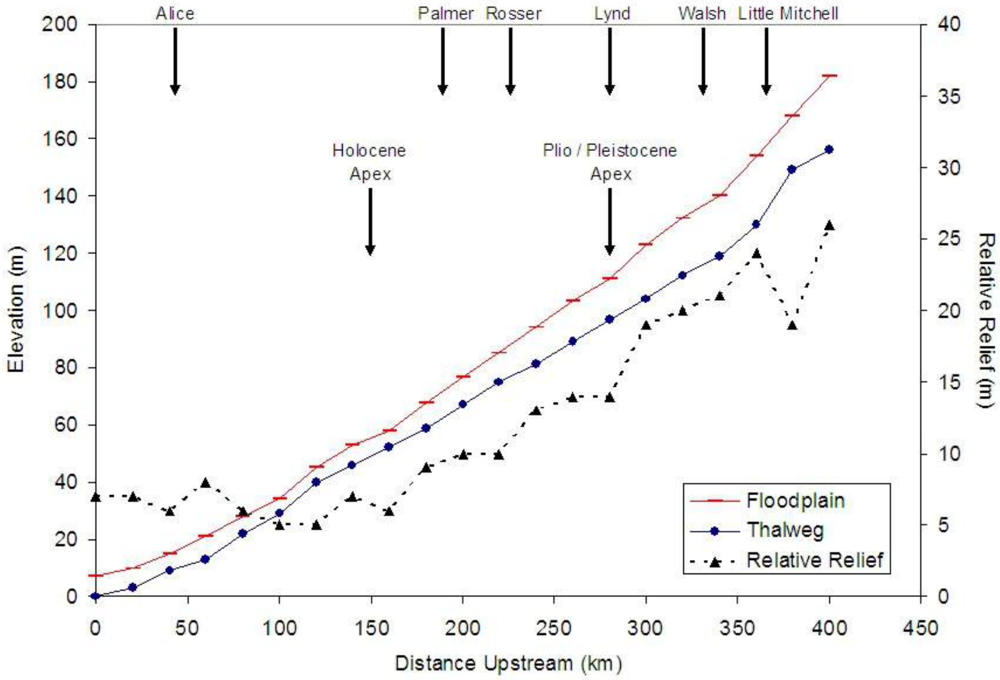


Figure 2-6 Longitudinal profile of the Mitchell River thalweg and adjacent megafan surface (floodplain or terrace). Locations of the key tributary confluences are noted as distances upstream (km), as are current and past fluvial megafan apexes.

2.4.6 Quantification of scarp heights at gully fronts

As can be seen in Figure 6, floodplain elevation decreases relatively consistently down the longitudinal profile of the megafan. Scarp height also varies in a predicable pattern with floodplain elevation (Figure 2-7), and mimics the pattern of relative relief between the river channel and floodplain (Figure 2-6). Floodplain elevation (E_l) adjacent to a gully (from 30 m SRTM DEM) can therefore be used to predict gully scarp heights (SH) with reasonable accuracy (R^2 = 0.77) (see Figure 2-7).

$$SH = 0.0004E_l^2 - 0{\cdot}0509E_l + 1.8373 \qquad (1\text{-}1)$$

Thus, where the river is incised into the upper part of the megafan, the floodplain elevation, relative relief and scarp height are greatest. These values decrease downstream toward the Holocene hydrological apex of the megafan below the Palmer River junction, where scarp height is the lowest. Relief and scarp heights increase again toward the Mitchell delta and Sandy Creek, for reasons discussed later.

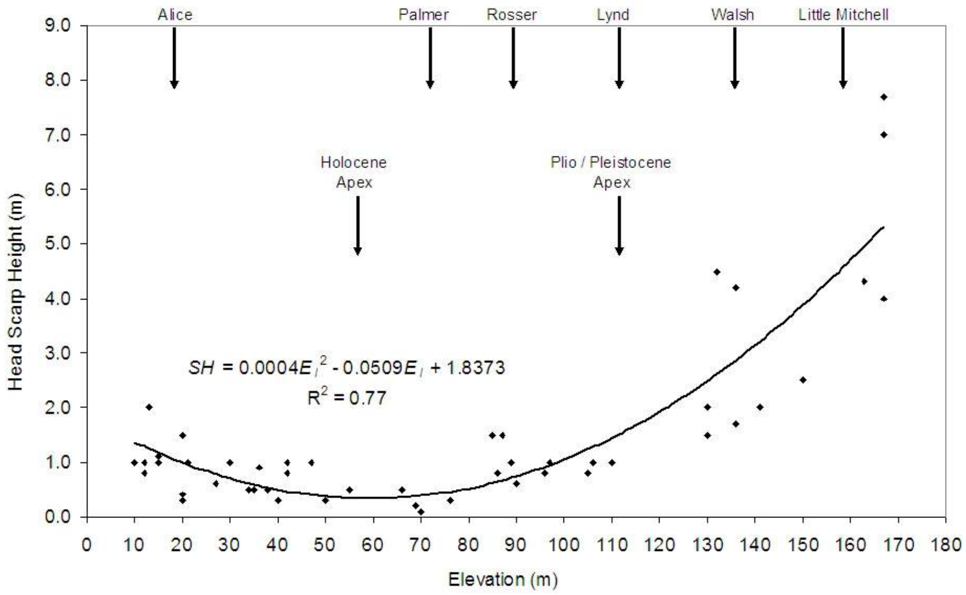


Figure 2-7 Relationship between measured gully head scarp height (SH) and adjacent floodplain surface elevation (E_l) as derived from the 30 m SRTM DEM.

2.4.7 Longitudinal gully profiles

Examples of longitudinal profiles of gully channel thalwegs measured using LiDAR are displayed in Figure 2-8. These profiles of gully tributaries are distributed down the greater longitudinal profile of the Mitchell (Figure 2-6). The correlation between gully scarp height (SH) and floodplain elevations (E_l) is evident from these profiles (Figure 2-8), similar to Figure 2-7. The thalweg bed slopes of gully outlet channels also appear to decrease downstream (Figure 2-8). However, the true nature of the relationship between gully channel slope and landscape positions is likely influenced by individual channel slope distances between a given head scarp and a local base level (e.g., main river channel). From these longitudinal profiles, it becomes apparent that alluvial gully channel slopes are steeper than the floodplain slopes they erode into by an order of magnitude (Figure 2-8). Indeed, some floodplain slopes dip slightly away from the main channel, which is indicative of the subtle ridge and swale topography on these floodplains. The importance of these slope differences during gully evolution will be discussed later.

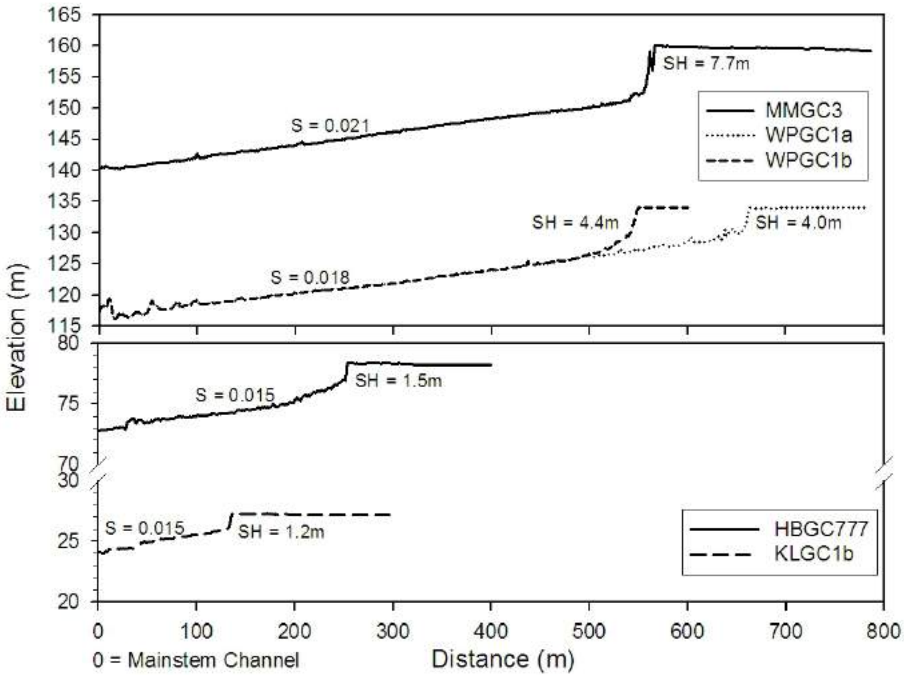


Figure 2-8 Longitudinal profiles of alluvial gully thalwegs between a main channel and adjacent floodplain. S = gully channel or floodplain slope. SH = scarp height.

2.4.8 Preliminary estimates of erosion rates at gully fronts

Measurements of maximum erosion rates along surveyed gully fronts varied by site and by specific alluvial gully lobes (Table 2-1). Specific lobes displayed the greatest amount of retreat activity, while a majority of the scarp length experiences less activity (Figure 2-9). For example, only 17% of the scarp length surveyed showed measurable signs of retreat, while some lobes eroded up to 14 m/y in certain locations.

Using an average rate of scarp retreat of 0.34 m/y (Table 2-1), distributed scarp heights ranging between 0.3 and 8 m, and an active alluvial gully front length of 5567 km, Brooks et al. (2008) estimated that >5 Mt/y of fine alluvial sediment was eroded from alluvial gullies per year across the Mitchell fluvial megafan.

Table 2-1 Surveyed lengths and erosion rates at alluvial gully head scarps sites

Years	Site ID	Survey Length (m)	Max Retreat (m/yr)	Mean Retreat (m/yr)
2006-2007	MMGC1	832	8.13	0.10
2005-2006	MMGC1	773	6.50	0.32
2006-2007	WPGC1	554	2.03	0.03
2006-2007	WPGC2	6782	10.26	0.38
2006-2007	WPGC3	4140	6.60	0.30
2005-2006	WPGC3	2534	8.09	0.09
2006-2007	GBGC1	1525	1.32	---
2005-2006	GBGC1	1431	1.93	---
2006-2007	GBGC2	969	14.10	0.82
2006-2007	GBGC3	1843	4.51	0.65
2006-2007	HBGC1	1763	3.85	0.53
2006-2007	KWGC1	2339	3.20	0.36
Total		**25,485**		
Median (50)			**5.51**	**0.34**
25th percentile			**2.91**	**0.15**
75th percentile			**8.10**	**0.49**

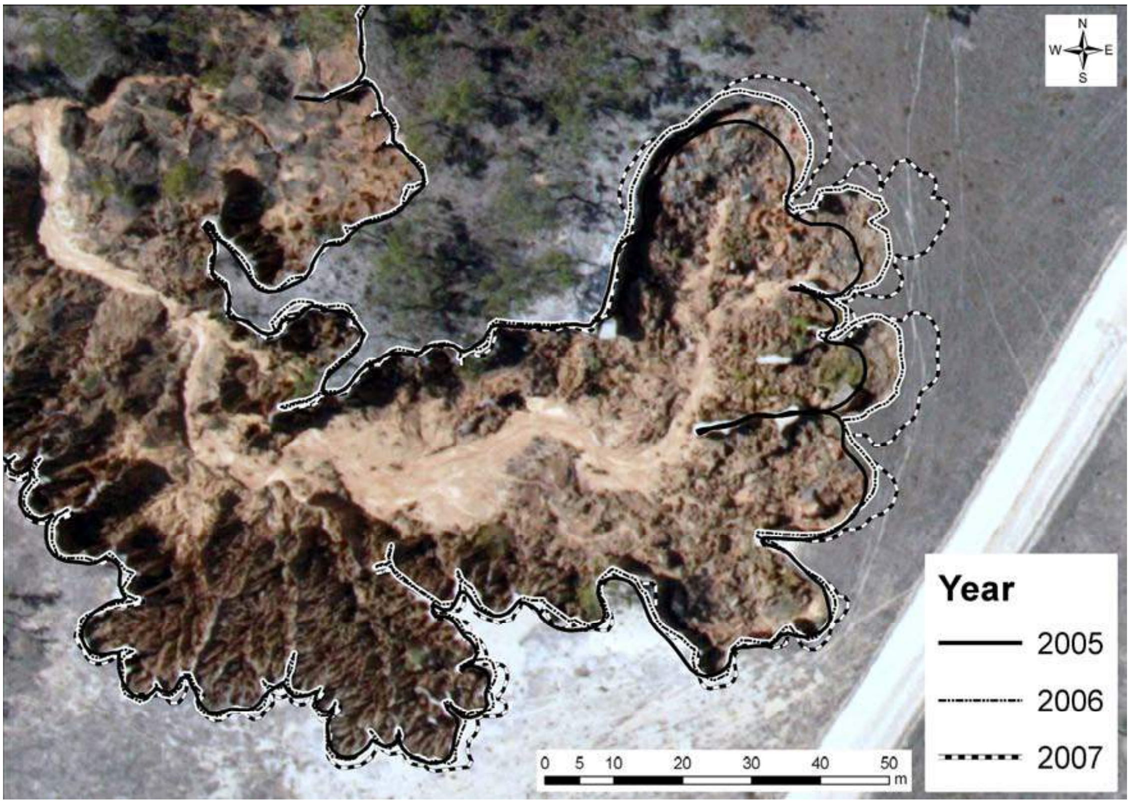


Figure 2-9 Annual gully scarp position between 2005 and 2007 at WPGC3. Note: cross over of some lines in inactive gully sections is due to measurement error, which is a combined function of limitations in the resolution of the Omnistar HP differential GPS survey technique, and the retracing of the survey track in consecutive years.

2.5 Discussion

2.5.1 Controls on distribution

From this analysis of alluvial gully distribution across the lower Mitchell catchment and megafan, several primary factors controlling the potential development of alluvial gullies emerge. A prerequisite for the occurrence of alluvial gulling is the initial deposition of alluvium, which in this case, has largely been controlled by the development of the Mitchell megafan from the Pliocene to Holocene. While the Mitchell River traverses what initially appears to be a vast expanse of homogenous alluvium, the actual heterogeneity in depth, width, texture, and chemistry of the deposits strongly influences the potential for alluvial gully development. Silty or loamy duplex soils with alkalinity at depth are most prone to gully erosion, due to their texture, chemistry, and river proximity. Coarse sand deposits within and near the river macro-channel, and clay wetland deposits tens of kilometres away from the main- and palaeo-channels, appear less vulnerable to alluvial gully erosion.

The erosional potential of these soils is enhanced by the incision of the Mitchell River into the upper sections of the megafan, which has increased local relative relief, and set up the potential energy needed for a secondary cycle of erosion into the adjacent Pliocene and Pleistocene alluvium. The strong relationships between local relative relief and gully scarp height and gully density support the idea that relief is a primary factor influencing alluvial gully erosion. The concept of relative relief and erosion potential is also applicable in the Mitchell River delta below the current hydrologic fan apex. Here, alluvial sediments have accumulated both behind and beyond the main Pleistocene chenier ridge. Over the last 6000 years, these sediments have been slightly elevated relative to sea level, due to a decline in regional sea levels (Chappell 1983; Woodroffe and Chappell 1993; Woodroffe and Horton 2005) and/or hydroisostatic warping (uplift) (Rhodes 1982; Chappell et al. 1982). Thus, in both the upper and lower sections of the Mitchell megafan, local base level (of the adjacent channel) influences potential energy available for gully erosion.

2.5.2 Classification of alluvial gully forms

Numerous insights into the various alluvial gully types were made using ground observations, ground photographs, aerial photographs, LiDAR topography, ASTER images, and direct measurement. Classification of gully types and understanding of basic gully processes were used to develop a conceptual model of alluvial gully evolution below. While many additional alluvial gully types likely exist across the extremely diverse landscape around the GoC, our observations from several hundred alluvial gullies in the Mitchell catchment and other drainages to the GoC indicate that there are some commonalities in form across the landscape.

As a way of providing some insight into gully process and evolution, the planform morphology of alluvial gullies can be broadly classified into four major groups (Brooks et al. 2006).

- **Linear:** these gullies have elongate planform morphologies without well developed secondary drainage networks. They are likely to be an incipient phase of other gully forms, which are usually preceded by rilling. They are also commonly associated with anthropogenic disturbances such as roads, stock tracks, or other linear disturbances that tend to concentrate overland flow (e.g., Figure 2-10a). In many respects, linear alluvial gullies early in developmental stages are little different to the standard hillslope gully model (discussed later).
- **Dendritic:** these gullies are associated with well defined drainage networks, separated by distinct interfluves. The gully head is often indistinct, grading relatively gradually into the adjacent floodplain (e.g., Figure 2-10b).
- **Amphitheatre:** these gullies are often as wide as or wider than they are long, due to the lack of structural control on their lateral expansion. They have well developed head scarps around three-quarters of the gully perimeter, and drain into relatively narrow outlet channels on the proximal or distal sides of alluvial ridges (e.g., Figure 2-10c).
- **Continuous Scarp Front:** these steep scarped gullies are located parallel with the main stem channel of major rivers. They develop from the coalescence of numerous amphitheatre gullies and/or from river bank erosion on meander bends. Thus they are either more mature than other forms (e.g., Figure 2-10d), or indicate sites where there has been a higher density of initiated gullies and/or higher lateral expansion rates leading to the coalescence of the gullies into a scarp front.

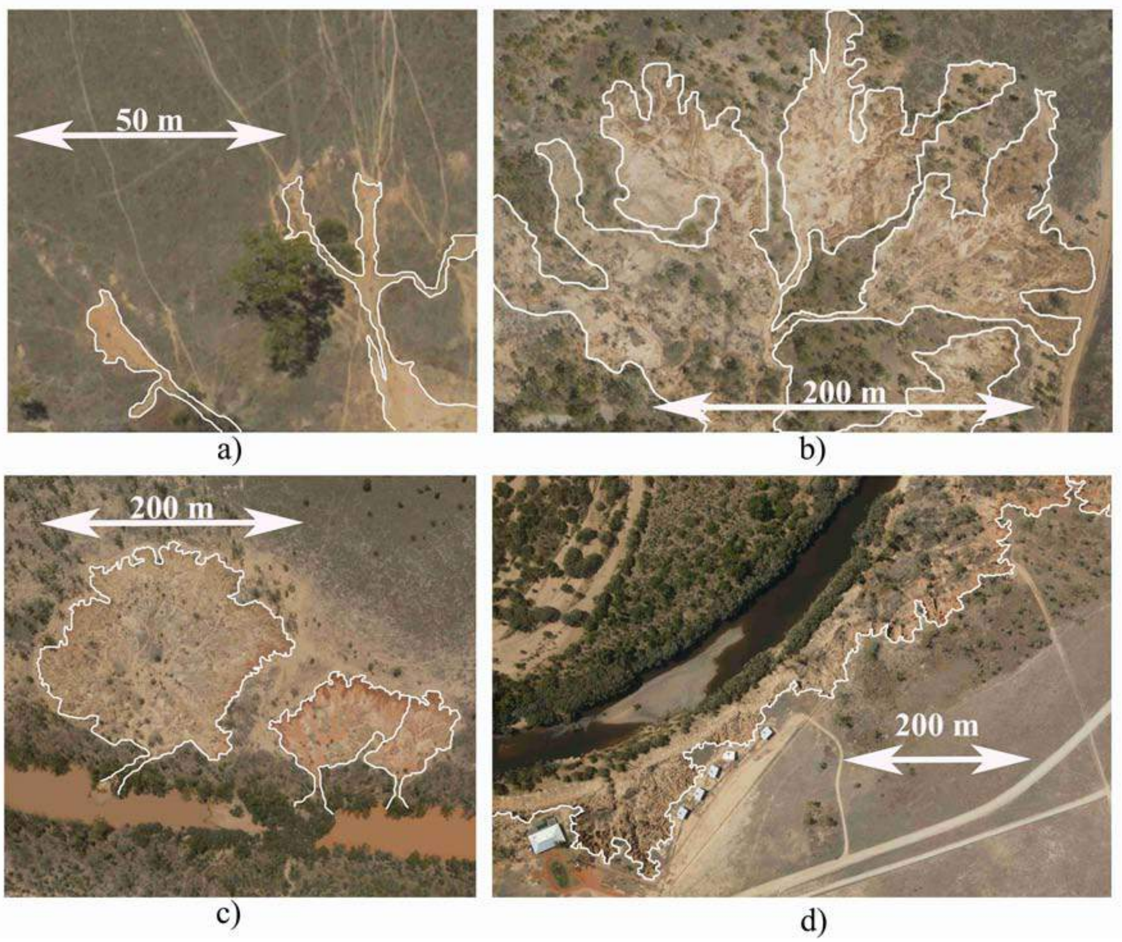


Figure 2-10 Examples of different planform morphologies of alluvial gullies: a) linear; b) dendritic; c) amphitheatre; d) continuous scarp front.

Further insight into the hydrologic processes driving alluvial gullying can be gained through analysis of their location within the floodplain and their proximity to the primary or subsidiary channel networks. Based on location, six alluvial gully types are generally observed across the alluvial landscape, which are highlighted and numbered in Figure 2-1 corresponding with numbers and descriptions below.

1. **Incipient Alluvial Gullies:** These small, generally linear gullies are fairly ubiquitous along the proximal banks and shallow alluvial ridges and levees of water bodies such as large rivers and their off-channel lagoons. They are often of recent development, growing out of rills developed along preferential surface flow paths and to a lesser extent groundwater seepage. Depending on available gradient and water sources, they may or may not develop further after initiation.
2. **Bounded Proximal Alluvial Gullies:** These moderately developed gullies drain off shallow alluvial ridges toward the main water body. Where relatively resistant portions of alluvial ridges are encountered during gully basin development, the alluvial ridge acts as a drainage divide and ultimate controller of extent.

3. **Unbounded Proximal Alluvial Gullies:** These moderately developed gullies also drain off shallow alluvial ridges toward the main water body. However, they have cut through relatively weaker points in shallow ridges, extending their drainage networks into the distal parts of the floodplain. Concepts of surface and groundwater divides breakdown with these gully types. Scarp retreat is not driven by surface runoff in this type of gully.
4. **Unbounded Alluvial Gully Complexes:** These relatively large catchments drain portions of distal floodplains. They have well developed gullied tributaries that each develops uniquely depending on their location and orientation. In sum, these gully complexes can form larger, fractal versions of smaller alluvial gullies. Since they cut through alluvial ridges either before or after ridge formation, they are relatively unbounded and unconstrained in their development.
5. **Bounded Distal Gullies:** These moderately developed gullies drain off relatively resistant portions of alluvial ridges away from the main channel, towards distal parts of the floodplain into tributaries, lagoons, backswamps, or larger gully complexes. Due to long channel slope distances to the main channel, their scarp heights are usually smaller than their adjacent proximal gullies, given the more gradual gully floor slope.
6. **Unbounded Distal Gullies:** These gullies are tributary to large gully complexes draining distal portions of the floodplain. They are relatively unconstrained by alluvial ridges near channels, but could be constrained by available water sources.

2.5.3 Hydrologic mechanisms for erosion

Largely depending on the gully position in the alluvial landscape and its connectivity with main channel hydrology (Figure 1 and the discussion earlier), the specific erosion mechanisms of alluvial gullies can vary dramatically in both time and space. Perhaps the defining feature of alluvial gullies, besides their lithology and morphology, is that multiple water sources can contribute to erosion across the floodplain perirheic zone or surface water mixing zone (*sensu* Mertes 1997) (Figure 2-2b). Water sources across the perirheic zone include direct local rainfall, local saturated overland flow, tributary discharge, main-channel discharge, off-channel flood backwater, overbank river flood discharge, emergence of shallow throughflow and groundwater, and emergence of deep groundwater. Individually or through mixing these water sources in turn provide different erosion mechanisms, which can be readily observed across the gullied alluvial landscape and include direct rainfall impact, local overland flow scour, direct scour from river or tributary discharge, river backwater saturation and soil dispersion, advected floodwater scour, and soil failure at the gully head from shallow groundwater seepage or floodwater drawdown.

Shallow groundwater flow resulting in basal seepage and soil dispersion often dominates erosion at the gully head scarp. This results in and is observed as tunnel scour (piping), vertical tension cracking, and soil block mass failure above seepage failure planes (e.g., Figure 2-11a). Sites with these erosion mechanisms appear to have the highest erosion rates at active lobes (e.g., Figure 2-9). Groundwater seepage is most common in proximally draining gullies with large hydraulic heads between the floodplain and channel. This is also the process that laterally transfers large concentrations of solutes to the gully floor, which then precipitates into nodular pisoliths via absolute accumulation (Goudie 1973; McFarlane 1976; Pain and Ollier 1992). Given that seepage erosion appears to be a key driving process, many alluvial gullies are not necessarily constrained by the surficial topographic drainage characteristics.

In contrast, gully scarps with few signs of groundwater seepage and block mass failure are often dominated by extensive fluting and carving of the erosion face (e.g., Figure 2-11b). This fluting can be quite deep and intricate, and is a result of direct rainfall and carving by overland flow in steep rills. These processes appear to operate in zones of less active scarp retreat where time is allowed for flute development, such as the majority of the inactive scarp length in Figure 2-9. It is also dominant in distally draining gullies where direct rainfall and overland flow are the main water sources. Fluting, carving, erosion of fine matrix material, and retention of resistant iron oxides (i.e., indurated mottles) results in the vertical concentration of solutes and nodular pisoliths, via relative accumulation per decensum (Goudie 1973; McFarlane 1991; Pain and Ollier 1992).

a) b)

Figure 2-11 Ground photographs of a) mass failure, and b) fluting and carving at head scarps.

Thus, varying alluvial gully erosion mechanisms in space and time at channel heads can span the full continuum of erosion models (Kirkby and Chorley 1967): from the end member of groundwater outcrop erosion (De Vries 1976) to shallow Darcian throughflow and return flow erosion (Kirkby and Chorley 1967) to shallow non-Darcian macropore and pipe flow erosion

(Kirkby 1988; Bryan and Jones 1997) to saturated overland flow (Dunne and Black 1970) to pure Hortonian overland flow (Horton 1933).

River backwater and overbank flooding of alluvial gullies can overwhelm these earlier mentioned erosion processes, by temporarily changing catchment divides and introducing a new suite of fluvial processes. This is especially common in proximally draining gullies that are well connected to main river channels with peak stage heights ranging from 5 to 20 m. For example, Figure 2-12 displays a photographic sequence of alluvial gully erosion over one wet season, beginning with rainfall induced erosion and progressing to backwater induced erosion and soil dispersion, overbank flooding, overland runoff, and finally groundwater seepage induced erosion. While most alluvial gully erosion only entails one or a few of these processes, this example serves as a more complicated extreme where many hydrologic erosion processes can interact in time and space.

Figure 2-12 Sequential time-lapse photographs over one wet season of an active alluvial gully lobe in the lower Mitchell River: a) 3 December 2007, b) 10 January 2008, c) 16 February 2008, d) 23 February 2008, e) 24 February 2008, f) 15 March 2008. Note the rainfall induced erosion between a) and b), the backwater induced erosion between b) and c), the overbank flooding induced erosion between c) and e), and the overland runoff (drainage) induced erosion between e) and f). Other alluvial gully lobes may have more or less of these erosion processes occurring during any one wet season.

2.5.4 Unique profile form of alluvial gullies

In contrast to hillslope gullies, mature alluvial gully channel slopes are often steeper than the lower gradient alluvial deposits (e.g., floodplains) they erode into (Figure 2-8). The major change in relief between gully channels and the river floodplains they cut into is typically located at the mouth of the gullies at the interface between the floodplain and river macro-channel or other water body. These mature alluvial gully channel profiles are similar to observations of channel profile development through wedges of sediment following changes in base level, such as with dam removal (e.g., Galay 1983; Cantelli et al. 2003).

In contrast to these mature alluvial gully profiles; hillslope gullies typically have channel slopes that are lower than the hill slope (Kirkby 2007). These differences suggest that there are fundamentally different erosion processes at work within hillslope gullies compared to alluvial gullies. Under hillslope erosional models, surface and shallow subsurface runoff from steeper hillslopes converge into gully heads where the slope breaks from steep to shallow. Stream power (i.e., slope and discharge) is typically high at these gully heads, surpassing thresholds for erosion initiation.

With mature alluvial gullies, surface water tends not to converge at the gully head, but subsurface water can converge at active erosional gully lobes. This subsurface water emerges at the gully head and break-in-slope at the base of the head scarp, and is combined with diffuse rainfall runoff and river flood- and back-water. Erosion is a partial result of convergent groundwater, but more importantly a result of the highly dispersive nature of the subsurface alluvium. It is not until after numerous alluvial gully tributaries combine into a main gully channel that stream power likely reaches its maximum in a given alluvial gully. This maximum stream power is likely coincident with the zone of deepest incision into floodplain alluvium toward the mouth of the gully complex.

The exception to this rule of alluvial gully channels having steeper slopes than surrounding floodplains is during the incipient stages of alluvial gully erosion. On steep bank slopes along water bodies (i.e., channels and lagoons or cutoffs), alluvial gullies are initiated from overland flow rills, bank seepage, or other disturbance. During this initial stage of channel development, the channel slope is lower than the bank slope. However as the channel incises and progresses up the bank, the channel head can migrate beyond the top of the bank and continues eroding into surrounding floodplain alluvium. This is the point where the gully floor to alluvial surface slope ratio changes from less than one to greater than one. This is also the point that slightly negative floodplain slopes can be encountered, due to subtle alluvial ridge topography. As the gully continues to develop into floodplain alluvium, the channel slope continues to remain stable or decline as an equilibrium profile develops (Figure 2-8). However, the alluvial channel slope never returns to less than the floodplain or hill slope. That the gully can continue to expand into flat alluvium suggests that surface derived flow is no longer driving headward retreat, and that direct subsoil dispersion is the dominant erosion process.

2.5.5 Conceptual model of alluvial gullying

From the earlier discussion, remote sensing and ground observations, a conceptual model is proposed for the evolution of alluvial gullies. A location-time substitution (Huggett 2004) is utilized to identify different stages of evolution, due to the present lack of data through the Holocene of alluvial gullies in the GoC. While this type of evolutionary approach can be misleading when heterogeneous landscape factors and processes other than time influence gully development, field observation of gully size and form in relatively uniform alluvial deposits on the same river bank suggests that general insight on evolution can be gained.

Two hillshade depictions of LiDAR topography along alluvial channel banks are shown in Figure 2-13. While these two locations are quite different in terms of river connectivity, relative relief, and scarp height (Figure 2-6; Figure 2-7; Figure 2-8; Figure 2-13), they generally have similar stages of gully development. It is hypothesized that small incipient gullies on channel banks (1a in Figure 2-13) are the starting point of alluvial gully development. They can begin as rills, stock tracks, roads, bank seepage points, or small bank slumps, which tend to concentrate both surface and subsurface flow (Dunne 1980; 1990). From their initially shallow channels and ubiquitous presence along steep alluvial banks, it is hypothesized that preferential groundwater flow paths are not requisite for channel initiation. Rather, concentrated overland flow following rainfall or flooding over steep banks is the dominant initial erosion mechanism, which is enhanced or resisted by surface soil condition and vegetative cover.

Over time, these incipient gullies (Figure 2-13, 1a) can develop further as they incise into alluvial banks and cut back into adjacent flat floodplains (Figure 2-13, 1b and 1c). Their further growth and development highly depends on available surface and subsurface water sources needed for erosion. The depth of gully development and the extent of lateral expansion also depend on the relative depth of dispersive sub-soil units, which is closely correlated with the relative relief. Alluvial gully growth potential can be stalled or truncated from either a reduction of future climatic or hydrologic events to drive erosion, or the development of adjacent gullies that capture available surface or groundwater sources. For example, the development of gully stages 1a, 1b, and 1c in Figure 2-13 have been affected by the growth of adjacent gullies 2a and 2b.

Gully development beyond these incipient stages (1a, 1b, and 1c) into larger bounded or unbounded proximal gully stages (2a to 2b) depends on chance, the heterogeneity of alluvial material composition, and the subtle differences in antecedent topography. For example, gully stage 2a in Figure 2-13a developed into a shallow pre-existing depression that likely influenced the success of its development. Over time with further gully catchment development away from the initiation point, these antecedent topographic irregularities become inconspicuous due to erosion (2b in Figure 2-13). From field observations of these different gully stages (e.g., Figure 2-9; Figure 2-11; Figure 2-12), it is hypothesized that groundwater discharge and seepage erosion become progressively more important components over time, due to deeply incised preferential drainage points and steep hydraulic gradients. However, surface runoff from rainfall and flooding always remain components in drainage basin evolution, but with a less dominant role.

The development of proximal bounded alluvial gullies into unbounded proximal alluvial gullies and gully complexes is less clear due to issues of scale and time. However, it is hypothesized that gullies that are initially bound by local alluvial ridges or levees can erode through low, weak, or irregular locations in these linear features (i.e., stages 2 to 3 in Figure 2-1). This process may be enhanced by extreme flood events and erosion from both sides of an alluvial ridge contributing to breaching. Once an alluvial ridge has been breached, the newly available surface and subsurface water sources strongly control gully complex development. Where large distal flood basins are encountered with previously poor drainage, large gully complexes can form through the erosion of dense channel networks into shallow alluvial depressions (i.e., stage 4 in Figure 2-1). The evolutionary sequence continues as individual tributaries of distal gully complexes encounter their own development constraints (i.e., stages 5 and 6 in Figure 2-1).

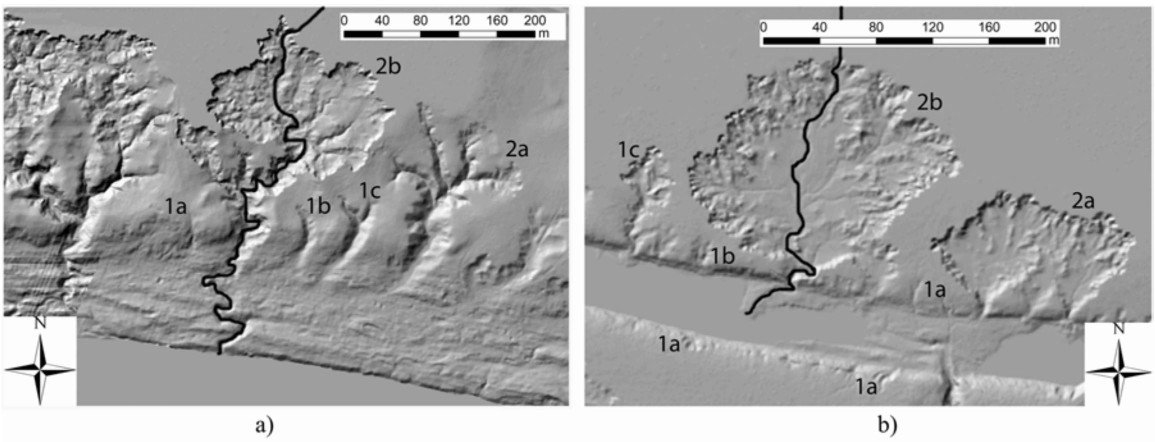


Figure 2-13 LiDAR DEM hillshades of alluvial gullies at different stages of evolution. a) The Mitchell River at an upstream distance of 370 km (Figure 6) and floodplain elevation of 160 m (Figure 2-7). Note the longitudinal profile (MMGC3) in Figure 2-8 from the same area (black line). b) A lagoon and palaeo-channel of the Mitchell River at an upstream distance of

210 km (Figure 2-6) and floodplain elevation of 85 m (Figure 2-7). Note the longitudinal profile (HBGC777) in Figure 2-8 from the same area (black line). Numbered gully labels in figures refer to stages of gully evolution: 1a to 1c are incipient gully stages, 2a and 2b are, respectively, bounded and unbounded proximal gully stages.

2.6 Conclusions

From this analysis of alluvial gully distribution, form and process across the Mitchell River megafan, it is evident that alluvial gullies are a distinct end member along a continuum of gully form-process associations, from colluvial hillslope gullies at one extreme to alluvial gullies at the other. However, the diversity in alluvial gully form and erosion process in the Mitchell, as well as across northern Australia and around the world prohibits using any one type example to define and represent their geomorphology. Further global research is needed to describe the unique varieties of alluvial gullies. This research could then be synthesized with the existing but inconsistent international literature on gullies eroding into alluvium, to develop a complete classification system.

In the Mitchell catchment, many data gaps remain toward developing a deeper understanding of alluvial gully erosion, both past, present and future. Two main research directions were evident following the development of this chapter. One focuses on the relationships between gully structure (e.g., morphology, location, soil composition) and the varying processes (e.g., hydrology, soil dispersion, vegetation cohesion) that create different structures across the megafan (see Chapter Three and Chapter Four). The second focuses on time and rates of gully erosion, in order to better understand the temporal evolution and genetic connection of different gully types hypothesized in the discussion (see Chapter Five and Chapter Six). Understanding rates of gully erosion pre- and post-European settlement will be essential to defining past human land-use impacts and the sensitivity of the landscape to further development.

It is hypothesized that changes in vegetation cover, due to intense cattle grazing concentrated in the riparian zones and fire regime modification during the post-European settlement period, have increased the initiation of alluvial gully erosion, via the incipient stage 1a described in the discussion (Figure 2-13). That is, the long-term evolution of the Mitchell megafan created the template for gully erosion potential, while short-term changes in soil erosion resistance promoted the acceleration of erosion rates, thereby increasing gully density along previously productive riparian areas. However it is hypothesized that once initiated by surficial processes, alluvial gully erosion becomes increasingly dominated by subsurface processes, which continue gully development until a new equilibrium drainage network and channel profile is developed. These hypotheses will be reviewed in more detail in Chapter Five and Chapter Six.

From the review of the international literature, it is clear that our description of gullies in the lower Mitchell catchment is by no means the first record of alluvial gullies (i.e., Brice 1966; Vandekerckhove et al. 2000; Oostwoud Wijdenes and Bryan 2001). However, it is also apparent that to date, similar types of alluvial gullies have simply been considered to be just another variant of generic ‘gully erosion’. It is our view that an understanding of the process initiating and propagating the vast gully networks documented in this study cannot be gained unless they are viewed as a distinct form of gully erosion with a characteristic suite of hydrologic processes and antecedent geomorphic controls (e.g., relative relief). These are a function of the particular climate and evolutionary sequence of the alluvium in which they are situated – in this case, the Mitchell fluvial megafan.

Clearly, a fluvial megafan is not a prerequisite for alluvial gully formation, as alluvial gullies have been described across other GoC rivers that lack fluvial megafans (Brooks et al. 2006). However in this case, the spatial distribution of gully forms is well explained by their position within the Mitchell megafan. The relative importance of the different hydrological drivers also appears to be explained by the specific location of a gully within the megafan and adjacent water bodies. This conceptual framework is being used to define an ongoing research programme within this region. However, a pressing question remains to what extent alluvial gully networks described in this study are characteristic features of the tropical savanna landscapes?

Tropical savannas in Australia, as in many other parts of the world, have and are experiencing increasing developmental pressure. An improved understanding of alluvial gullying is likely to become increasingly more important if land use and development is to be appropriately managed in these landscapes. Understanding the role of land use on gully initiation and erosion rates is key to predicting future impacts on these landscapes (see Chapter Five and Chapter Six). Furthermore, if realistic sediment budget models are to be developed for the catchments in the Australian tropical savanna, it is crucial that alluvial gullying be treated as a separate sediment source to colluvial gullying. This has been recently attempted by Rustomji, Shellberg, Brooks, Spencer, Caitcheon (2010) for a sediment budget modelling exercise for the Mitchell catchment. The contrast between the two types of gullying is exemplified by the fact that alluvial gullying is located in parts of the catchment that are generally considered to be sediment sinks (i.e., floodplains).

Chapter Three: The Hydrogeomorphic Influences on Alluvial Gully Erosion along the Mitchell River Fluvial Megafan

3.1 Introduction

Alluvial gullies are incisional features entrenched into alluvium typically not previously incised since initial deposition. They are often located adjacent to large rivers or floodplain water bodies (Chapter Two; Brooks et al. 2009). Alluvial gullies have been inconsistently described in the literature as valley-bottom gullies, bank gullies, ravines, and alluvial breakaways from locations around the world [Brice 1966; Piest et al. 1975; Thomas et al. 2004 (USA); Simpson and Doutch 1977; Condon 1986; Pickup 1991; Pringle et al. 2006; Brooks et al. 2006; 2008; 2009, McCloskey 2010 (Australia); Poesen 1993; Vandekerckhove et al. 2000, 2001; 2003 (Europe); Oostwoud Wijdenes and Bryan 2001 (Africa); Singh and Dubey 2000; Yadav and Bhushan 2002 (India)]. Alluvial gully initiation and evolution can span large spatial and temporal scales in floodplain environments, from small anthropogenically-enhanced alluvial-gullies (e.g., Vandekerckhove et al. 2001; 2003) to large alluvial-gully tributaries cut into floodplains during low sea-level stands and backwatered during high stands (e.g., Parker et al. 2008; Mertes and Dunne 2008).

Only a few studies have quantified the hydrologic mechanisms responsible for the propagation or initiation of alluvial gully erosion. Valley-bottom gullies in Iowa are eroded by both direct rainfall-runoff and groundwater seepage enhancing mass-failure (Piest et al. 1975; Thomas et al. 2004). In Kenya, Oostwoud Wijdenes and Bryan (2001) observed that rainfall-runoff processes dominated erosion in a "catchment-controlled" alluvial gully, but did not quantify hydrologic processes at "base-level-controlled" gullies along floodplain rivers. Alluvial "bank gullies" in Spain are driven by rainfall-runoff processes enhanced by agriculture activities (Oostwoud Wijdenes et al. 2000; Vandekerckhove et al. 2000, 2001; 2003). In India, alluvial "ravine" gullies are influenced by surface-water runoff from agricultural land (Haigh 1998; Yadav and Bhushan 2002), tunnel erosion and groundwater seepage (Sharma 1987), and river backwater during flood (Singh and Dubey 2000; Yadav and Bhushan 2002). For alluvial gully erosion in northern Australia, preliminary observations (Chapter Two; Brooks et al. 2009) suggested that hydrological mechanisms influencing gully initiation or propagation could span the full continuum of surface and subsurface erosion models (Horton 1933; Kirkby and Chorley 1967; Dunne and Black 1970; De Vries 1976; Kirkby 1988; Bryan and Jones 1997), in addition to erosion induced by river backwater and overbank flooding. If predictive models of gully initiation and development are to be developed and incorporated into sediment budgets, it is imperative that we understand the relative importance of the various hydrological drivers of alluvial gully erosion.

3.1.1 Study Objectives

The objective of this chapter was to quantify hydrogeomorphic processes that influence alluvial gully erosion along the Mitchell River fluvial megafan in northern Australia. The specific objectives were: 1) to quantify longitudinal changes in inundation hydrology and river connectivity with adjacent floodplains and alluvial gullies; 2) to quantify the intra-annual hydrology and erosion dynamics of alluvial gullies as influenced by local rainfall-runoff and floodplain inundation; and 3) to update conceptual models of how different water sources across the floodplain perirheic zone (*sensu* Mertes 1997) influence the initiation or propagation of alluvial gullies. A nested hierarchical approach was taken that addressed both uniqueness in space but also the major geomorphic structures and hydrodynamics at multiple spatial and temporal scales (Poole 2002), from the entire fluvial megafan, to river segments, to large gully complexes, and the individual head-cut lobes within a gully complex.

3.2 Regional Setting

3.2.1 Mitchell fluvial megafan and alluvial gullying

The study was focused within the Mitchell River fluvial megafan, a 31 000 km^2 complex of nested fluvial fans and floodplains concentrated in the lower half of the Mitchell River catchment (71 630 km^2) (Figure 3-1; Brooks et al. 2009; Chapter Two). The evolution of the megafan from the Pliocene to Holocene (Grimes and Doutch 1978) has developed a unique assemblage of geomorphic units and process zones that vary both longitudinally and transversely across the megafan (Galloway et al. 1970). River incision into the megafan and backfilled floodplain units upstream has shifted the hydrologic apex from near the Lynd River confluence (morphologic apex) to below the Palmer River confluence (Figure 3-1; Figure 3-2). The increase in local relative relief over geologic time has set up the potential energy needed for a secondary cycle of erosion (*sensu* Pickup 1985), enhancing the potential for alluvial gully erosion that is widespread (> 129 km^2) along the lower Mitchell River (Brooks et al. 2009; Chapter Two). These gullies are an effective and dominant source of sediment in the Mitchell catchment [Brooks et al. 2008; Chapter Four; Chapter Five; Chapter Six; Rustomji et al. 2010].

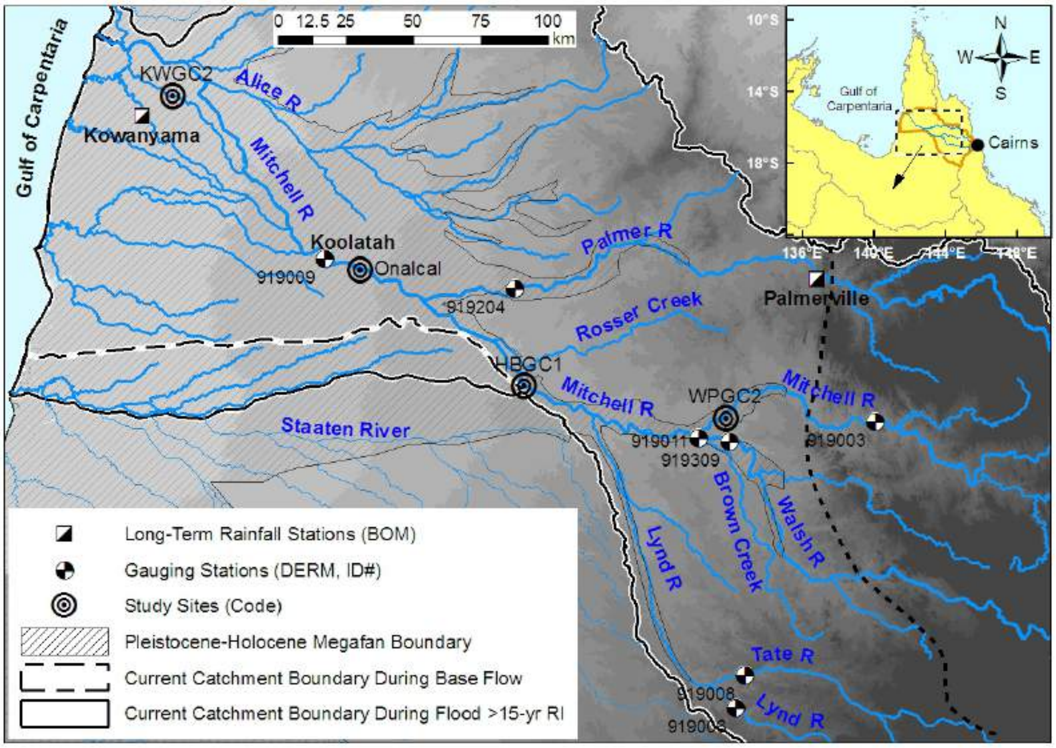


Figure 3-1 Map of the lower Mitchell megafan boundary (Pleistocene-Holocene, Grimes and Doutch 1978), study sites, and gauging stations. The greyscale background represents 30m elevation bands derived from the 1-sec Shuttle Radar Topography Mission (SRTM). The four major study sites from upstream to downstream are Wrotham Park (WPGC2), Highbury (HBGC1), Koolatah (Onalcal Bar), and Sandy Creek (KWGC2). Dashed line is the Palmerville fault.

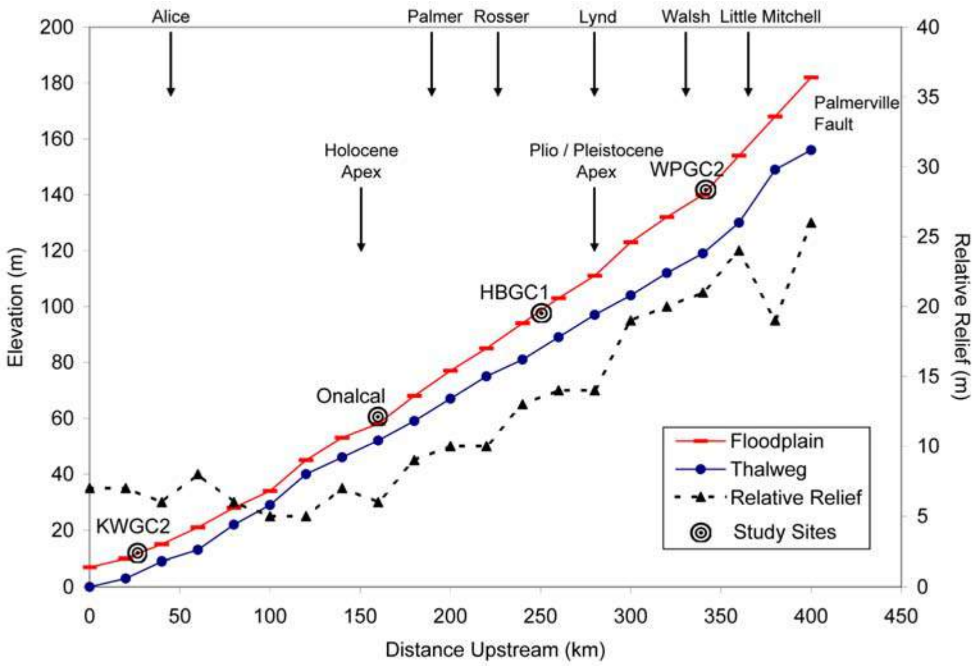


Figure 3-2 Longitudinal profile of the Mitchell River thalweg and adjacent megafan surface derived from cross-sections using the 1-sec SRTM DEM. The four major study sites from upstream to downstream are Wrotham Park (WPGC2), Highbury (HBGC1), Koolatah (Onalcal Bar), and Sandy Creek (KWGC2). Upstream river tributary distances (in kilometres), and current and past megafan apexes are also noted.

3.2.2 Climate

The monsoonal, wet-dry tropical climate of the Mitchell catchment (Stewart 1993; Ward et al. 2011) is important from both surface soil erosion and floodplain inundation perspectives. The catchment receives >80% of its annual rainfall and river runoff from December to March. Annual rainfall in the lower catchment averages 1015 mm and varies between 500 and 2100 mm (ABOM 2010). Storm rainfall intensity and erosivity (r-factors) are moderately high (Stewart, 1993; Yu 1998; Lu and Yu 2002). Potential evapotranspiration is 1700 to 2000 mm per year, while actual evapotranspiration is 600-900 mm per year (ABOM 2010). Soils are completely desiccated by the late dry season. Soil moisture also can be partially or fully depleted between storms and synoptic disturbances within the wet season due to high actual evapotranspiration and low infiltration.

3.2.3 Land use

The dominant land use across the lower Mitchell catchment is cattle grazing across savanna woodlands and grasslands. During the long dry season, cattle grazing intensity and impacts are heavily concentrated along “waterway frontages” or riparian zones of main rivers and tributaries. Access to in-channel pools and lagoons has allowed for the continuous stocking of cattle near waterbodies throughout the year (Tothill et al. 1985). Many of the alluvial gullies across the Mitchell megafan initiated post European settlement during the period when cattle numbers increased significantly from the 1880’s onwards [Shellberg et al. 2010; Chapter Five; Chapter Six]. Gully initiation points were located at relatively steep river banks or within un-channelled floodplain-hollows, where cattle impacts such as overgrazing and soil disturbance were the greatest.

3.3 Materials and Method

3.3.1 Study Sites

Alluvial gully erosion study sites and adjacent river reaches were situated along the longitudinal continuum of the Mitchell River fluvial megafan (Figure 3-1; Figure 3-2). Three quantitative gully sites at Wrotham Park (WPGC2), Highbury (HBGC1), and Sandy Creek (KWGC2) were selected based on their major differences in relative relief between the river high-floodplain and adjacent river channel. One additional gully was only qualitatively observed through time at Onalcal near Koolatah (Figure 3-1), due to the scarcity and relative stability of alluvial gullies in this area (Brooks et al. 2009; Chapter Two). Gully sites were representative of the most common proximally-draining alluvial gullies mapped and visited by Brooks et al. (2008; 2009; Chapter Two), in contrast to distally-draining gullies and alluvial gullies tributary to small creeks on the surface of the megafan.

3.3.2 River reach characteristics

At each gully site, a reach of river centred on the gully confluence was selected to investigate geomorphic and hydrologic characteristics and interactions between the gully and river channel (Table 3-1). The reaches were delineated using airborne Light Detection and Ranging (LiDAR) surveys. These data were used to define the topographic, geomorphic, and hydraulic characteristics of the river reach, the adjacent gully catchment, and their interactions. The geomorphology of each river reach was unique, but sites were representative of major processes zones down the Mitchell megafan.

3.3.3 Gully characteristics

LiDAR data uncovered the topographic variability in the proximal gully sites and associated floodplains (Figure 3-3). At all sites, pre-gully floodplain-hollows, paleo-channel depressions, and other shallow fluvial drainage forms existed on river inset- and high-floodplains, as indicated by remnant and partially dissected floodplain features. Subsequently, a major unprecedented phase of gully incision progressed via head cutting through many of these features, migrating from the riparian zone into the relatively-flat river high-floodplains and Eucalyptus woodlands. Alternatively, gully erosion also incised directly into the river high-floodplains at river banks in the absence of any precursing drainage forms (Figure 3-3) (Brooks et al. 2009; Chapter Two; Chapter Four; Shellberg et al. 2010; Chapter Five; Chapter Six).

The silt and clay soils along river high-floodplains 1-2 km from the river are generally massive, sodic, hard-setting, low in organic matter, and scald prone, with textural-contrasts at depth (Table 3-2). Due to their sodic nature and exchangable sodium percentage (ESP) values > 6%, these soils are highly dispersive with a predisposition to erosion (Naidu at al. 1995). Their weathered tropical chemistry and cyclic wetting and drying also promote the formation of soil mottling (iron, manganese) and carbonate concretion development, which readily produce surface lags of pisoliths of ferricrete and calcrete after permanent oxidation following gullying (Pain and Ollier 1992; Goudie 1973).

Table 3-1 River reach characteristics at study sites.

River Reach	Wrotham Park	Highbury	Onalcal	Sandy Creek
Channel Type*	Planform Controlled, Inset Wandering, Gravel-Bed River	Planform Controlled, Low-Sinuosity, Bar-Braided, Sand-Bed River	Wandering Sand-Bed River (meandering to braided transition)	Distributary (Near Tidal Interface)
Bed Material	Gravel w> sand chutes & shale outcrops	Sand/gravel w> outcrops of indurated sandstone alluvium	Sand with minor gravel	Sand w/outcrops of indurated sandstone alluvium
River Floodplains	Sand and gravel capped with sand/silt/clay	Sand and indurated alluvium capped with silt/clay	Sand capped with silt/clay	Indurated alluvium capped with silt/clay
Riparian Forests	Thalweg: *Melaleuca spp.* River Inset-Floodplain: *Eucalyptus spp., Cryptostegia grandiflora* (exotic), rainforest spp. River High-Floodplain: Mixed *Eucalyptus spp.* open woodland	Thalweg: *Melaleuca spp.* River Inset-Floodplain: *Eucalyptus spp.*, rainforest spp. River High-Floodplain: Mixed *Eucalyptus spp.* open woodland	Thalweg: *Melaleuca spp.* River Inset-Floodplain: *Eucalyptus spp., Nauclea orientalis, Cryptostegia grandiflora* (exotic), rainforest spp. River High-Floodplain: Mixed *Eucalyptus spp.* open woodland	Thalweg: *Melaleuca spp.* River Inset-Floodplain: *Corypha utan, Melaleuca spp., Eucalyptus spp.* River High-Floodplain: *Eucalyptus microtheca* and other *Eucalyptus spp.*
Macro-Channel Width (km)	0.8 to 1.2	0.6 to 0.9	1.5 to 3.0	0.1 to 0.3
Slope (m/m)	0.0029§	0.0014#	Average: 0.00037† Range: 0.00027 to 0.00052	~ 0.0001 (near tidal interface)
LiDAR Reach Length (km)	1.5	2.0	6.5	1.3
LiDAR Total Area (km^2)	6.8	5.8	26	1.4
Cross-Sections (#) Extracted from LiDAR	30	52	87	N/A
Composite Manning's n Roughness (Channel = Back Calculated)	Channel: 0.08 to 0.15 Floodplain: 0.20	Channel: 0.03 to 0.06 Floodplain: 0.15	Channel: 0.025 to 0.045 Floodplain: 0.10	N/A
Discharge (Q) Estimates Local Stage Correlations w/ QDERM Gauged Q	Q Mitchell at Gamboola (919011) minus Q Walsh at Trimbles (919309), corrected for basin area differences.	Q Mitchell at Koolatah (919009) minus Q Palmer at Drumduff (919204), corrected for basin area differences and 30% water loss.	Q Mitchell at Koolatah (919009)	N/A
Flood-Frequency (RI) Estimates	Average of RI Mitchell at Gamboola (919011) RI Walsh at Trimbles (919309)	Q at Target RI from Mitchell at Gamboola (919011) + Q Tate at Torwood (919008) + Q Lynd at Torwood (919006), corrected for basin area differences.	RI Mitchell at Koolatah (919009)	RI Mitchell at Koolatah (919009)

* Modified from Brennan and Gardiner 2004; § Estimated from LiDAR reach bed slope and measured flood water surface slope(s) at Gamboola gauge (919011); # Estimated from LiDAR reach bed slope; † Measured flood water surface slope (average) from continuous stage gauges 8 km apart; N/A = not available.

Table 3-2 Gully characteristics at study sites.

Gully	WPGC2 (Wrotham Park)	HBGC1 (Highbury)	Onalcal (Koolatah)	KWGC2 (Sandy Creek)
Internal Gully Area (ha)	7.8	50	1	6
Gully Complex Area (ha)	~50	55	1	8
Drainage Direction	Proximal 1-2 km from river	Proximal 1-2 km from river	Proximal <1 km from river	Proximal <1 km from river
Floodplain Soil Texture	Distal: silt/clay Proximal: sand/gravel capped by silt	Distal: silt/clay Proximal: sand capped by silt	Silt/Clay	Silt/Clay
Soil Type at gully eroding into high-floodplains	Sodic, hardsetting, duplex, red- and yellow earths.	Sodic, hardsetting, duplex, red- and yellow earths.	N/A	Sodic, hardsetting, duplex, yellow earths.
$\mathbf{d_{50}}$ (µm)§	50	40	N/A	20
Max Depositional Age*	Plio-Pleistocene	Pleistocene	Holocene	Holocene
Bulk Density (kg/m^3)	Average: 2035 Range: 1800-2200 increasing w/depth	Average: 2057 Range: 1950-2100 increasing w/depth	N/A	Average: 1859 Range: 1720-1970, peak at 50cm
Soil Conductivity (µS cm^{-1} @ 25C) (1:5 soil/water ratio)	Average: 161 Range: 14-520 increasing w/depth	Average: 313 Range: 134-764 increasing w/depth	N/A	Average: 718 Range: 25-2700 increasing w/depth
pH (1:5 soil/water ratio)	Average: 7.3 Range: 5.0-9.1 increasing w/depth	Average: 5.6 Range: 4.5-7.5 increasing w/depth	N/A	Average: 6.4 Range: 4.8-7.5 increasing w/depth
Exchangeable Sodium Percentage (ESP)#	Average: 11.2 Range: 5-17 increasing w/depth	Average: 45.5 Range: 26-66 increasing w/depth	N/A	Average: 5.9 Range: 4-8 increasing w/depth

§ Measurement using a Coulter multisizer, McTanish et al. 1997;
* Grimes and Doutch 1978, upper surfaces could be younger;
# Exchangable Sodium Percentage (ESP) = $[(Na^+)/(K^+ + Na^+ + Ca^{+2} + Mg^{+2})] \times 100$ using units of meq/100g. Values > 6 represent sodic soils. Methods followed Rayment and Higginson (1992) using a pre-treatment for soluable salts (ethanol/glycerol) and cation extraction using ammonium acetate (CH_3COONH_4) at pH 7.
N/A = not available.

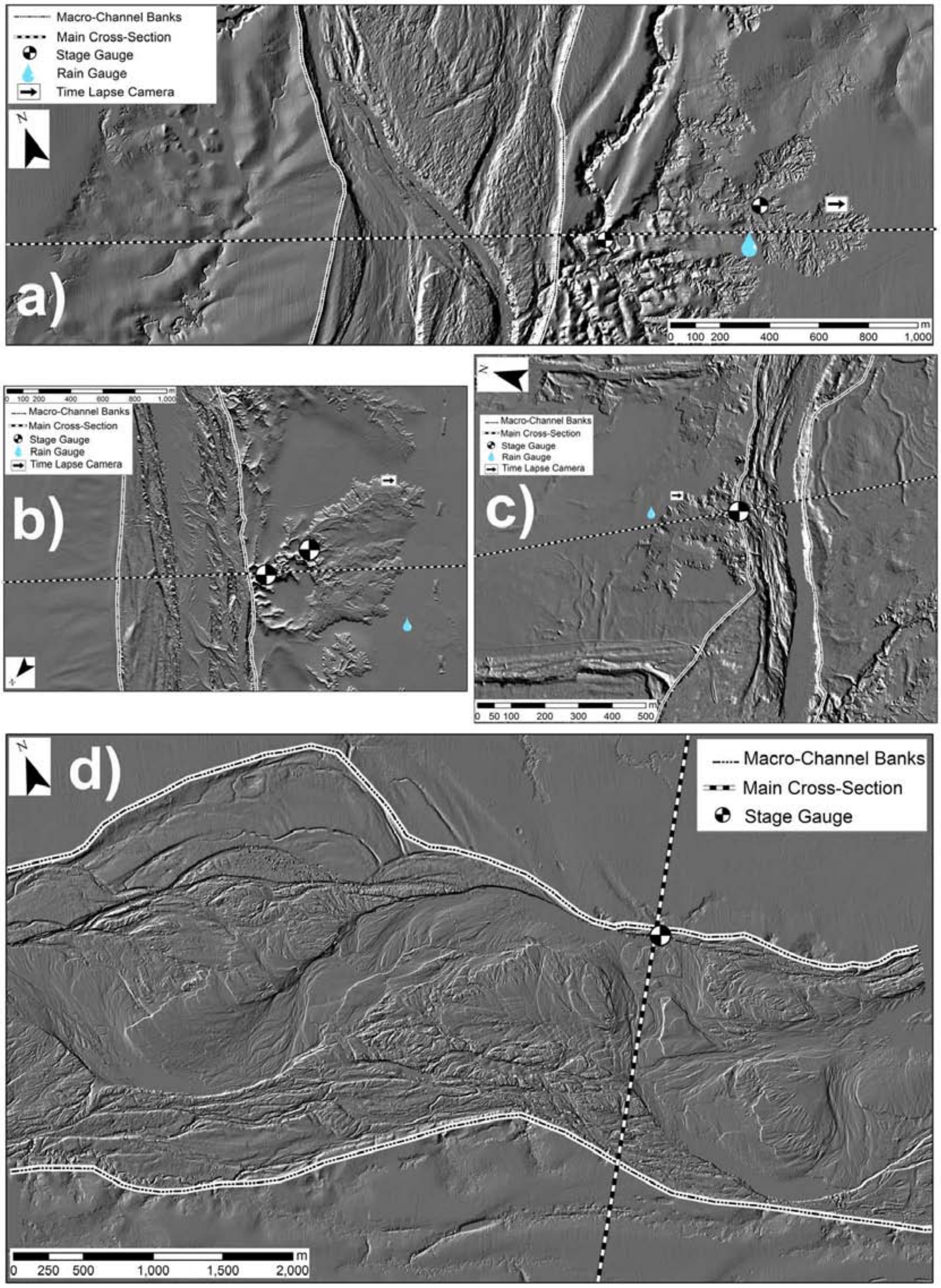


Figure 3-3 LiDAR hillshade maps of the different alluvial gully study sites and adjacent river reaches used for hydraulic analysis a) Mitchell River at Wrotham Park (WPGC2), b) Mitchell River at Highbury (HBGC1), c) Sandy Creek near Kowanyama (KWGC2), and d) Mitchell River near Koolatah (Onalcal Bar). Flow direction is from top-to-bottom for a)-c) and from right-to-left for d). Main cross-section data for locations in a) – d) are also displayed in Figure 3-7.

3.3.4 Water stage and discharge data

Continuous water stage recorders were installed to define the inundation hydrology at each of the four mainstem river reaches and adjacent alluvial gully sites during water year WY 2008 to WY 2010 (Figure 3-3). Submersible pressure transducers with local barometric compensation were installed along the lower reach of each gully outlet channel. This location measured both surface runoff from alluvial gullies during low river stage, and river stage and backwater conditions into alluvial gullies during flood conditions. At WPGC2 and HBGC1 where the relative relief was greatest, a second set of stage recorders was installed higher in the gully networks to better isolate local rainfall-runoff processes in the absence of anticipated river backwater. Only at the WPGC2 upper gauge was a stage-discharge relationship developed specifically for the gully channel in isolation of backwater effects (see Chapter Four).

Instantaneous water stage and discharge data from permanent river gauges in the lower Mitchell catchment (Figure 3-1; QDERM 2010) were obtained for the period of record. These data were used for flood frequency analysis and correlation with stage data collected at alluvial gully sites to 1) estimate river discharge flowing through the study reaches, and 2) to estimate the flood frequency of specific stage and discharge conditions at study reaches.

3.3.5 Flood frequency from gauge records

At river gauge stations, annual peak discharges for the period of record were used to estimate annual flood recurrence intervals (RI, inverse of exceedance probability) following the Log-Pearson Type III distribution (USWRC 1981; Cudworth 1989). Weighted skew coefficients were calculated from station coefficients and a generalized skew coefficient from 15 regional gauging stations (>20-yrs data within ~150km radius) (USWRC 1981). The fitted Log-Pearson Type III distribution was as reasonable as any other estimate of the population distribution, since the data were hampered by 1) sample size (< 40-years), 2) flood discharge measurement error (± 15-25 %), and 3) rating curve extrapolation for discharge events > 10-year recurrence interval (Cudworth 1989; QDERM, Stephen Parker, personal communication).

3.3.6 Discharge and flood frequency correlations

Discharge and flood frequency data at river gauge stations were transferred to study reaches through correlation with local continuous water stage. For different peak flood events, peak instantaneous discharge values at gauged sites were corrected for gauged tributary inputs and ungauged catchment area, and then correlated to peak stage values at study sites, offset in time due to flood wave transmission. At each study reach, stage-discharge curves at low to moderate flood stages measured during the study period were developed. These data were used to calibrate one-dimensional (1-D) hydraulic models (HEC-RAS) for each reach (described below), from which the upper portions of the local rating curves were modelled.

3.3.6.a.1 Wrotham Park

The peak discharge for specific flood events during the study period (<12-yr RI) was estimated at the Wrotham Park reach by subtracting the Walsh River at Trimbles (919309) discharge from the Mitchell River at Gamboola (919011) discharge, corrected for ungauged catchment area differences (Figure 3-1; Table 3-1). This reach's flood RI's during the study period (<12-yr RI) were estimated as the average RI from the same peak flood event at the Gamboola and Trimbles gauges. Flood discharge estimates at targeted recurrence intervals (25, 50, 100-yr RI) were calculated by again subtracting the Walsh (919309) from Mitchell (919011) discharge at the target recurrence interval, corrected by catchment area. The local-reach water stages of these high magnitude peak discharges and recurrence intervals were estimated from HEC-RAS 1-D hydraulic modelling.

3.3.6.a.2 Highbury

Hydrologic analysis at Highbury was hampered by discontinued data collection at the Lynd gauging stations (919006, 919008; Figure 3-1). Therefore, discharge was measured directly at this river reach during river flood (Feb 2009, peak of 6.15 m and 7115 $m^3 \cdot s^{-1}$) using both boat mounted current meters (Ott-C31) and an acoustic Doppler current profiler (ADCP, RD Instruments). These data were used to confirm correlations with the downstream gauges during the study period. Highbury peak discharge was estimated by subtracting Palmer (919204) peak discharge data from Koolatah (919009) discharge, corrected for unmeasured catchment area and 30% channel water loss measured during sequential down river discharge measurements below bankfull (Figure 3-1; Table 3-1). This method output was generally comparable to Highbury peak discharge estimates from a basic basin area correction of the upstream Gamboola (919011) peak flood data (Gamboola area 58% of Highbury due to Lynd River) (Figure 3-1).

Flood discharge estimates at targeted recurrence intervals (10- and 25-yr RI) were calculated by adding the peak discharges from the Mitchell at Gamboola (919011), Tate at Torwood (919008), and Lynd at Torwood (919006) gauges, corrected for unmeasured catchment area. This method avoided issues with excessive water loss at Koolatah during extreme events. It provides a maximum estimate of peak discharge, assuming that Mitchell and Lynd flood peaks arrive at the same time and RI, which might not be unreasonable during the landfall of synoptic-scale tropical cyclones common in this catchment (Nott et al. 2007).

3.3.6.a.3 Onalcal

Continuous discharge data during the study period were available for the Koolatah gauge (919009) 16 km downstream of the Onalcal reach (Figure 3-1). Flood peak timing was only slightly offset and transfer of discharge and flood frequency data was relatively direct (Table 3-1). These data along with local discharge measurements (Feb 2009) were used to calibrate the

HEC-RAS 1-D hydraulic model for this reach and estimate water stages for specific discharges and RI's.

3.3.6.a.4 Sandy Creek

No discharge estimates were made for the Sandy Creek reach (KWGC2) since it is one of dozens of distributaries fed by the Mitchell River below the Koolatah gauge (919009). Rather, direct correlations were made between peak stage at Sandy Creek and peak stage and RI at the Koolatah gauge. No estimates of flood frequency were made beyond the bankfull stage defined by LiDAR cross-sections, as a majority of the landscape becomes inundated beyond this elevation.

3.3.7 Hydraulic modelling

LiDAR topographic data were collected at extreme baseflow conditions (Nov 2008) and used to create 1 m^2 pixel digital elevation models (DEMs) for each reach (Figure 3-3). HEC-GeoRAS (Cameron and Ackerman 2009) was used to extract reach cross-sections and estimate other geomorphic parameters (Table 3-1). HEC-RAS models (Brunner 2010) were calibrated for the study period (excluding Sandy Creek reach) using the above described stage-discharge correlations. Representative energy slopes were estimated from the LiDAR reach bed slopes, water surface slopes measured at gauging stations during flood (i.e., Gamboola, 919009), and paired water stage recorders 8 km apart at the Onalcal reach (Table 3-1). Spatially-uniform channel roughness values within the macro-channel were back-calculated from estimated low and moderate flood discharge values, known water surface elevations, and channel geometry data. Dense overbank riparian vegetation areas were visually assigned Manning's n roughness values (Chow 1959). To estimate water surface elevations for larger target RI discharges, back-calculated roughness values for the macro-channel were adjusted slightly for increasing trends in roughness with increasing stage as forested inset-floodplains in the river macro-channel became inundated, as supported by empirical trends.

3.3.8 Remote sensing of flood frequency

Remote sensing analysis of floodplain inundation frequency for the lower Mitchell fan-delta was conducted by Dr. Doug Ward (Griffith University), which supplements the atypical flood frequency curves for the Koolatah (919009) gauge. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery (2003-2009) covering over a dozen flood events not obstructed by cloud cover was used to estimate the *visual* inundation frequency of different parts of the Mitchell fan-delta (Ward et al. 2011). These data provide minimum inundation frequency estimates due to image availability, pixel size and mixed spectral signals, masking by dense riparian vegetation cover, and other issues detecting episodic shallow inundation from local rainfall or floods. This minimum inundation frequency was compared to the mapped minimum extent of alluvial gullies (Brooks et al. 2009; Chapter Two), and the percentage of alluvial gullies inundated one or more times was estimated.

3.3.9 Gully scarp erosion measurements

Inter-annual changes in gully scarp location along the total gully perimeter of each site were measured annually between 2007 and 2010 using a differential global positioning system (GPS) with ±50 cm accuracy (Trimble with Omnistar HP) (Brooks et al. 2009). Intra-annual variation in gully scarp erosion was assessed and measured using time-lapse cameras (digital, non-photogrammetric, small-format), which were programmed to take daily photographs at specific index scarp sections (Figure 3-3). These sections were representative of average conditions across the total gully perimeter. Cameras were operated from WY 2008 to WY 2010. However camera failure occurred during WY 2008 at both WPGC2 and HBGC1 and an additional data were collected opportunistically at WPGC2 during WY 2011. Cameras were mounted on stable trees and pointed at an oblique angle at index scarp sections. The digital photographs (2848 x 2136 pixels, ~ 6 MP) were internally rectified to each other in a GIS using ground control points. The gully scarp edge was digitized daily after intervals of observable change. Due to the oblique angle, only a relative change in gully area at the scarp edge could be measured, which was calculated as the percentage of daily change divided by the total change over the period of record. To estimate actual planform change, the percentage of daily change divided by the total change was multiplied against the horizontal area change measured during annual GPS surveys (Brooks et al. 2009; Chapter Two; Chapter Four; Chapter Six). These erosion index data were then compared against daily rainfall metrics, water surface stages, and photographic observations of hydrological processes.

3.3.10 Local rainfall and water stage metrics

Continuous rainfall data were collected using automated tipping buckets (0.2mm per tip) at WPGC2, HBGC1, KWGC2 (Figure 3-1; Figure 3-3) during WY 2008-2010, and opportunistically during WY 2011 at WPGC2. Rainfall metrics were derived from these data to compare to daily changes in scarp erosion documented from time-lapse cameras. These included the 24-hr, 48-hr, and 72-hr total rainfall, daily maximum 30-min rainfall intensity (max I_{30}), daily rainfall erosivity (EI_{30}), and a normalized antecedent precipitation index (NAPI). EI_{30} was calculated as the product of the daily sum of storm kinetic energy (E) times the daily maximum 30-minute intensity (I_{30}) (Yu 1998; Renard et al. 1997). Storms with >12.7 mm (0.5in) of total rainfall (i.e., effective storms) separated by 6 hrs of no rain were used to compute daily EI_{30} (Yu 1998). A 5-day inclusive normalized antecedent precipitation index (NAPI) (Heggen 2001) was calculated using daily rainfall totals and two different decay coefficients (k), 0.8 and 0.2. The former is a typical literature value while the later was more representative of the rapid decay of rainfall-runoff and soil moisture at alluvial gully sites due to climatic factors.

These rainfall metrics along with daily mean and max water stage were analysed as independent variables in a stepwise multiple linear regression model to predict the dependent variable of daily scarp erosion documented from time-lapse cameras. Due to the intercorrelation between many of the rainfall metrics, the multiple linear regression analysis was used to select the most predictive independent rainfall variable for final analysis, in addition to water stage variables.

3.3.11 Pore-water pressure

At the index scarp section and time-lapse camera site at WPGC2, four tensiometers (UMS T4e) were used to measure soil pore-water pressure within a 180 cm scarp profile of an active gully lobe. Tensiometers were situated as pairs at two depths down-profile (30 and 105 cm), inserted horizontally (5°) into the scarp face at two distances (40 and 45 cm deep), and backfilled with a slurry of native, hardsetting, silt-clay material. Tensiometers were initially installed in January 2010; however below average wet season rainfall resulted in dry soil conditions and poor measurement conditions. Tensiometers were redeployed during a wetter 20-day period in December 2010. Due to the remote location, tensiometers were only able to be maintained for short durations and were not reinstalled after soil block failure. Available pore-water pressure measurements were compared to measurements and observations of scarp retreat from time-lapse photographs and local rainfall.

3.4 Results

3.4.1 Flood frequency across the Mitchell Megafan

The flood discharge magnitude and frequency at which river inset- and high-floodplains become inundated varied longitudinally down the Mitchell fluvial megafan due to river incision over geologic time (Figure 3-2). Along the more confined river and tributary segments of the upper megafan, gauged flood frequency curves displayed linear trends on a log-probability plot (Figure 3-4). In contrast, flood frequency at Koolatah (919009A) displayed a non-linear trend due to the lack of confinement near the Holocene fan apex (Figure 3-1; Figure 3-2). Above the ~3-yr RI, there was a progressive loss of water to unmeasured overbank discharge on the floodplain or down distributaries (Figure 3-4).

MODIS satellite imagery (2003-2009) also confirmed the minimum inundation frequency of the lower Mitchell Holocene floodplains and loss of water from the river channel into distributaries (Figure 3-5). Comparing the minimum area inundated to the minimum area of active alluvial gullies (Brooks et al. 2009; Chapter Two) suggested that 61% of mapped gullies have been partially or fully inundated at least once between 2003 and 2009. Only 25% have been regularly inundated four or more times, or every two years or so, which were concentrated in the lower fan-delta. Gullies eroding into high-floodplain margins of the upper megafan were less frequently inundated, but assessment was difficult due to channel confinement and mixed spectral signals within large pixels.

Flood stage data and hydraulic modelling at study reaches also defined longitudinal increases in floodplain and gully connectivity and flood duration (Figure 3-6; Figure 3-7). At Wrotham Park (WPGC2), the river high-floodplain would only be inundated during stages > 100-yr RI, while major gully backwatering occurs during events > 10-yr RI (Figure 3-6; Figure 3-7a). As a consequence of local relief and reduced connectivity, the upper floodplain surfaces are extensively dissected by alluvial gullies predominantly driven by rainfall-runoff processes (Figure 3-3a; Chapter Four). At Highbury (HBGC1), the river high-floodplain was estimated to be inundated at stages > 15-yr RI, with gully backwatering observed for 2- to 5-yr RI events (Figure 3-7b). Beyond the 15-yr RI at Highbury, floodwater spills over the subtle catchment divide into the Staaten River, reactivating this section of the fluvial megafan (Figure 3-1; Brooks et al, 2009; Chapter Two; Figure 2-2ab).

At Onalcal Bar, discharge measurement, hydraulic modelling, Koolatah gauge data, and MODIS imagery all confirmed that distributaries become increasingly active above the 2-yr RI (Figure 3-7c). Extensive floodplain inundation occurs at or above the 5-yr RI, while geomorphic units inset within the macro-channel are active during events < 2-yr RI (Figure 3-3). Similarly at Sandy Creek (KWGC2), high-frequency overbank-flooding and partial and full gully inundation were observed every year during the study period (Figure 3-5; Figure 3-6). Stage correlation with the Koolatah gauge suggested that widespread floodplain inundation from river water occurred at the 5-yr RI (Figure 3-7d). The highest surfaces would be inundated beyond the 7-yr RI, which is possibly a result of slight increases in relative relief into the Mitchell fan-delta (Figure 3-2; Brooks et al. 2009). However, RI results could be influenced by errors inherent in the Koolatah data and correlations over long distances, as compared to the local observations of almost annual floodplain inundation from both river water and local rainfall saturation of deltaic floodplains. This inundation and saturation has large ramifications for gully scarp retreat rates, as demonstrated below.

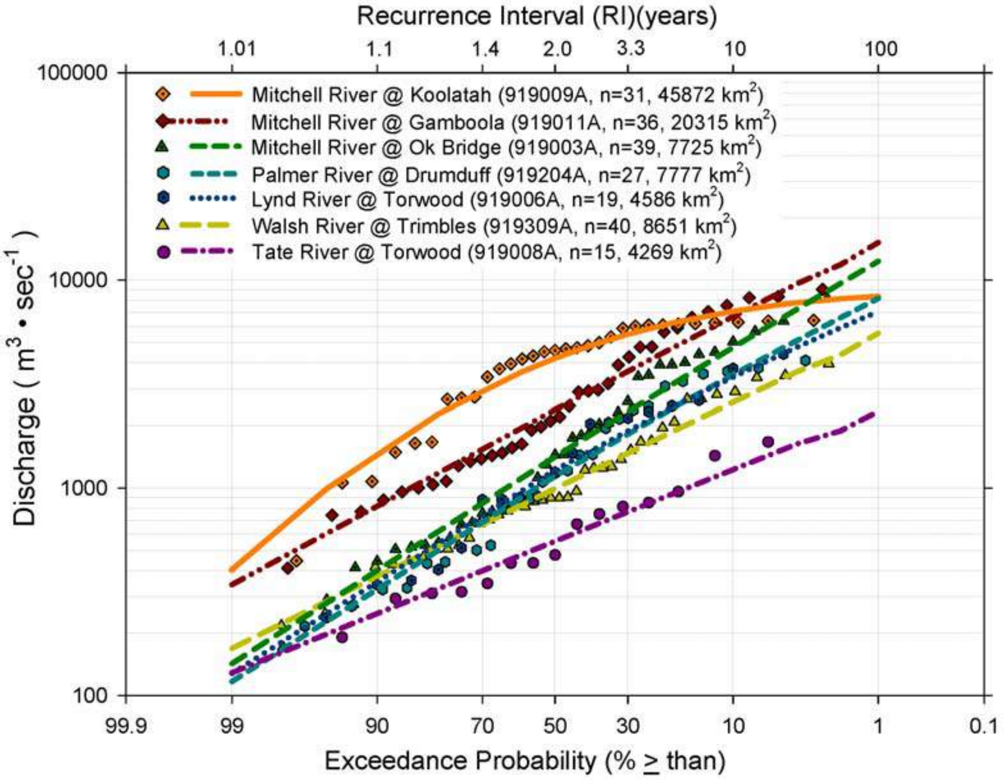


Figure 3-4 Weibull plotting positions (symbols) and fitted Log-Pearson Type III flood frequency curves (lines) for discharge gauging sites located in the lower half of the Mitchell catchment [note station ID, sample sizes (n=years), and upstream catchment area].

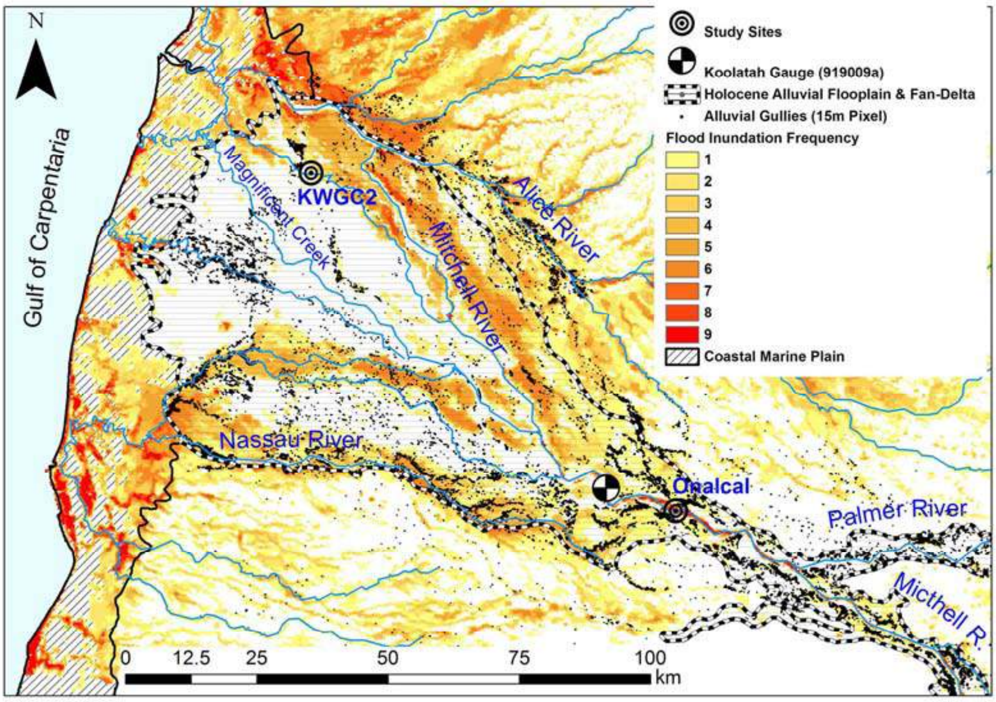


Figure 3-5 Alluvial gully distribution and flood inundation frequency map of the lower Mitchell catchment. Flood inundation was derived from MODIS (2003-2009) to quantify the number of times inundated. The soil dataset from the BRS (1991) was used to highlight the boundary of the active Holocene floodplains, fan-delta, and coastal plains of the lower Mitchell River.

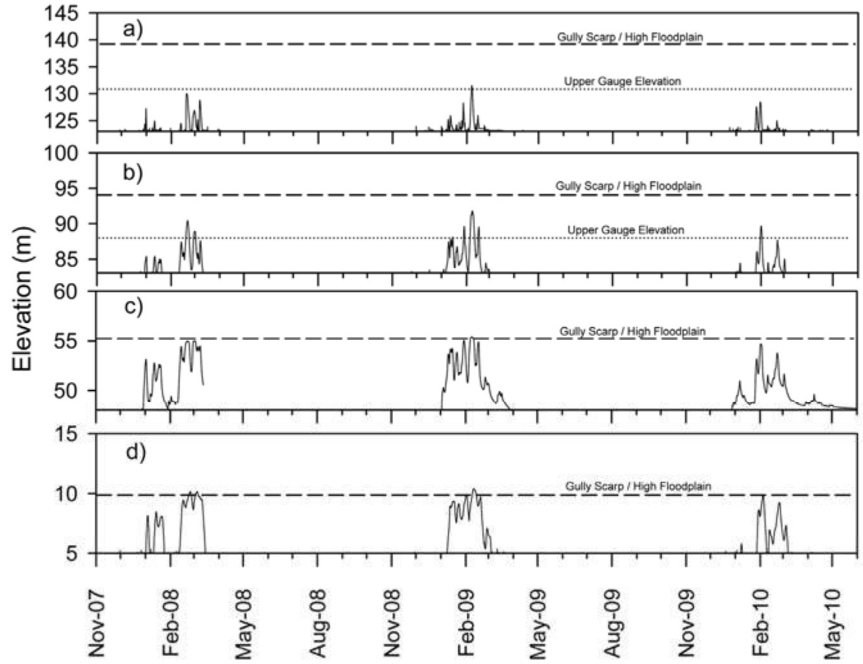


Figure 3-6 Measured hydrographs of water surface elevation at different alluvial gully sites down the longitudinal profile of the Mitchell megafan, a) Wrotham Park (WPGC2), b) Highbury (HBGC1), c) Koolatah (Onalcal Bar), d) Sandy Creek (KWGC2). Long dashed lines represent the elevation of the river high-floodplain surface that local alluvial gullies are eroding into at the gully scarp. The short dashed line represents the elevation of the zero point of the stage gauges nested in the upper alluvial gully complexes of WPGC2 and HBGC1.

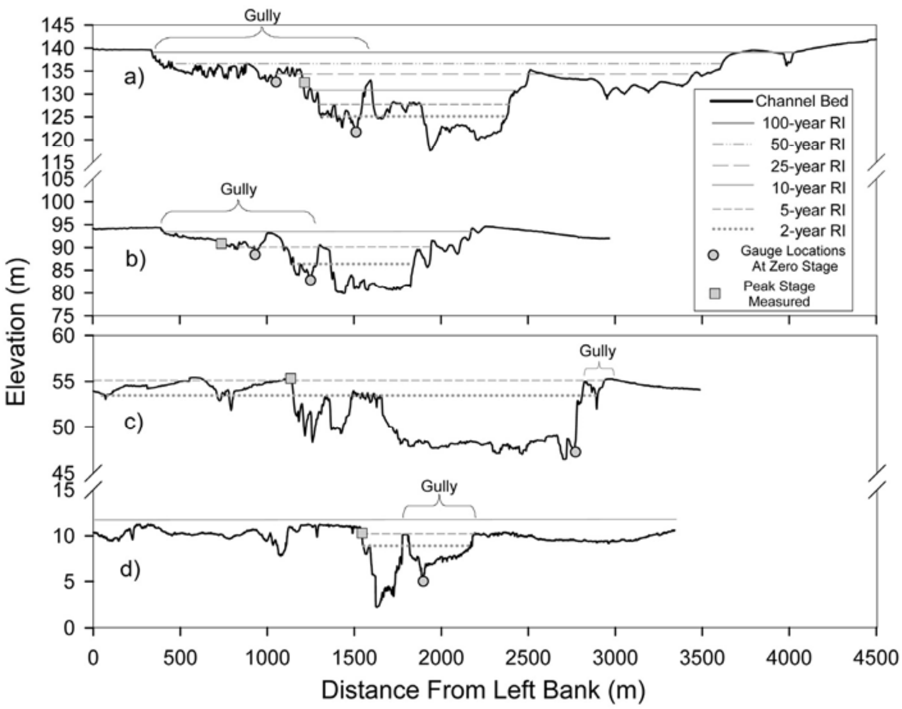


Figure 3-7 Water surface elevations for different flood frequencies at full river cross-sections adjacent to alluvial gully sites down the longitudinal profile of the Mitchell megafan, a) Wrotham Park (WPGC2), b) Highbury (HBGC1), c) Koolatah (Onalcal Bar), d) Sandy Creek (KWGC2). River cross-sections were extracted from LiDAR data at gauge locations within the modelled reach (Figure 3-3), which also show longitudinal sections of adjacent gullies (not continuous profiles). Gauge zero and peak staged measured refer to stage data collected between 2007 and 2010 at the specific cross-section (Figure 3-6).

3.4.2 Gully area change

3.4.2.a.1 Qualitative observations

Daily time-lapse photography demonstrated that annual scarp retreat was the cumulative sum of both subtle and major incremental failures of discrete soil blocks or smaller flakes, and driven by multiple water sources and erosion mechanisms (Figure 3-8). Observed water sources for erosion at WPGC2 and HBGC1 came from the combination of direct rainfall, diffuse infiltration-excess water dripping over the scarp face, and infiltration-excess runoff plunging off the scarp face. At KWGC2, additional sources came from backwater into and full inundation of the scarp face from river flood water.

Direct rain drop impact gave the appearance of deflating internal gully surfaces in time-lapse, due to direct particle displacement, mechanical slaking, physio-chemical dispersion, and surface wash. Wetting and drying of the scarp face resulted in the spalling of the soil surface from flakes of wetter soil breaking off from the drier material underneath. Linear debris lines of deposited organic material on the floodplain surface demarcated subtle overland-flow paths that resulted in water dripping or plunging off the scarp face at concave lobes (in planform), which were preferential locations of scarp retreat compared to convex inter-lobes that retreated slower. Infiltration-excess runoff from the floodplain was relatively clear compared to turbid runoff below the scarp face following erosion, indicating that scarps were compressed transition zones between sediment supply- and transport-limited conditions. River backwater and overbank flooding at KWGC2 episodically overwhelmed more typical rainfall and runoff processes (Figure 3-9). River backwater promoted local saturation, soil dispersion and removal of failed soil blocks, steepening the scarp face (Figure 3-9c). Floodwater drawdown following full inundation created turbulent flow plunging over the scarp face enhancing scarp retreat (Figure 3-9d).

A prerequisite for block failure at active lobes was an over-steepened scarp face undermined by sub-soil erosion and dispersion. Erosion of alcoves at the base of scarps was enhanced by the spalling or flaking of surface soils on scarp faces during rainfall wetting and drying, water dripping or plunging off scarp faces, and down-profile changes in chemical and physical properties (Table 3-2). Tension cracks slowly developed around individual blocks and were enhanced by soil wetting and drying, preferential water flow into cracks, and changes in pore-water pressure (see below). Undermined scarp blocks often did not fail until subsequent water delivery events surpassed unquantified geotechnical-stability thresholds. Debris slopes of failed soil blocks would temporarily reduce scarp retreat, until the erosion cycle began again with in situ breakdown of failed soil blocks and renewed scarp undermining. The presence of trees and their roots near the scarp edge often stalled the advancement of the scarp front along convex inter-lobes, compared to surrounding concave lobes that were more active (in planform). However, active scarp lobes often advanced around trees and their roots, which were eventually undermined by surrounding scarp failure (e.g., Figure 3-9) or retained on remnant pedestals that slowly eroded in situ over time.

3.4.2.a.2 Daily quantitative scarp change

The 24-hr rainfall total was the best predictor of daily scarp area change for all sites (Table 3-3). All other rainfall metrics [NAPI (k=0.2); EI_{30}] were also positively correlated to scarp retreat, but were also intercorrelated to 24-hr rainfall total. The 24-hr rainfall was used for final linear correlations (Figure 3-10), as it is the most direct metric and likely represents a proxy measure for a whole suite of measured and unmeasured variables.

Utilizing rainfall (i.e., 24-hr) and stage (i.e., mean daily) metrics in a multiple linear regression only marginally improved erosion prediction at all sites. Stage was a poor predictor of scarp erosion due to the varying incursion of river backwater in gullies unrelated to local rainfall and runoff. The exception was WPGC2, where max stage uninfluenced by backwater was a modest predictive variable. Gauged water runoff volume at WPGC2 was also highly correlated to scarp retreat, but also intercorrelated to 24-hr rainfall (Table 3-3; Chapter Four).

At KWGC2, backwater and overbank flooding did not consistently result in increased scarp erosion and weakened correlations between rainfall metrics and scarp retreat when the full dataset was used (Table 3-3). A small number of overbank flood days produced the majority of daily area change, while others produced much less change (Figure 3-10c). A subset of data was analyzed for only events driven by rainfall-runoff processes without backwater/overbank flooding, which displayed stronger correlations between 24-hr rainfall and scarp retreat (Table 3-3; Figure 3-10). When river overbank flooding did occur, scarp retreat magnitude often reached high values compared to rainfall or river backwater only (Figure 3-10c).

For erosion events driven by rainfall and infiltration-excess runoff, linear regressions between 24-hr rainfall and scarp area change suggested a threshold of ~ 10 mm of rainfall needed for initiation of scarp retreat (Figure 3-10). Beyond this threshold, scarp retreat increased with additional rainfall, but daily rainfall totals still only explained 60-70% of the variability in scarp retreat. The remaining variability might be explained by complex intrinsic factors that influence the priming of a scarp face for erosion on a given event, such as antecedent soil moisture and pore-water pressure, cycles of soil block undermining and tension crack development, local heterogeneity in soil properties, or preferential surface water flow or drip off the scarp face.

Additional seasonal differences were also observed between regressions of 24-hr rainfall and scarp area change. Early wet season (December, January) regression slopes were significantly different than late wet season slopes (February, March) at WPGC1 ($p<0.001$, n=47 early, n=49 late, WY 2009-11) and KWGC2 ($p<0.001$, n=59 early, n=62 late, WY 2008-10, rainfall events only); however slopes were not significantly different for HBGC1 ($p=0.26$, n=52 early, n=47 late, WY 2009-10). While the causation of these season differences is likely multi-factorial, they do hint at the influence of seasonal changes in ground vegetation on water interception, storage, and runoff toward gully scarps. Major season changes in grass/weed cover were especially observed at WPGC2 around the gully scarp and contributing surface catchment area (Figure 3-8ab), with modest cover change at KWGC2 and minimal change at HBGC1 due to scalding and soil surface sealing (Figure 3-8cd).

3.4.2.a.3 Pore-water pressure

During WY 2010 at the WPGC2 time-lapse camera index site (Figure 3-3a; Figure 3-8a), tensiometer measurements of subsurface pore-water pressure were unsuccessful due to below average rainfall and dry sub-soil conditions. For example, measurements during a 30 mm daily rainfall event in January 2010 indicated that sub-soils 30 and 105 cm down-profile and 40-45 cm into the scarp face remained dry (< -90 kPa) despite rainfall-runoff and surface erosion that produced high suspended sediment concentrations (Chapter Four).

During wetter conditions in December 2011 during a 20 day measurement period, upper-profile tensiometers (30 cm down, 40-45 cm deep) measured fluctuations in pore-water pressure towards positive values following specific rainfall events and substantial seasonal antecedent rainfall (Figure 3-11, T1-T2). Lower-profile tensiometers (105 cm down, 40-45 cm deep) did not respond directly to episodic rainfall events, but rather measured subtle increases in pore-water pressure as cumulative seasonal rainfall increased (Figure 3-11, T3-T4). Measurements of local scarp retreat from daily photographs indicated that the failure of over-hanging soil blocks was coincident with both rainfall input and increases in upper-profile pore-water pressure. However, only 6 out of 9 events with positive pore-water pressure in the upper-profile resulted in scarp retreat (Figure 3-11).

The upper-profile tensiometer deeper into the scarp face (T1, 45 cm) experienced higher pore-water pressures than the shallower tensiometer (T2, 40 cm), while the opposite was true for the lower-profile tensiometers. These data suggest either local soil moisture variability and/or the influence of horizontal wetting and drying fronts and subtle seepage gradients. The continuous matrix suction in the lower-profile and pressure gradients directed into the scarp face suggest that emergent soil- or ground-water are not driving scarp undercutting and retreat. Development of alcoves at the base of scarps is potentially enhanced by water infiltrating into dispersible sub-soils of the scarp face, resulting in the spalling of the face as flakes of wetter soil break off from the drier material underneath. However in the upper profile, positive pore-water pressures and potential seepage gradients out of the scarp face are contributing to reduced shear strength and the failure of small overhanging blocks.

The measurement period ended when the tensiometers became disturbed from their contact with the soil or were ripped off the scarp face during complete block failure. This occurred during a small rainfall event (16mm) for a lower-profile tensiometer (T4) and during a larger event (45 mm) for the remaining tensiometers (T1, T2, T3). Complete block failure and major scarp retreat on 27-Dec-10 was not associated with major increases in pore-water pressure in the lower-profile (T3, 105 cm), while upper-profile pressures did reach positive values (Figure 3-11).

3.4.2.a.4 Annual quantitative change

At the annual scale at WPGC2 and HBGC1, direct rainfall, infiltration-excess runoff, and other associated processes fully dominated erosion at scarps (Table 3-4). River backwater and overbank flooding could influence erosion during more extreme events (Figure 3-7ab). In contrast at KWGC2, the total percentage of daily erosion from river backwater (8.3%) and overbank flooding (35.1%) over WY 2008 to 2010 was considerable, but erosion from just rainfall-runoff events still dominated (56.6%)(Table 3-4). The contribution of these different processes to scarp erosion varied between years and events. For example, 1 day of overbank flooding in WY 2009 resulted in 10% of the total change in scarp area between WY 2008 and 2010 (Figure 3-9d), while 5 days of overbank flooding later in WY 2009 only resulted in 1.3% of the total change.

Average annual rainfall erosivity (r-factor) values from cumulative storms at each site were generally near the 75th percentile value for the region (9456), but with year to year variability (Table 3-4; Yu 1998; Lu and Yu 2002). Combining data for all years at all sites but excluding backwater and overbank flooding events, the annual scarp change at index sections was correlated to both annual rainfall erosivity values (r^2 =0.75) and annual rainfall totals (r^2 =0.61) (Table 3-4).

Mean annual scarp retreats rates measured using GPS across entire scarp fronts were poorly correlated (r^2 =0.10) to measurements of annual rainfall or annual storm erosivity (Table 3-4). Long lengths of relatively inactive scarp front and horizontal GPS error (± 20-50cm) resulted in low signal to noise ratios and overlap of error margins around total gully area change between individual years. Thus at the annual scale across long lengths of gully front, these GPS data are relatively coarse and are more appropriate for change documentation over multiple years or decades (Chapter Six).

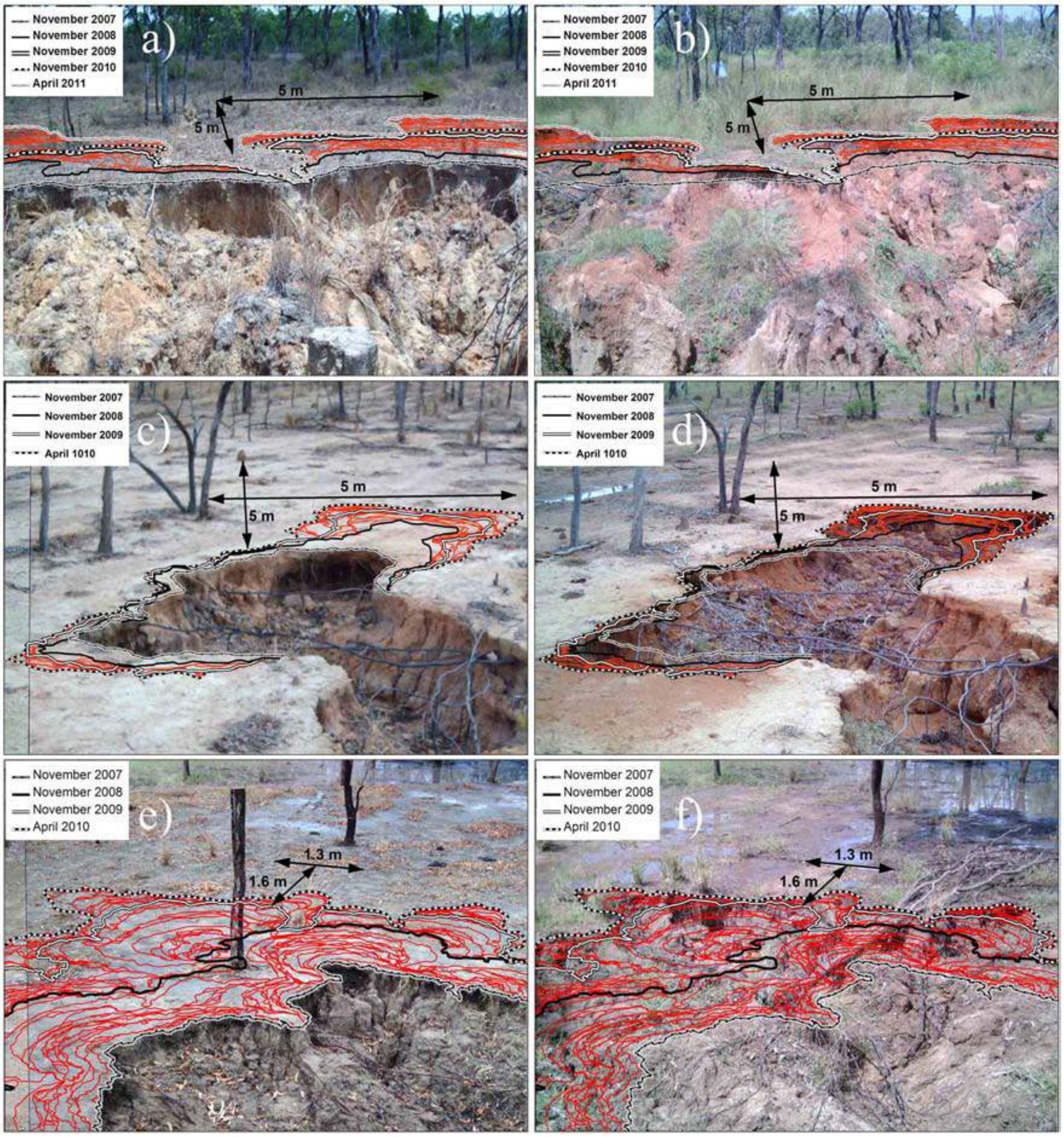


Figure 3-8 Gully-scarp oblique-area change at time-lapse camera index sites for a)WPGC2 November 2007, b) WPGC2 April 2011, c) HBGC1 November 2007, d) HBGC1 April 2010, e) KWGC2 November 2007, and f) KWGC2 April 2010. Note thin red lines represent daily incremental changes where data available.

Figure 3-9 Sequential time-lapse photographs over WY 2009 of an active alluvial gully lobe at the KWGC2 index section in the lower Mitchell River: (a) 28 November 2008, (b) 11 January 2009, (c) 17 January 2009, (d) 01 February 2009, (e) 02 February 2009, (f) 06 February 2009. Note rainfall induced erosion between (a) and (b), backwater and rainfall induced erosion between (b) and (c), backwater and overbank flooding induced erosion between (c) and (d), and the overland runoff and flood drawdown induced erosion between (d) and (f).

Table 3-3 Matrix of Pearson correlation coefficients (r) between the dependent (daily scarp change) and independent (daily rainfall and water stage) variables.

		Scarp Change (m^2)	Rainfall Total (24hr)	Rainfall Total (48hr)	Rainfall Total (72hr)	I_{30} (Daily Max)	EI_{30} (Daily)	NAPI (k=0.8)	NAPI (k=0.2)	Mean Daily Stage	Peak Daily Stage	Daily Runoff Volume
WPGC2 n=96	Scarp Change (m^2)	1.000	**.877**	.635	.511	.612	.770	.563	.853	.198	.420	.825
	Rainfall Total (24hr)	**.877**	1.000	.770	.645	.702	.821	.726	.985	.431	.624	.915
	Rainfall Total (48hr)	.635	.770	1.000	.882	.491	.591	.880	.867	.272	.391	.756
	Rainfall Total (72hr)	.511	.645	.882	1.000	.351	.456	.923	.751	.169	.246	.635
	I_{30} (Daily Max)	.612	.702	.491	.351	1.000	.887	.453	.675	.124	.705	.605
	EI_{30} (Daily)	.770	.821	.591	.456	.887	1.000	.543	.796	.208	.587	.759
	NAPI (k=0.8)	.563	.726	.880	.923	.453	.543	1.000	.811	.222	.354	.693
	NAPI (k=0.2)	.853	.985	.867	.751	.675	.796	.811	1.000	.405	.587	.914
	Mean Daily Stage	.198	.431	.272	.169	.124	.208	.222	.405	1.000	.598	.489
	Peak Daily Stage	.420	.624	.391	.246	.705	.587	.354	.587	.598	1.000	.603
	Daily Runoff Volume	.825	.915	.756	.635	.605	.759	.693	.914	.489	.603	1.000
HBGC2 n=97	Scarp Change (m^2)	1.000	**.774**	.596	.408	.611	.647	.395	.747	-.027	.082	N/A
	Rainfall Total (24hr)	**.774**	1.000	.811	.628	.786	.859	.636	.984	.034	.177	N/A
	Rainfall Total (48hr)	.596	.811	1.000	.861	.557	.644	.816	.901	.067	.207	N/A
	Rainfall Total (72hr)	.408	.628	.861	1.000	.390	.477	.912	.742	.079	.215	N/A
	I_{30} (Daily Max)	.611	.786	.557	.390	1.000	.835	.382	.747	.011	.184	N/A
	EI_{30} (Daily)	.647	.859	.644	.477	.835	1.000	.509	.828	-.002	.165	N/A
	NAPI (k=0.8)	.395	.636	.816	.912	.382	.509	1.000	.734	.171	.292	N/A
	NAPI (k=0.2)	.747	.984	.901	.742	.747	.828	.734	1.000	.049	.199	N/A
	Mean Daily Stage	-.027	.034	.067	.079	.011	-.002	.171	.049	1.000	.943	N/A
	Peak Daily Stage	.082	.177	.207	.215	.184	.165	.292	.199	.943	1.000	N/A
KWGC2 n=188 (n=156)	Scarp Change (m^2)	1.000	**.370 (.795)**	.256 (.530)	.216 (.419)	.310 (.735)	.365 (.784)	.204 (.419)	.344 (.744)	.205	.215	N/A
	Rainfall Total (24hr)	**.370 (.795)**	1.000	.760 (.759)	.632 (.637)	.844 (.850)	.806 (.817)	.620 (.649)	.976 (.975)	-.060	-.025	N/A
	Rainfall Total (48hr)	.256 (.530)	.760 (.759)	1.000	.881 (.894)	.556 (.546)	.543 (.546)	.841 (.867)	.870 (.871)	.050	.075	N/A
	Rainfall Total (72hr)	.216 (.419)	.632 (.637)	.881 (.894)	1.000	.417 (.414)	.403 (.410)	.929 (.942)	.748 (.756)	.110	.137	N/A
	I_{30} (Daily Max)	.310 (.735)	.844 (.850)	.556 (.546)	.417 (.414)	1.000	.850 (.861)	.384 (.408)	.793 (.795)	-.126	-.093	N/A
	EI_{30} (Daily)	.365 (.784)	.806 (.817)	.543 (.546)	.403 (.410)	.850 (.861)	1.000	.391 (.411)	.750 (.759)	-.094	-.061	N/A
	NAPI (k=0.8)	.204 (.419)	.620 (.649)	.841 (.867)	.929 (.942)	.384 (.408)	.391 (.411)	1.000	.733 (.763)	.190	.220	N/A
	NAPI (k=0.2)	.344 (.744)	.976 (.975)	.870 (.871)	.748 (.756)	.793 (.795)	.750 (.759)	.733 (.763)	1.000	-.029	.006	N/A
	Mean Daily Stage	.205	-.060	.050	.110	-.126	-.094	.190	-.029	1.000	.995	N/A
	Peak Daily Stage	.215	-.025	.075	.137	-.093	-.061	.220	.006	.995	1.000	N/A

Note for KWGC2, values in parentheses (.###) are from a subset of days with rainfall only, without river backwater or overbank flow at the scarp zone.

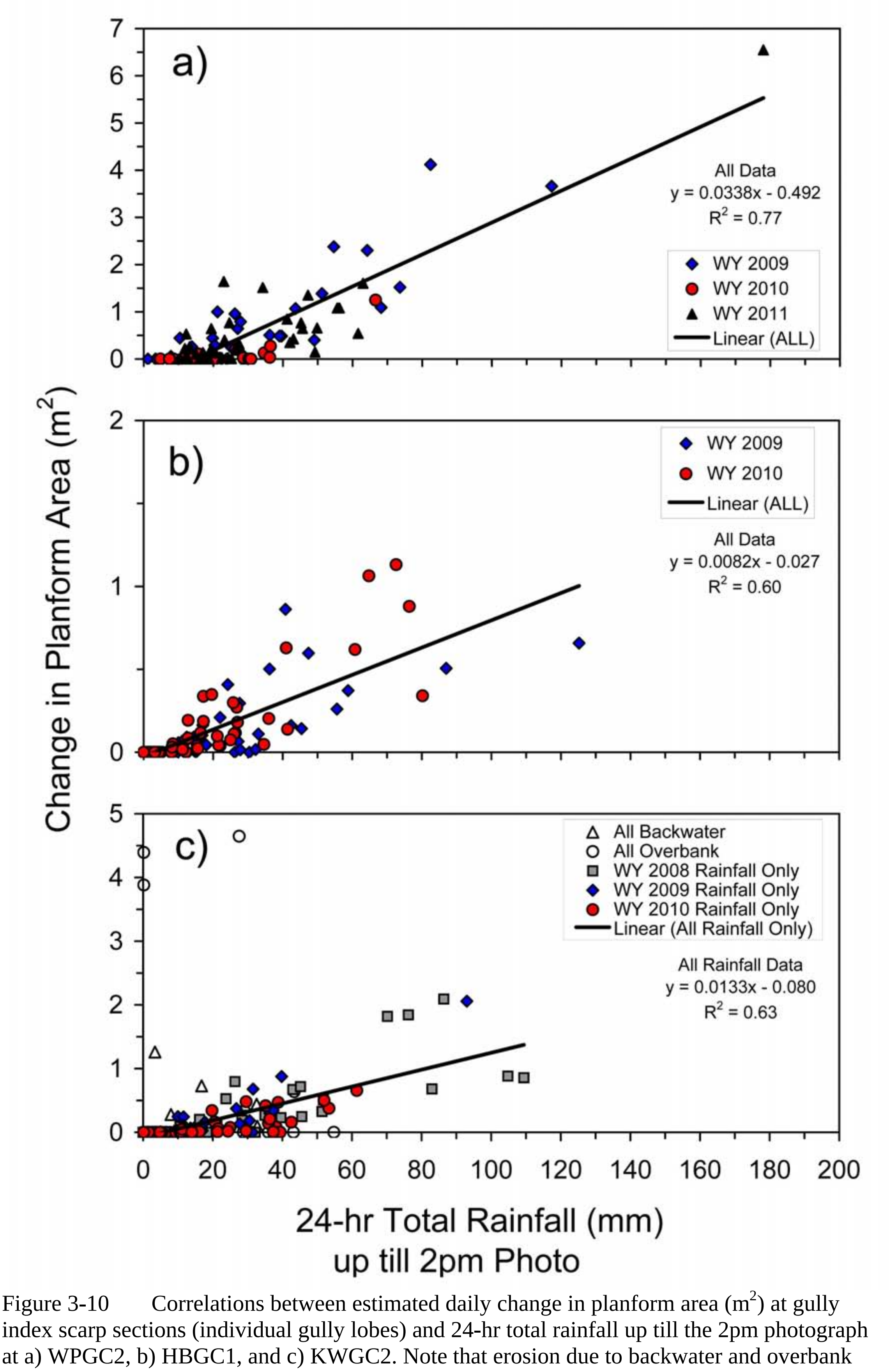


Figure 3-10 Correlations between estimated daily change in planform area (m^2) at gully index scarp sections (individual gully lobes) and 24-hr total rainfall up till the 2pm photograph at a) WPGC2, b) HBGC1, and c) KWGC2. Note that erosion due to backwater and overbank flooding at KWGC2 (c) are included to demonstrate scarp area changes uncorrelated to rainfall.

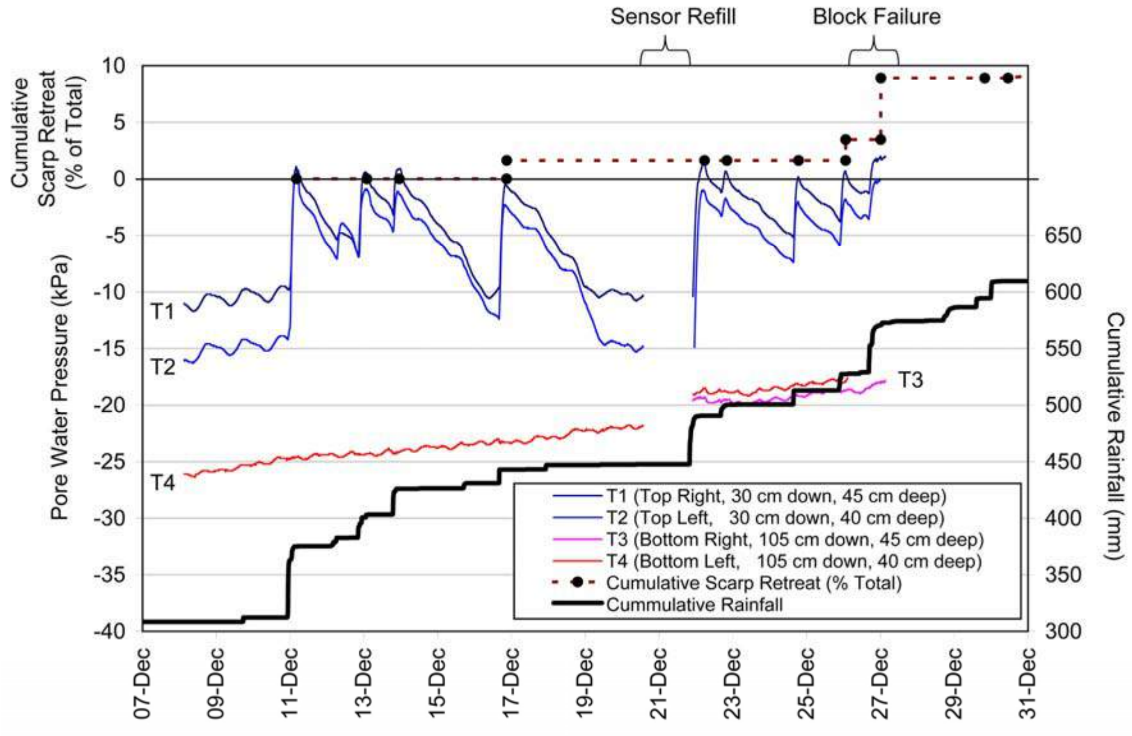


Figure 3-11 Pore-water pressure (kPa) trends at WPGC2 during WY 2011 from paired tensiometers inserted horizontally in a scarp face at 30 cm and 105 cm depth, along with continuous rainfall and scarp retreat at the top edge measured from daily time-lapse cameras.

Table 3-4 Annual erosion measured from time-lapse photos of index scarp sections (individual lobes) in relation to erosion processes and rainfall totals, river backwater, and overbank flooding

	Time-Lapse Camera, Scarp Index Sections				**Local Rain Gauge**		**GPS Surveys for Entire Gully Scarp**	
	% Erosion from Direct Rainfall Only (# of days rain >12.7mm, with no backwater or flooding)	**% Erosion from River Backwater + Rainfall** (# of days)	**% Erosion from Overbank Flooding + Rainfall** (# of days)	**% of Total Change per WY During Study Period**	**Annual Rainfall** (# days rain >12.7mm)	**Annual Rainfall Erosivity** r-factor MJ·mm / ha·hr·yr (# storms >12.7mm)	**GPS Mean Scarp Retreat Rate** m/yr (Length Scarp Front Surveyed)	**GPS Max Scarp Retreat Rate** m/yr
WPGC2 WY 2008	100 % (31 days)	0 %§	0 %	27.9 %	1217 mm (31 days)	6507 (27 storms)	0.17 (5507)	4.8
WPGC2 WY 2009	100 % (30 days)	0 %§	0 %	34.7 %	1235 mm (30 days)	9103 (29 storms)	0.21 (5799)	6.4
WPGC2 WY 2010	100 % (15 days)	0 %§	0 %	2.9 %	717 mm (15 days)	2841 (14 storms)	0.16 (5762)	1.6
WPGC2 WY 2011	100 % (44 days)	0 %§	0 %	34.5 %	1884 mm (44 days)	14558 (39 storms)	N/A	N/A
WPGC2 WY 2008 to 2010	100 %	0 %§	0 %	---	Ave = 1263 mm	Ave = 8252	Ave = 0.18	---
HBGC1 WY 2008	100 % (33 days)	0 %†	0 %	31.1 %	1406 mm (33 days)	9882 (26 storms)	.14 (6260)	3.4
HBGC1 WY 2009	100 % (28 days)	0 %†	0 %	41.9 %	1303 mm (28 days)	11409 (32 storms)	.10 (6566)	2.4
HBGC1 WY 2010	100 % (27 days)	0 %†	0 %	27.0 %	1001 mm (27 days)	6077 (26 storms)	.25 (6823)	4.2
HBGC1 WY 2008 to 2010	100 %	0 %†	0 %	---	Ave = 1237 mm	Ave = 9123	Ave = 0.16	---
KWGC2 WY 2008	55.9 % (24 days)	6.3 % (13 days)	37.8 % (8 days)	56.6 %	1730 mm (35 days)	14889 (38 storms)	0.14 (2845)	1.6
KWGC2 WY 2009	48.1 % (27 days)	14.1 % (18 days)	37.8 % (6 days)	30.5 %	1175 mm (31 days)	7559 (29 storms)	0.11 (2879)	3.1
KWGC2 WY 2010	79.5 % (26 days)	3.1 % (6 days)	17.4 % (1 days)	12.9 %	1102 mm (29 days)	7460 (29 storms)	0.17 (2864)	1.6
KWGC2 WY 2008 to 2010	56.6 %	8.3 %	35.1 %	---	Ave = 1336 mm	Ave = 9969	Ave = 0.14	---

§ Note that backwater from river flooding did enter WPGC2 gully floor during all years, but only reached to 130m in WY 2008, 131.5m in WY 2009, 128.5 in WY 2010, and 131 in WY 2011, which was > 5 m below the elevation of the bottom of the gully scarp (137m) or > 7 m top of the gully scarp and river high-floodplain (139.5m) (Figure 3-7a).

† Note that backwater from river flooding did enter HBGC1 gully floor during all years, but only reached to 90.5m in WY 2008, 91.8m in WY 2009, and 89.7m in WY 2010, which was > 1 m below the elevation of the bottom of the gully scarp (93.0m) or > 2 m below the top of the gully scarp and river high-floodplain (94.3m) (Figure 3-7b).

3.5 Discussion

3.5.1 Local scarp retreat

The time-lapse photography from non-photogrammetric digital cameras proved to be valuable for quantifying daily scarp retreat and qualifying basic geomorphic processes in remote locations. While not ideal, oblique photos provided useful estimates of relative planform area change. Error inherent in the cameras (Wackrow et al. 2007) or due to oblique distance/scale issues (Chandler et al. 2002) could have partially influenced results. However, the cameras' close proximity to scarps and large relative changes in scarp location likely masked any inherent error. More robust photogrammetric cameras, methods, and setups for DEM creation (e.g., Chandler 1999) could be used in the future, such as vertical views (i.e., towers or trees) or horizontal views of the gully face (Welch et al. 1984; Sneddon et al. 1988; Pyle et al. 1997). Low-altitude large-scale aerial photographs (Marzolff and Poesen 2009) or high resolution terrestrial laser scanning (LiDAR) (Heritage and Hetherington 2007; Resop and Hession 2010) would be ideal for planform and volumetric change assessment before and after storm events.

The correlation of 24-hr rainfall totals with daily scarp retreat is suggestive of a cause and effect relationship in the context of intense tropical rainfall impacting, saturating, running off, and eroding exposed and dispersible soils. Surprisingly, daily rainfall erosivity (EI_{30}) was not the best predictor of daily scarp retreat despite its integration of multiple storm attributes. However, annual erosivity (r-factor) was a better predictor of annual scarp retreat compared to annual rainfall. The variability ($r^2 \approx 0.5$) within rainfall intensity/kinetic energy models used here (Yu 1998; Renard et al. 1997) or elsewhere (van Dijk et al. 2002) could be influencing these results, in addition to the lack of empirical rainfall energy data in this part of the wet-dry tropics. Regardless, 24-hr rainfall or EI_{30} are just proxy measures for a whole suite of measured and unmeasured variables influencing erosion and scarp retreat. More detailed mechanistic field studies are needed to understand the direct erosion of surface and sub-surface soils, internal geotechnical stability and pore-water pressure dynamics, vegetative influences on water runoff, and the transformation of rainfall and runoff energy into scarp retreat. The mechanistic influence of partial and full floodplain inundation on ~ 25% of the alluvial gullies in the Mitchell also needs to be investigated in more detail.

Negative pore-water pressures in deeper sub-soils during major rainfall and scarp failure events suggest that emergent soil moisture or groundwater seepage out of scarp faces are not dominant or required for scarp failure, in contrast to hypotheses of Brooks et al. (2009). The presence of undermined alcoves in sub-soils beneath overhanging scarps was misleading as an indicator of water seepage. Alcove features were observed to be enhanced by direct rainfall, spalling or flaking of the scarp face by wetting fronts, and surface water drip and runoff over the scarp face onto exposed erodible sub-soils. Evidence for turbulent flow through macro-pipes was only occasionally observed elsewhere in reconnaissance surveys where pipes followed soil tension cracks, root voids, and other soil irregularities and were fed by surface water runoff. However, lack of evidence for emergent soil moisture or groundwater seepage out of the WPGC2 scarp face does not discount their presence elsewhere. Furthermore, the complete saturation of sub-soils during river backwater and overbank flood events at some gullies would undoubtably create positive pore-water pressures throughout scarp profiles, which would enhance erosion and undercutting during drawdown and subsequent rainfall events (Figure 3-9; Figure 3-10c).

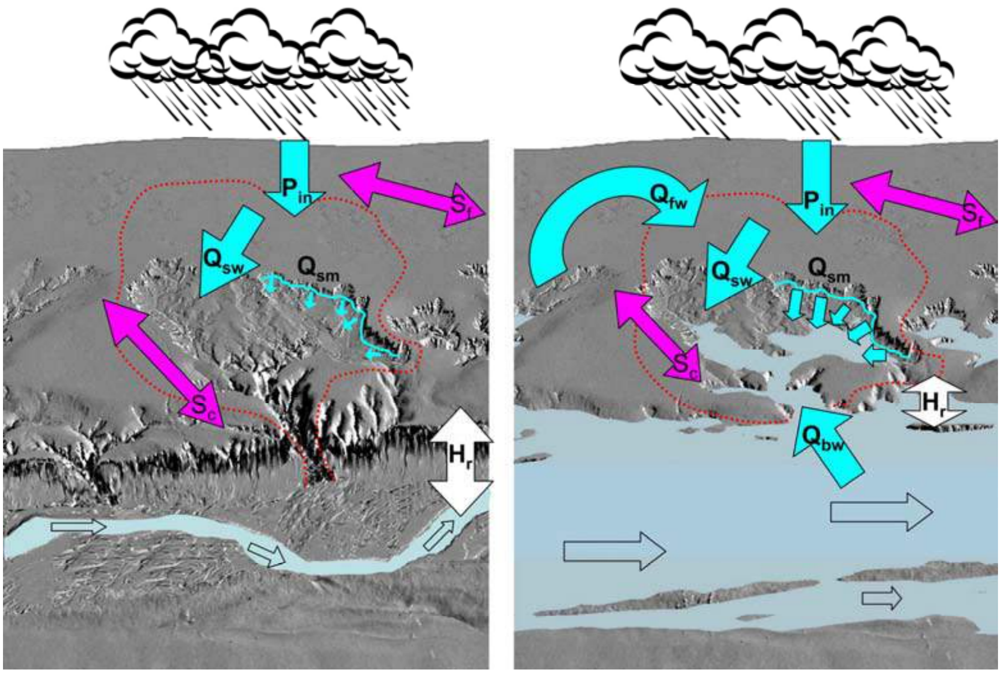
3.5.2 Land-use implications

The importance of 1) direct rainfall and infiltration-excess runoff on alluvial gully scarp retreat and 2) seasonal influences of ground vegetation on water runoff and scarp retreat have implications for grazing land management impacts on soil-surface and grassland-vegetation conditions. The current land management paradigm of grazing down available grass cover to minimal levels in the late dry season, along with very early-wet season fire burning of remnant vegetative stubble, results in bare, exposed, and disturbed soils at the beginning of the tropical monsoon rains. The duplex, sodic, hardsetting, silt/clay soils of the Mitchell floodplains are naturally prone to structural breakdown, surface sealing, and enhanced water runoff, which promote gullying. Perennial grass cover as influenced by rangeland management is likely a key factor mitigating this erosion vulnerability and water runoff, through increased rain drop interception, root cohesion, aggregate stability from organic matter, soil permeability, and water infiltration (e.g., Bridge et al. 1983; Greene et al. 1994; McIvor et al. 1995; Roth 2004). Direct soil compaction and destruction of biological crusts by cattle can also influence water infiltration and runoff volumes (Trimble and Mendel 1995; Evans 1998). Once runoff occurs, perennial grass cover can increase the resistance of the soil to erosion through root cohesion and surface roughness, which increases the critical shear stress needed for sheet erosion, rilling, and gullying (Graf 1979; Prosser and Slade 1994; Knapen et al. 2007; Knapen and Poesen 2010). However, cattle pads (tracks) can overwhelm vegetative roughness by concentrating overland flow and increasing local shear stress.

In the lower Mitchell catchment, the introduction of cattle in the late 1800’s was coincident with the widespread initiation of alluvial gullies into floodplain soils (Shellberg et al. 2010; Chapter Six). Reduced vegetative cover and increased physical disturbance of soil by cattle along river banks and near river hollows is hypothesized to have pushed this naturally sensitive landscape across a threshold towards instability. Specific land management actions need to be locally identified and used to slow or halt alluvial gullies once they have developed into large scarp fronts studied here, in addition to reducing their future initiation. More detailed surface water balance and erosion research will be required in connection with treatment and control gullies that isolate and identify specific cause and effect factors in gully initiation, propagation, and stabilization (see Chapter Seven).

3.5.3 Conceptual model of alluvial gully hydrogeomorphology

Alluvial gullies along floodplain rivers are influenced by a range of hydrogeomorphic processes and are situated within the floodplain perirheic zone, or surface water mixing zone (Mertes, 1997). The dominance or mixture of various water sources and erosional drivers depends on the vertical and lateral connectivity of the river with adjacent floodplain or gully surfaces, which is displayed in a conceptual model of alluvial gully erosion (Figure 3-12ab). This connectivity is temporally dynamic according to the flood pulse concept (Junk et al. 1989; Tockner et al. 2000), varies spatially and longitudinally along the river continuum and associated process domains (Vannote et al. 1980; Montgomery 1999), and is serially discontinuous due to geomorphic variability (Ward and Stanford 1995). The locally inherited geomorphic template controls factors such as local relief and topographic slope(s), which are metered by river stage (Figure 3-12ab). Climate, geology, and land use control sediment supply and the balance of floodplain deposition and erosion. Resistance to erosion is provided by edaphic factors (soil texture, structure, chemistry, pore water pressure) and vegetative conditions (type, root density, surface cover, soil organic matter). Natural cycles (seasons, drought, flooding, fire) and human land use (cattle grazing, woodland clearing, agriculture, weed invasion, altered fire regimes) can influence vegetative protection and soil disturbance. All of these factors in turn influence the fragile balance of floodplain stability, and whether thresholds are crossed that result in the initiation, propagation, and stabilization of alluvial gullies (Brooks et al. 2009; Chapter Six).



a) b)

Figure 3-12 Conceptual model of perirheic-zone erosional-drivers of a proximal alluvial gully during: a) low river water and high relative relief (H_r) when water sources are dominated by direct precipitation (P_{in}), surface water from overland flow off the floodplain (Q_{sw}), and emergent soil moisture (or groundwater) at breaks in slope (Q_{sm}); and b) high river water and low relative relief (H_r) when water sources additionally include river backwater (Q_{bw}) during common floods and overbank floodplain water (Q_{fw}) during larger magnitude floods. Potential energy factors include relative relief (H_r), the alluvial gully channel slope (S_c), and the often smaller floodplain slope (S_f). Base image is an oblique LiDAR hillshade of HBGC1 with maximum backwater inundation during the study period in b) (Figure 3-6b; Figure 3-7b).

The paradox that floodplains can be both sources and sinks of water and sediment is in contrast to many conceptual views of floodplains as pure depositional environments (Vannote et al. 1980; Junk et al. 1989; Tockner et al. 2000). However, the geomorphic position of a floodplain along the (dis)continuum of sediment production, transfer, and sink zones in fluvial systems (Schumm 1997; Montgomery 1999) can influence the spatial and temporal scales of sediment storage (e.g., Trimble 1981). It is more appropriate to conceptualize and model floodplain aggradation and degradation as hierarchically nested erosion cells (Pickup 1985; 1991), especially in relation to gully erosion dynamics (Schumm and Hadley 1957). Small-scale erosion cells (cyclical source, transfer and sinks zones) are typically nested within large-scale fluvial landforms that have similar zones operating at larger and longer time scales.

Alluvial gully complexes along the incised upper Mitchell megafan (e.g., WPGC2) are operating as new erosion cells, with gully head scarps serving as local sediment sources and inset-floodplains in gully complexes and adjacent river macro-channels (e.g., local benches) serving as sediment sinks. At the landscape scale, these erosion cells near the top of the megafan (Chapter Two; Brooks et al. 2009) are net sediment sources to downstream floodplain environments, which have their own balance of nested erosion cells (e.g., KWGC2) or consist of longer-term sinks like deltaic-floodplains or off-shore environments. These floodplain and erosion cell processes are contingent on not only geomorphic evolution over geologic time (Grimes and Doutch 1978), but also inherited geomorphic and biogeochemical templates (Galloway et al. 1970), contemporary hydrologic regimes (Ward et al. 2011), and human land-use disturbances influencing landform stability (Chapter Six).

3.6 Conclusions

This study has defined the broad hydrogeomorphic context of the Mitchell megafan in relation to alluvial gully erosion, and some locally specific erosional drivers of gully scarp retreat. Land, river, and restoration management should be guided by a firm understanding of physical processes acting on a large floodplain river system and influencing different management units important to human and ecological systems. In the lower Mitchell catchment, these management units are best defined from process zones arranged hierarchically according to large-scale megafan units, river segment scale floodplain connectivity, and reach scale dynamics such erosion cell development. Many land management paradigms (e.g., cattle grazing concentrated along waterways), catchment rehabilitation projects (e.g., gully stabilization), or infrastructure development projects (e.g., roads, mines, community infrastructure) are environmentally damaging or ineffective because they do not take these basic hydrogeomorphic forms and processes into account.

Chapter Four: Determining Suspended Sediment Production and Yield From An Alluvial Gully: Empirical and Theoretical Approaches

4.1 Introduction

Numerical modelling of gully evolution (e.g., Bull and Kirkby 1997; Sidorchuk 1999; Kirkby et al. 2003; Kirkby and Bracken 2009) and distributed soil erosion and water/sediment yield (e.g., Hessel and van Asch 2003; Jetten et al. 2003; Stolte et al. 2003; Yu 2005) have become popular to advance the theoretical understanding of physical erosion processes within gullies. However this recent push toward theoretical modelling should not be at the expense of the ongoing collection of field-based empirical data that are at the foundation of scientific observations in hydrology and geomorphology (Silberstein 2006), especially in empirically data poor regions of the world. Ideally, observational data and theoretical modelling should be used in concert, but not solely for model calibration per se. Rather, different data sets and modelling tools can be used to test the same hypotheses and advance our process-based understanding of the complex array of geomorphic forms of erosion. The purpose of this chapter was to combine both empirical and theoretical approaches to further our basic understanding of erosion and sediment transport processes with an alluvial gully in northern Australia. It builds off a more regional investigation of the hydrogeomorphology of alluvial gully erosion (Chapter Three).

Alluvial gullies are incisional fluvial features entrenched into alluvium typically not previously incised since initial deposition (Chapter Two; Brooks et al. 2009). Alluvial gullies have been inconsistently described and quantified in the literature as valley-bottom gullies, bank gullies, ravines, fan and finger gullies, and alluvial breakaways depending on their location in Australia (Simpson and Doutch 1977; Payne 1979; Condon 1986; Pickup 1991; Pringle et al. 2006; Brooks et al. 2008; 2009; Chapter Two) or around the world (Brice 1966; Piest et al. 1975; Haigh 1984; Poesen 1993; Singh and Dubey 2000; Vandekerckhove et al. 2000; Oostwoud Wijdenes and Bryan 2001; Yadav and Bhushan 2002). Only a handful of key studies have empirically quantified sediment yields or erosion processes from alluvial gullies over time (e.g., Piest et al. 1975; Bradford and Piest 1980; Thomas et al. 2004; Singh and Dubey 2000; Oostwoud Wijdenes et al. 2000; Oostwoud Wijdenes and Bryan 2001; Vandekerckhove et al. 2001; 2003). This is in contrast to the abundant literature on sediment yield from hillslope, colluvial or ephemeral gullies or soft-rock badlands (e.g., citations within Prosser and Winchester 1996; Poesen et al. 2003; Poesen et al. 2006). Preliminary data in the Mitchell catchment suggest that alluvial gullies are likely *the* major sediment source (Brooks et al. 2008;

Rustomji et al. 2010; Chapter Six). However, the dearth of empirical data and theoretical models on erosion and sediment yield from these features confounds the creation of robust sediment budgets for the large savanna rivers of northern Australia where alluvial gullies are widespread.

4.1.1 Study objectives

To further the understanding of alluvial gully erosion, the specific objectives of this research were to 1) empirically measure sediment supply and yield over various time scales from a rainfall-dominated alluvial gully, 2) utilize theoretical models of erosion and sediment transport to elucidate the physical processes influencing sediment transport and yield, and 3) compare empirical and theoretical estimates of sediment yield to improve future measurement and modelling of alluvial gully erosion at the local and landscape scale. It was hypothesized that transport-limited conditions (*sensu* Bravo-Espinosa et al. 2003) predominate along the outlet channels of alluvial gully complexes, in contrast to supply-limited conditions (*sensu* Bravo-Espinosa et al. 2003) immediately at and above gully head scarps. Where conditions are partially or fully transport-limited, sediment transport could be modelled by theoretical equation(s) such as those of Bagnold (1966) and Rose (1993), which predict the maximum equilibrium sediment concentration at the transport limit during specific discharge conditions.

4.2 Methods

4.2.1 Study catchment

The WPGC2a gully catchment is located in northern Queensland, Australia (-16°28’16”, 143°46’36”; see Figure 3-1). It is one alluvial gully of thousands delineated (>129 km^2) and described by Brooks et al. (2008; 2009; Chapter Two) on the Mitchell River fluvial megafan. The regional climate, hydrology, land use, megafan geomorphology, and floodplain soils are described elsewhere (Brooks et al. 2009; Chapter Two; Chapter Three). The larger study catchment (WPGC2) is representative of floodplain alluvial gullies where rainfall and runoff dominate erosion, with only infrequent river backwater and overbank inundation (Chapter Three).

WPGC2a has an internal gully area 7.8 ha of exposed soils below the head scarp, and a 33 ha catchment surface area (Figure 4-1). It is one tributary catchment of a large complex of alluvial gully erosion (~100 ha) that erodes into the high-floodplain of the Mitchell River 1 to 2 km from the river thalweg (see Figure 3-3a in Chapter Three). These gullies initiated near the relatively steep banks of the river macro-channel and progressed into un-channelled hollows or featureless high floodplains after European settlement and cattle introduction circa 1880-1900 (Shellberg et al. 2010; Chapter Six).

The alluvial silt/clay soils of WPGC2a are situated on a gradient of coarser, lower, and more active floodplain surfaces towards the Mitchell River (sands and gravels capped by silt) and finer, higher, and older floodplains distally, which WPGC2a is actively eroding into. These later Pleistocene red- and yellow-earths are dense in bulk (> 1800 kg/m^3), hard-setting, slightly alkaline at depth, and sodic (ESP > 6) (Chapter Three). They are highly prone to soil dispersion, loss of the thin A-horizon, scalding, and reduction of infiltration capacity, which results in surface and gully erosion. The only partial protection these soils have from the tropical elements, when un-vegetated, comes from patchy surface lags of pisoliths of ferricrete and calcrete, which readily form on the surface of exposed gullies after initial soil mottles and solutes permanently oxidize.

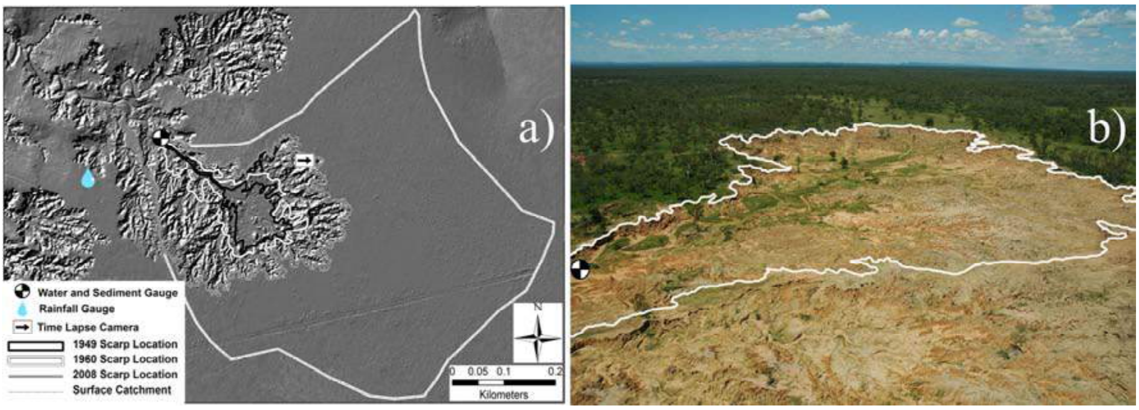


Figure 4-1 a) Planform map with LiDAR hillshade showing the surface catchment area and key gully features, and b) oblique overview of WPGC2a catchment with gully scarp boundary highlighted.

4.2.2 Gully area change

The alluvial gully front or scarp location around WPGC2a was surveyed annually between 2006 and 2010 using a differential global positioning system (GPS) with ±50 cm accuracy (Trimble with Omnistar HP). Georeferenced air photographs from 1949 and 1960 were used to estimate historic scarp locations (±2 m) and changes over time.

Light Detection and Ranging (LiDAR) topographic data were collected in 2008 and used to create a 1 m^2 ground-surface digital elevation model (DEM) (Figure 4-1a). To estimate the pre-gully erosion surface, an inverse distance weighted (IDW) algorithm (power 2; 500 point search radius) was used to interpolate across the eroded gully from elevation data at uneroded points along the external perimeter and internal pedestals. The gully volume was calculated by subtracting the LiDAR DEM elevations from the interpolated pre-gully surface elevations. Earlier gully volume estimates (1949, 1960, 2006, 2007) were similarly calculated, but the DEMs were clipped to gully area extent for those periods. This method assumes a vertical head scarp, complete export of sediment, and no changes in gully floor storage, which are first order assumptions for a gully eroding into dispersible silts and clays. Additional volume changes into 2009 and 2010 were estimated from the measured area change times a measured 1.5 m average scarp depth.

For more detailed change detection, a digital time-lapse camera was used to take daily photographs between 2008 and 2010 to quantify daily gully head scarp retreat and internal erosion processes at a small sub-section of active scarp (Figure 4-1a). Scarp change quantification methods from time-lapse photos are described in Chapter Three (Section 3.3.9), as are comparisons between daily scarp retreat and daily rainfall metrics (Section 3.4.2).

4.2.3 Hydrological measurements

Rainfall was measured at WPGC2a with an automated tipping bucket (0.2mm per tip) during water year (October to September) WY 2009 and WY 2010, from which daily and annual rainfall metrics were calculated (Chapter Three; Section 3.3.10). A continuous water stage (H) gauge was operated at 15 min intervals in a semi-confined sand-bed channel reach at the bottom of the WPGC2a (Figure 4-1; Figure 4-2). This gauge is located just upstream of known Mitchell River backwater conditions during major overbank floods, measured by a lower stage recorder (Chapter Three). Thus, water sources in WPGC2a are dominated by direct rainfall, rainfall runoff, and possibly seepage of soil water at gully scarps.

Measurements of discharge (Q) were made on the rising and falling stages of several flood events using standard methods, along with indirect estimates of Q using slope-area techniques (Rantz 1982). Before, during, and after each wet season, elevation cross-sections, thalweg profiles, and peak flood marks were surveyed over a distance greater than 10 channel widths. A 1-D HEC-RAS hydraulic model (Brunner 2010) was created for the reach for several slightly different boundary conditions. The model was calibrated using direct H and Q measurements. Calculated composite Manning’s n roughness values (~0.035) were used in the model to predict discharge values at high stages. H-Q rating curves were using both measured and modelled data. Errors in Q from current meter measurements were taken as ±10% while slope-area estimates were ±20%.

Figure 4-2 Cross-section at WPGC2s gauge station during the a) dry season, and b) wet season.

4.2.4 Sediment load definitions

Fundamental to any sediment erosion/yield research is the definition of how sediment load is transported, measured in the field, and modelled, by source or mode of transport (Knighton 1998; Hicks and Gomez 2003):

- Total particle load = bedload + suspended load (i.e., load by mode of transport)
- Total particle load = bed material load + washload (i.e., load by source)

For load by source, here we adopted the arbitrary but frequently used washload cut-off of 63 μm (sand vs. silt/clay) due to the fine texture of alluvial gully soils and supporting data presented below. For load by mode of transport, we used the near-bed "unsampled zone" below the measurement reach of a depth-integrated suspended-sediment sampler (US DH-48) to define the bedload transport zone, which was < 9 cm above the bed. During this study, both washload and suspended load were empirically measured and theoretically modelled, while bedload transport was only theoretically modelled.

4.2.5 Empirical estimates of suspended load

Due to the remote location, single-stage suspended-sediment samplers (U.S. U59C; Colby 1961) were installed across a cross-section at staggered elevations, in order to automatically collect suspended sediment concentration (SSC) samples from specific points in the cross-section during different stage conditions during WY 2009 and WY 2010 (Colby 1961; Edwards and Glysson 1998). Additional width- and depth-integrated samples of average SSC were collected manually by wading on the rising and falling stages of several flood events in WY 2010 using a US DH-48 SSC sampler and the equal-width-increment method (Edwards and Glysson 1998). All samples were analysed using the SSC analysis protocol of the total sample volume via evaporation and dissolved salt correction (ASTM 2002), which avoided negative sand biases associated with sub-sampling (i.e., TSS protocol; Gray et al. 2000). Error in SSC laboratory measurements were taken as ±1%.

Sediment loads components were calculated as the product of Q and SSC, where SSC was predicted from Q-SSC rating curves and Q predicted from H-Q curves for discrete time intervals. The total standard error (δ_T) relative to the component sediment load ($\overline{T}$) was calculated as:

$$\frac{\delta_T}{\overline{T}} = \sqrt{\left(\frac{\delta_Q}{\overline{Q}}\right) + \left(\frac{\delta_{SSC}}{\overline{SSC}}\right) + \left(\frac{\delta_{Q \propto H}}{\overline{Q \propto H}}\right) + \left(\frac{\delta_{SSC \propto Q}}{\overline{SSC \propto Q}}\right)} \quad (4\text{-}1)$$

where δ_Q is the standard error in field Q measurement using either current meter methods (WY 2010, $\delta_Q / Q = 0.10$) or slope-area methods (WY 2009, $\delta_Q / Q = 0.20$), δ_{SSC} is the laboratory error in SSC measurement ($\delta_{SSC} / SSC = 0.01$), $\delta_{Q \propto H}$ is the standard error between the H and Q relationship, and $\delta_{SSC \propto Q}$ is the standard error between the discharge and SSC relationship.

4.2.6 Particle size distributions

4.2.6.a.1 Suspended load

SSC samples collected during flood were sieved at 63 μm to determine the percent sand (>63 μm) and silt/clay (< 63 μm) contributions to the total suspended sediment concentration, and bed material load and washload respectively. More detailed particle size distributions were measured in duplicate on SSC samples collected during width- and depth-integrated sampling, using a Coulter Multisizer following the methods of McTainsh et al. (1997). For particles between 1 μm and 256 μm, a four tube Coulter Multisizer analysis was conducted, while the % of total sediment by dry weight >256 μm was measured by wet sieving. These SSC samples were already dispersed (disaggregated) due to the naturally high soil dispersibility and stream turbulence along flow paths. However, samples were potentially further dispersed during the SSC particle size splitting and then the Coulter analysis, which utilized sodium hexametaphosphate as a liquid electrolyte.

4.2.6.a.2 Washload and bed material load

For the coarse bed material load sourced from the sand-bed channel near the gauge (Figure 4-1), the particle size distribution was measured from bulk samples (>1 kg) using gentle wet sieving at whole phi intervals down to 38 μm. For finer washload sediment sources originating from the silt/clay soils at gully scarps, the Coulter Multisizer and sodium hexametaphosphate were again utilized to ensure comparability with the suspended sediment particle size analysis above. From these washload sediment *source* areas, nine sediment samples from three vertical scarp profiles and three depths (30, 100, 200 cm) were analysed. Duplicate analyses were conducted to ensure consistency of results. The average particle size distribution of all samples was used to characterize washload sediment sourced from gully scarps. Additionally, one sample from the surface of an actively accreting gully inset-floodplain near the gauge was used to quantify the size distribution of recent deposition.

4.2.7 Modelling load by mode of transport (suspended load + bedload)

4.2.7.a.1 Theoretical total suspended load

Theoretical total suspended sediment load was estimated using the theory of equilibrium sediment concentration at the transport limit, as adapted from Rose (1993) and supported by theory in Bagnold (1966). The theoretical suspended concentration (c_s) at the transport limit achieved in an open channel is an outcome of the magnitude of the two competing rate processes, erosion and deposition, regardless of particle source:

$$c_s = \frac{F_s \rho_w \rho_s S V_w}{\phi_s (\rho_s - \rho_w)} \qquad (4\text{-}2)$$

where F_s is the fraction of the stream power used for suspended load transport (similar to Bagnold's (1966) efficiency term e_s), ρ_s is the average density of eroding soil particles (measured at WPGC2a as 2600 kg/m^3), ρ_w is the density of water (997 kg/m^3 at 25°C), S is channel slope (0.0051 m/m), V_w is average cross-section water velocity, and ϕ_s is the mean settling velocity of particles travelling in suspension. In this case where discharge (Q) and cross-section area (A) have been estimated via gauging at specific time intervals, average velocity can be estimated from $V_w = Q / A$. Total suspended sediment load was calculated as the product of theoretical c_s and measured Q. Initially the fraction F_s was unknown, but could be assumed to be ~ 0.015 (Bagnold 1966). However here, we solved for F_s by either 1) minimizing the difference between total empirical and theoretical suspended sediment loads for a two day test period and over the two water years, or by 2) minimizing the difference between the instantaneous empirical (c_e) and theoretical concentrations (c_t) for each 15-minute time step of the model.

Since particles transported in suspension are derived *both* from washload sourced from upstream eroding gully scarps and local temporarily suspended bed material, the particle size distributions (and thus settling velocity distributions) of neither the bed material nor the washload source material are independently representative of the mean settling velocity of particles in suspension. Therefore, full particle size distributions of several suspended sediment field samples collected at varying discharges were measured using the Coulter Multisizer. These particle size distributions were converted to settling velocity distributions using a combination of Stokes' Law (dia < 100 μm) and relationships in Cheng (1997) (dia > 100 μm), from which ϕ_s was determined. An empirical exponential model was used to correlate ϕ_s to Q and thus continuously predict ϕ_s in Equation 4-2. Subsequently, three different model setups were used with different methods of estimating the parameters F_s and ϕ_s in equation 4-2.

- Setup 1: Varied $\phi_s \propto Q$ for each 15-minute time step and calculated F_s by minimizing the empirical and theoretical load differences for the test period and each water year.
- Setup 2: Varied $\phi_s \propto Q$ for each 15-minute time step and calculated F_s for each 15-minute time step by minimizing the instantaneous concentration difference between theoretical and empirical estimates. Calculated an overall $\overline{F}_s$ and standard deviation δ.
- Setup 3: Used a constant ϕ_s calculated as the mean settling velocity of particles < 150um originating from gully scarp soils. Suspended particles were predominantly < 150 μm during moderate discharges, with 90% of the particles < 150 μm at ~ 1.0 m^3/s (Figure 4-7). Calculated F_s by minimizing the empirical and theoretical load differences for the test period and each water year.

For each setup, model performance was assessed using the discrepancy ratio (Yang 1991):

$$R_i = \frac{c_t}{c_e} \tag{4-3}$$

where c_t is the theoretical modelled sediment concentration, c_e is the empirically estimated sediment concentration, and R_i is the ratio at each hydrograph time step (15-min). The average ($\overline{R}$) and standard deviation (σ) of all discrepancy ratios (R_i) were used for overall model assessment.

4.2.7.a.2 Theoretical bedload (NOT ANALYSED)

Modelling theoretical bedload transport of sand particles along the bed was not conducted due to a lack of empirical bedload transport data collected in the field for comparison to theoretical estimates. However interest and effort in modelling sand bedload transport in alluvial gullies are ongoing with co-authors, along with the potential future collection of field bedload transport data from gullies. It is possible using similar theories of equilibrium sediment transport to estimate the concentration of sand particles in motion in the bedload layer (Bagnold 1973; Bridge and Dominic 1984). Methods are also available to estimate bedload grain velocities (Bridge and Dominic 1984; Tang and Yang 2009). Model estimates of bedload concentration and velocity can be coupled with estimates of bedload layer thickness and bed width to estimate the total bedload. In addition, the modelled concentration of sand particles in motion in the bedload layer can be used as a reference concentration in well known exponential equations

(Dingman 1984) which can predict the concentration of suspended bed sediment at any point in a water profile if shear velocity and particle setting velocity characteristics can be estimated. These modelled estimates can then be compared to measured data of suspended and bedload sediment transport.

4.2.8 Modelling load by source (washload + bed material load)

4.2.8.a.1 Theoretical washload

The theoretical washload (<63 μm) concentration (c_w) at the transport limit can also be related to the equilibrium between erosional and depositional forces by the equation:

$$c_w = \frac{F_w \rho_w \rho_s S V_w}{\phi_w (\rho_s - \rho_w)} \tag{4-4}$$

where F_w is the fraction of the stream power used in washload transport, ϕ_w is the mean settling velocity of washload particles <63 μm originating from the gully scarp, and the other parameters previous defined. Total washload was calculated at the product of c_w and Q. An alternative washload model has been formulated by Land and Nichols (1997); however their formula is almost functionally, but not structurally, identical to Equation 4-4 since both draw off principles in Bagnold (1966).

For washload, ϕ_w should be defined by particles sufficiently fine that they do not participate in bed material transport. In contrast to ϕ_s, it is reasonable to assume that ϕ_w does not change appreciably with Q, as this material is abundant at all runoff conditions from highly dispersible and erodible gully soils. Thus, the average particle size distribution of gully scarp soils was truncated at 63 μm to only represent smaller particles that travel as washload. This distribution was converted to a settling velocity distribution using Stokes' Law, from which ϕ_w was determined.

The fraction F_w of the streampower used to transport fine washload sediment < 63 μm was unknown, but assumed to be < 0.015 (Bagnold 1966). However, F_w was solved by minimizing the difference between empirical and theoretical washload concentrations (< 63 μm) for the test period and both water years. Again, average discrepancy ratios ($\overline{R}$) were used for model assessment.

4.2.8.a.2 Theoretical total bed material load

For a theoretical estimate of the total bed material load (bedload + suspended bed material), the empirically-calibrated equations of Yang (1973) and Ackers and White (1973) were employed.

These models estimate the average bed material load concentration, regardless of transport mechanism of bed material along the bed or in suspension. Again, the empirical H-Q relationship and cross-section data were used to estimate hydraulic parameters in the models at discrete time intervals, along with Q for load estimation in conjunction with modelled concentrations. The full particle size distribution of bed material was used to estimate a median (d_{50}) particle size, in addition to using Stokes Law (dia < 100 μm) and equations in Cheng (1997) (dia > 100 μm) to estimate mean settling velocity.

4.3 Results

4.3.1 Gully area change

The area of WPGC2a increased 7.6 times its initial 1949 size by 2010 (Figure 1-1a; Table 4-1). The trend in area was linear ($r^2 = 0.99$), but the relationship is weakened by lack of data between 1960 and 2006. Recent GPS survey data at WPGC2a continued to measure increased area growth at the annual scale, but area error margins often overlapped (Table 4-1). This uncertainty was a result of survey error (±50 cm) and overlap along slowly retreating inter-lobe zones of the scarp, compared to more active concave lobes (in planform) where distinct annual change was evident (Figure 4-3). However over longer decadal scales, the entire gully scarp eventually retreated as one front as active lobes merged, disconnected interfluves were abandoned, and these remnant pedestals weathered in situ.

As gully area expanded, the perimeter of the active scarp also increased, but the ratio of area to perimeter did not stay constant. The mean retreat rate (area/perimeter) and mean depth (volume/area) subsequently decreased, as the perimeter expanded in a tortuous fashion and the erosion wedge (and scarp height) decreased, respectively. However gully volume continued to increase at a linear rate ($r^2 = 0.99$), suggesting that changes in area likely dominate volumetric sediment yield if the volumetric calculation assumptions are true. The estimated scarp erosion yield (t/yr) decreased over time, but these trends are influenced by the overlapping error margins around recent GPS data. When only the 1949, 1960, and 2008 air photos are used over much longer time intervals, along with the 2008 LiDAR data for volume calculation, the estimated long-term sediment yields overlap within error margins (Table 4-1). These yield data provide an order of magnitude estimate of sediment production at the gully scarp to compare to gully gauge data.

Table 4-1 Changes in WPGC2a gully parameters over time above gauge location.

Year	**Area (m^2)#**		**Perimeter (m)**	**Mean Retreat (m/yr)**	**Max Retreat (m/yr)**	**Gully Volume (m^3)**	**Mean Gully Depth (m)**	**Tonnes/yr Scarp Erosion*** w/ Recent GPS Data	**Tonnes/yr Scarp Erosion #*** Long-Term Photos Only		**Annual Rainfall (mm)$**
1949	10,491	12,726 8,256	1,137	---	---	36,166	3.44	---	---		---
1960	21,641	24,398 18,884	1,391	0.80	3.50	68,203	3.15	5,926	5,926	8,959 2,893	986
2006	77,071	78,548 75,593	3,100	0.54	2.51	172,153	2.23	4,599	---		952
2007	78,139	79,699 76,579	3,257	0.34	10.26	174,444	2.23	4,664	---		1,037
2008	78,506	80,263 76,750	3,694	0.11	4.88	175,788	2.24	2,736	4,561	5,096 4,026	1,217
2009	79,391	81,188 77,594	3,788	0.24	6.50	177,707	2.24	3,903	---		1,235
2010	80,106	81,810 78,402	3,671	0.19	0.96	179,137	2.24	2,911	---		590

upper and lower area error margins are ± 2m historic and ±50 cm recent, which also translates to error in estimated scarp erosion.
***** site average bulk density of 2035 kg/m^3.
$ rainfall data for WY 2008-2010 were measured at WPGC2a; WY 2007 data were estimated for WPGC2a from Australian Bureau of Meteorology (ABOM) monthly interpolated 5-km (0.05°) gridded rainfall data, while the average ABOM rainfall was calculated for the periods WY 1950-1960 and WY 1961-2006.

Daily delineation of scarp locations from photographs (see Chapter Three Section 3.4.2) demonstrated that the total scarp retreat was the cumulative sum of numerous and variable daily changes over each wet season, most often as discrete failures of overhanging soil blocks. Both direct rainfall and infiltration-excess runoff dominated scarp retreat. Shallow overland flow from the vegetated floodplain above the scarp was relatively clear compared to the turbid water runoff following erosion on the scarp face. Oblique changes in area, corrected to planform area, showed strong correlations to 24-hr rainfall total ($r^2 = 0.77$) (Chapter Three; Figure 3-10a), as well as other rainfall metrics (Table 3-3). Detectible changes in scarp location did not occur until the 24-hr rainfall exceeded 10 to 20 mm (Figure 3-10a).

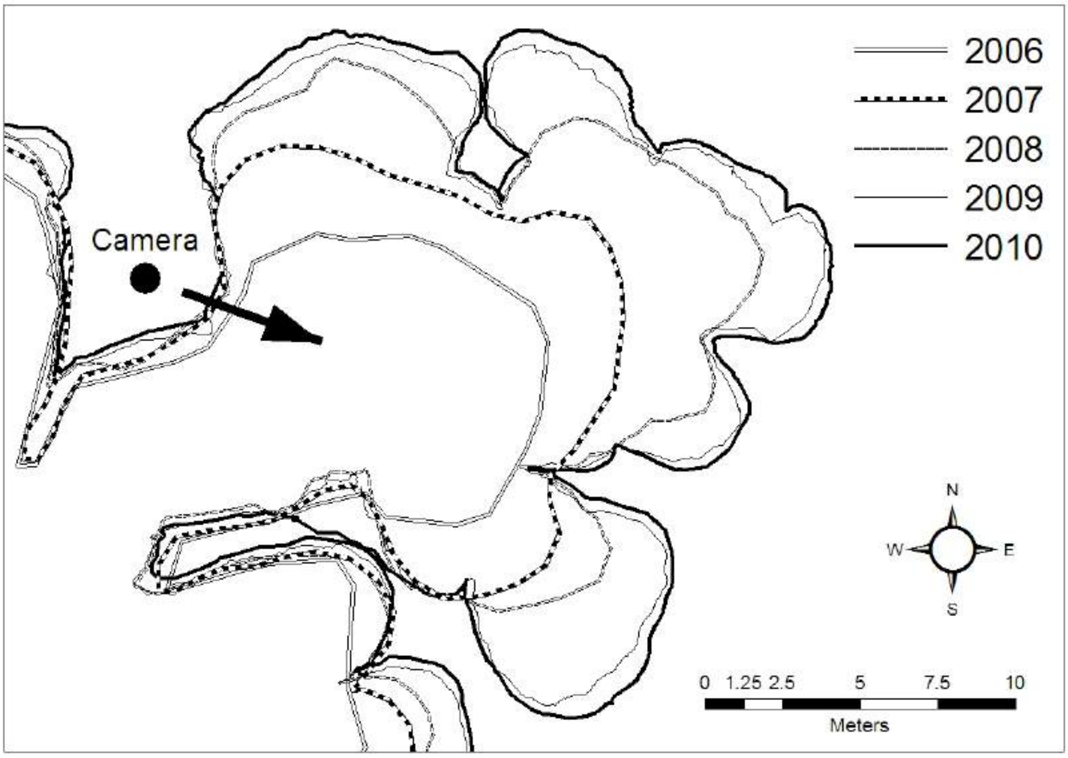


Figure 4-3 Gully planform area change measured with GPS at the time-lapse camera index site (see Figure 4-1a for location).

4.3.2 Empirical estimates of suspended load and washload

Rating curves of stage vs. discharge for WY 2009 and WY 2010 (Figure 4-4), estimated that peak Q during WY 2009 exceeded 1.5 m^3/s while WY 2010 peaks were typically less than 1.0 m^3/s (Figure 4-5). Peak events commenced rapidly following intense convective rainfall, with typical durations of 2 hours. Rainfall and runoff volumes in WY 2010 were approximately half that of WY 2009, with runoff coefficients one-quarter of rainfall input to the surface catchment (Table 4-3).

SSC data collected during 2009 and 2010 using both single-stage samplers and a depth-integrated sampler were pooled together to form one rating curve for silt/clay (<63 μm) and one for suspended sand (>63 μm) (Figure 4-4). Single-stage samplers that collected near-surface water samples had SSC values similar to width- and depth-integrated samples, suggesting that suspended sediment was well mixed through the cross-section during turbulent flood conditions (Figure 4-2b). Total SSC values during runoff events consistently exceeded 10,000 mg/L and peaked greater than 100,000 mg/L. These concentrations are 1 to 2 orders of magnitude more than peak concentrations measured in the nearby Mitchell River during floods (~1,000 mg/L). In WPGC2a, washload (silt/clay <63 μm) dominated total SSC and values remained high for low discharges and only varied over one order of magnitude. Suspended bed material (sand > 63 μm) increased more rapidly with discharge, spanned three orders of magnitude, and was a larger contributor to total SSC during the highest discharges (i.e., 10-20%) (Figure 4-4).

Empirical total suspended sediment load estimates for WY 2009 and WY 2010 (Table 4-3) were dominated by washload <63 μm (84.5% and 90.0%) from the fresh erosion of bare gully surfaces. The contribution of suspended bed material >63 was low at ~ 10-15% of the total suspended load. In partial contrast, the particle size distributions of suspended sediment during individual flood events (Figure 4-7) suggested that 5 to 40% of the suspended sediment was coarser than 63 μm. However on average over the period of record, the cumulative sum of smaller events resulted in a lower coarse sediment contribution of 10-15%, on average.

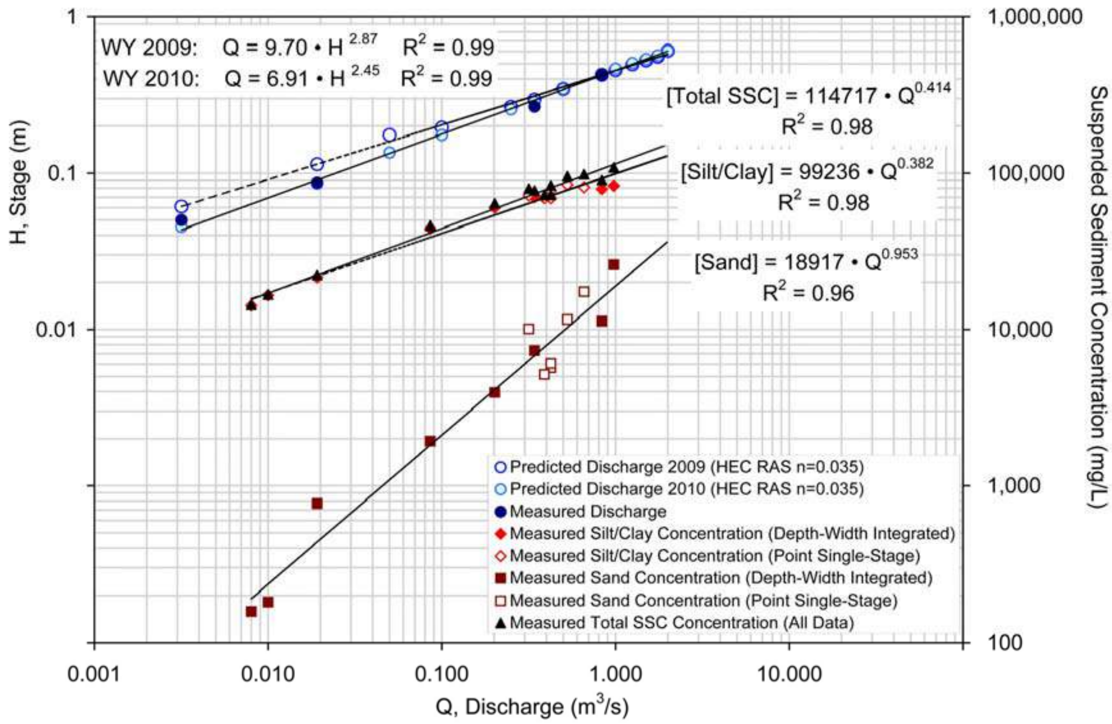


Figure 4-4 Rating curves at gauge station between 1) stage (H) and discharge (Q) for WY 2009 and 2010, 2) Q and suspended silt/clay concentration, 3) Q and suspended sand concentration, and 4) Q and total suspended sediment concentration (SSC) for both years combined.

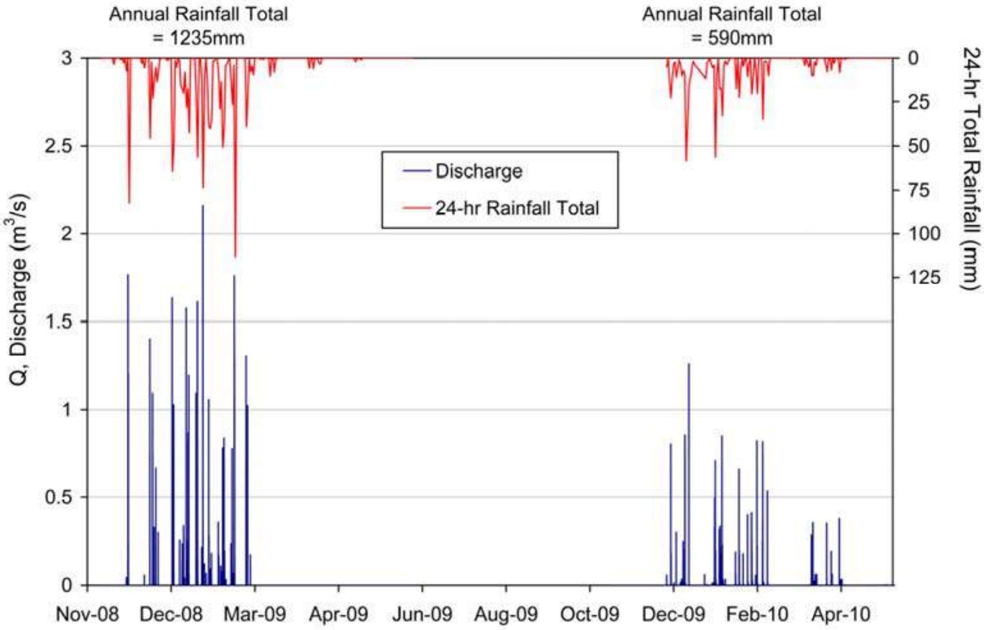


Figure 4-5 Measurements of discharge and rainfall over study period.

Correlations between 24-hr total rainfall and daily suspended sediment yield (Figure 4-6) suggested that the export of suspended sediment was intricately linked to the input of rainfall and resultant runoff. This is supported by photographic measurements of sediment supply from daily scarp retreat that were linearly correlated to 24-hr rainfall totals (Chapter Three; Figure

3-10a). However, 24-hr rainfall total is just a proxy for a suite of internal erosion processes that vary with time and rainfall magnitude. For example, below rainfall thresholds for scarp retreat (> 10 to 20 mm; Figure 3-10a), direct particle detachment from rain drops and erosion from overland flow still contributed to measureable sediment yield above a ~ 3 mm threshold (Figure 4-6). These smaller rainfall-runoff responses were more variable due to water and sediment measurement error at extremely low discharge, possible existence of unmeasured hysteresis in Q-SSC rating curves, and/or variability in rainfall intensity and erosion effectiveness.

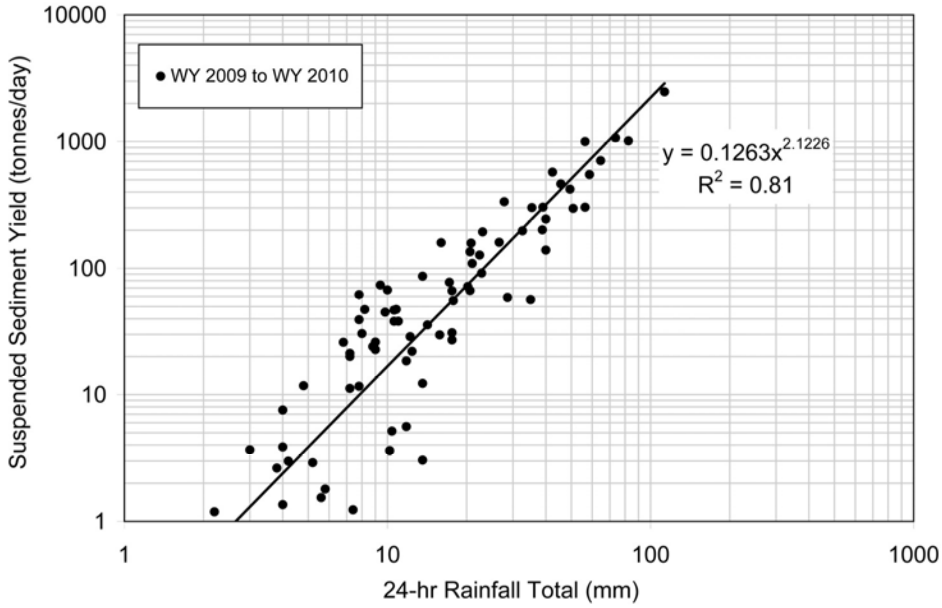


Figure 4-6 Relationship between local 24-hr total rainfall and daily suspended sediment yield at the catchment outlet, estimated from H-Q-SSC rating curves in Figure 4-4 for WY 2009 and WY 2010.

4.3.3 Particle size and settling velocity analysis

The particle size distribution of local bed material (wet sieving) provided some support for the 63 μm value used as a cut-off between washload and suspended-bed-material load (Figure 4-7), where only ~10% of the bed material was less than 63 μm. Additionally during small runoff events when turbulent suspension of sand bed material load was not active in the outlet channel, ~95% of the sediment washed off gully surfaces and transported in suspension was < 63 μm (Coulter analysis)(Figure 4-7).

In comparing particle size results from the Coulter analysis and basic wet sieving during SSC analysis, some inconstancies became apparent for samples where sand was common. For the SSC sample at 0.97 m^3/s, the wet sieve split at 63 μm before SSC analysis indicated that ~ 25% of the sediment was coarser than 63 μm (Figure 4-4), while the Coulter analysis suggested that ~ 40% was coarser than 63 μm (Figure 4-7). Intuitively the Coulter analysis should result in reduced coarse sediment due to additional aggregate dispersion; however the opposite was true. Despite consistent results from duplicate samples for Coulter analysis, these inconsistencies in different methodologies are likely a result of 1) sand bias during Coulter sub-sampling (several water drops from over 150 mL of water during intense stirring) and 2) the degree and length of washing samples during wet sieving. While additional repeat analyses will be needed to uncover sources of bias, the results here were internally consistent by method and useful for basic analyses.

The average particle size distribution of soils from the gully head scarp (Coulter analysis) estimated 60% of the sediment was finer than 63 μm and 40% coarser (Figure 4-7). Soils of gully inset-floodplains were coarser, indicating the preferential deposition of sand in these environments. During peak runoff (~1.0 m^3/s), the particle size of suspended sediment closely matched the average distribution of scarp soils (Figure 4-7). This suggests a direct and inherent connection at the event scale between head-scarp sediment supply and sediment transport in the outlet channel 600 m away. Coarse lags of sand (>63 μm) on the gully floor and outlet channel were also suspended during these larger events. During smaller discharges, suspended particle sizes lowered toward the fine silt fraction, during which average settling velocities reduced below 0.0005 m/s and water remained concentrated with fine suspended particles (Figure 4-7; Figure 4-8).

The relationship between Q and ϕ_s followed an exponential trend over the measurement range up to 1.0 m^3/s (Figure 4-8), with an transition above 0.8 m^3/s as progressively more sand bed material > 63 μm became suspended. This exponential relationship was used in Equation 4-2 to model suspended sediment load as a function of Q at 15-minute intervals (Model Setup 1 and 2; Table 4-3). Due to the lack of SSC samples at discharges > 1.0 m^3/s such as during WY 2009, this relationship was only used for WY 2010 when most discharge events were < 1.0 m^3/s (Figure 4-5). Additional sampling will be needed to define ϕ_s for Q > 1.0 m^3/s. It is hypothesized that the particle size distribution of the bed material (Figure 4-7) will represent the maximum range of potential suspended sediment, which when converted to settling velocities has a ϕ_s of 0.032 m/s. Alternatively, additional soil detachment/failure from the gully scarp during extreme events could dilute suspended-sand bed-material and keep ϕ_s closer to that of the average scarp soil (Figure 4-7), which equates to 0.00876 m/s (Table 4-2).

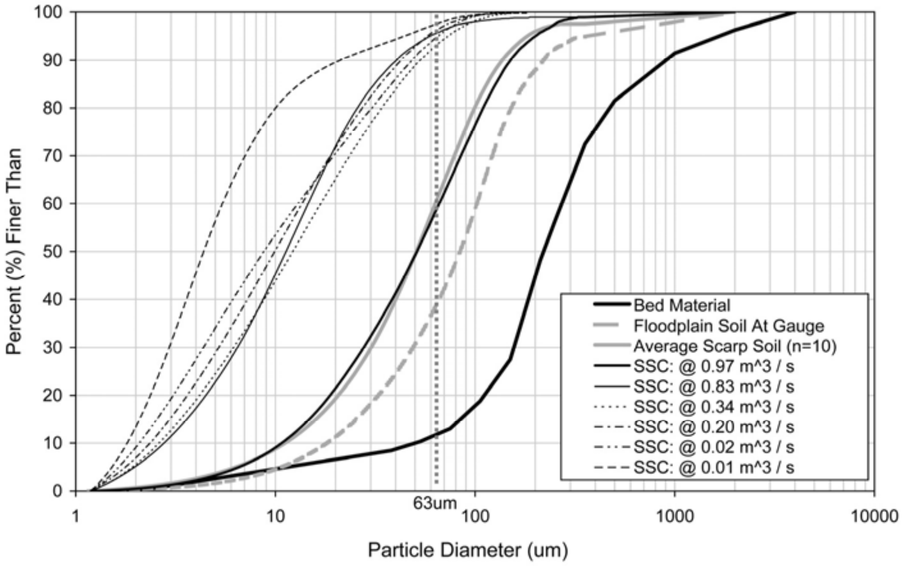


Figure 4-7 Particle size distributions measured using a Coulter Multisizer for fine soil and suspended sediment material and wet sieving for channel bed material.

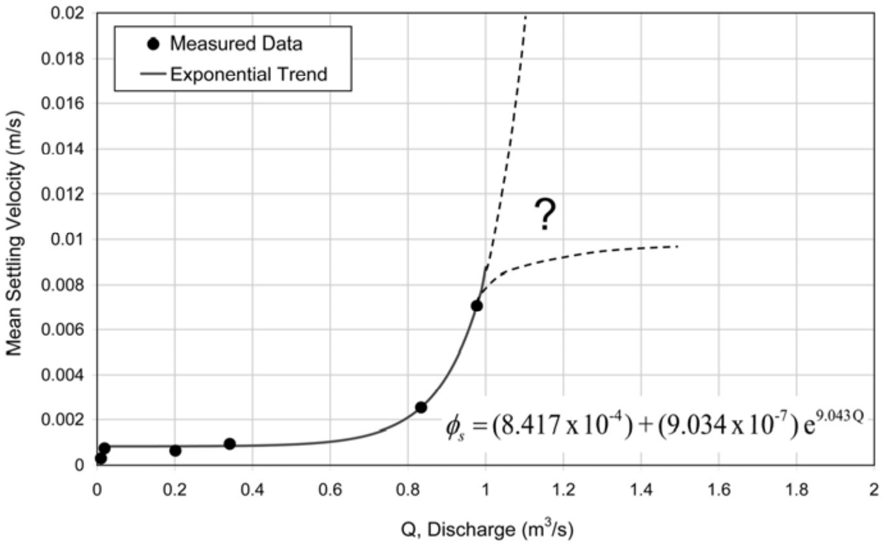


Figure 4-8 Empirical relationship between measured discharge (Q) and the measured mean settling velocity (ϕ_s) of suspended sediment during several flood events in WPGC2a, *without* extrapolation of the trend beyond 1 m^3/s due to a lack of supporting empirical data.

Table 4-2 Estimated mean settling velocities (ϕ_s) for different source material calculated by converting particle size distributions to settling velocity distributions using a combination of Stokes' Law (diameter < 100 μm) and relationships in Cheng (1997) (diameter > 100 μm).

Source Material	**Mean Settling Velocity, ϕ**	**Use**
Average Gully Scarp Soils (Full Distribution)	0.00876 m/s	N/A
Average Gully Scarp Soils (< 150 μm)	0.00347 m/s	Suspended Sediment Model Setup 3 (Equation 4-2)
Average Gully Scarp Soils (< 63 μm)	0.00125 m/s	Washload Model (Equation 4-2)
Bed Material Load (Full Distribution)	0.032 m/s	Bed Material Load Model (Yang 1973)

4.3.4 Theoretical load estimates compared to field measurements

4.3.4.a.1 Total suspended load

4.3.4.a1.1 <u>*Model setup 1*</u>

The theoretical estimates of suspended sediment load from Equation 4-2, coupled with empirical relations between Q and ϕ_s (Figure 4-8), generally matched empirical load estimates generated from field data (Figure 4-9). For the test period, F_s was optimized to 2.31% by minimizing the total load difference between empirical and theoretical values. Values for WY 2010 were of a similar magnitude (2.14%), while values for WY 2009 were not calculated.

Average discrepancy ratios ($\overline{R}$) suggested reasonable matches for both the test period and WY 2010 (Figure 4-9). R_i ratios greater than unity were due to over predictions of c_s due to under prediction of ϕ_s (Figure 4-8) during the most frequent low- and moderate-discharges (Figure 4-9). During the more infrequent large discharge peaks in WY 2010, R_i ratios were well below unity as a result of high mean settling velocities that were over predicted from Figure 4-8. Since model setup 1 was calibrated to match total loads for a given period by adjusting the fraction of stream power, F_s, to *a single* optimal value, the WY 2010 theoretical load values were balanced by over predicting concentrations at low to moderate discharges (Figure 4-9) and under predicting concentrations at the highest WY 2010 discharges (not shown). These issues were addressed in model setup 2.

4.3.4.a1.2 <u>*Model setup 2*</u>

By calculating F_s for each 15-minute time step and varying $\phi_s \propto Q$, F_s values varied over the calculation period around a mean $\overline{F}_s$ and standard deviation δ, which equalled 1.87% and 1.88% for the test period and WY 2010 respectively (Table 4-3; Figure 4-9). By using this method, the individual and average discrepancy ratios both equalled unity and concentrations and loads perfectly matched in both graphical and tabular forms.

4.3.4.a1.3 <u>*Model setup 3*</u>

As an alternative more simplistic approach, ϕ_s was modelled as constant average value (0.00347 m/s for average scarp soils < 150 μm; Table 4-2). The 150 μm cut-off value was chosen to exclude typical bedload particles and focus on suspended particle sizes dominant during moderate discharges (e.g., > 90% of the particles < 150 μm at 1.0 m^3/s or less, Figure 4-7). Using this approach, F_s values were calculated to be much higher than the previous model setups (1 and 2), at 6.61%, 6.28%, and 6.58% for the test period, WY 2009, and WY 2010 respectively (Table 4-3), with $\overline{R}$ ratios slightly less than unity.

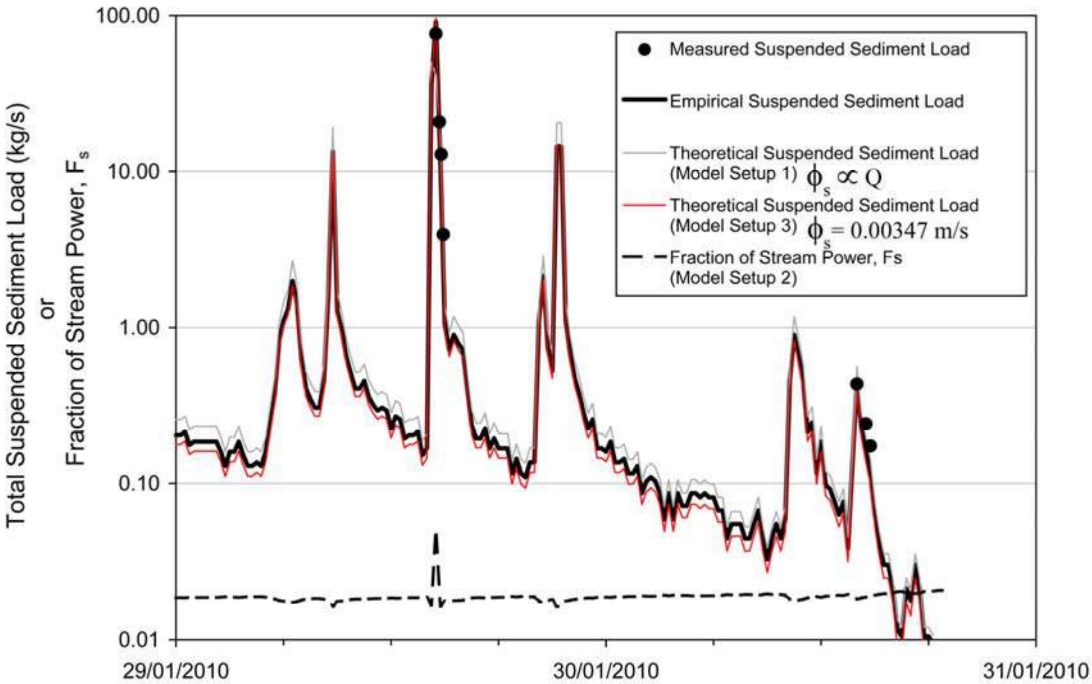


Figure 4-9 Comparison of suspended sediment load (kg/s) estimates from field point measurements, empirical rating curves, and theoretical data (Equation 4-2) for the test period. Fractions of stream power F_s for individual time steps are also shown for model setup 2. Theoretical estimates for model setup 2 are identical to empirical values by calibration design.

Table 4-3 Summary of rainfall and runoff measurements, and empirical and theoretical sediment load estimates from the 33ha catchment of WPGC2a.

	29-Jan-2010 to 30-Jan-2010	**WY 2009**	**WY 2010**
Total Rainfall (mm)	36.6	1235	590
Total Runoff (mm) **(**33 ha surface catchment)	12	327	157
Total Runoff (m^3)	3855	109,213	52,501
Runoff Coefficient	0.33	0.26	0.27
Empirical Total Suspended Sediment Load # Tonnes of Sand/Silt/Clay in suspension	206.1 ±53%	10,931 ±63%	2,823 ±53%
Empirical Washload # Tonnes of Silt/Clay <63 μm in suspension (% total suspended load)	185.8 ±51% (90.2%)	9,241 ±60% (84.5%)	2,542 ±51% (90.0%)
Empirical Suspended Bed Material Load # Tonnes Sand >63 μm in suspension (% total suspended load)	20.3 ±72% (9.8%)	1,690 ±78% (15.5%)	281 ±72% (10.0%)
Theoretical Suspended Sediment, Calibrated, Model 2, Equation 4-2 Tonnes of Sand/Silt/Clay suspended**,**	206.1	10,931	2,823
Model Setup 1 F_s **Fraction Stream Power**, Calibrated Constant Equation 4-2; Varied $\phi_s \propto Q$ in Figure 4-8	0.0231	N/A	0.0214
Model Setup 1 $\overline{R}$ **Average Discrepancy Ratio** (and σ)	1.24 (0.08)	N/A	1.15 (0.08)
Model Setup 2 $\overline{F}_s$ **Average Fraction Stream Power** (and σ) Calculated F_s by discrete time steps, minimizing C_t - C_e Equation 4-2; Varied $\phi_s \propto Q$ in Figure 4-8	0.0187 (0.0026)	N/A	0.0188 (0.0037)
Model Setup 3 F_s **Fraction Stream Power,** Calibrated Constant, Equation 4-2; $\phi_s \equiv 0.00347$ m/s for particles < 150 μm	0.0661	0.0628	0.0658
Model Setup 3 $\overline{R}$ **Average Discrepancy Ratio** (and σ)	0.87 (0.04)	0.92 (0.05)	0.86 (0.05)
Theoretical Washload, Calibrated Constant, Equation 4-4 Tonnes of Silt/Clay <63 μm suspended	185.8	9,241	2,542
F_w **Fraction Stream Power,** Calibrated Constant, Equation 4-4	0.0215	0.0159	0.0214
$\overline{R}$ **Average Discrepancy Ratio** (and σ)	0.78 (0.06)	1.29 (0.19)	0.78 (0.08)
Theoretical Bed Material Load Yang 1973, d_{50} = 220 μm, $\phi_{av} = 0.032$ m/s (% Total Load = Wash + Bed Material Load)	6.6 (3.4%)	623 (6.3%)	93 (3.5%)
Theoretical Bed Material Load Ackers and White 1973, d_{50} = 220 μm (% Total Load = Wash + Bed Material Load)	4.7 (2.5%)	608 (6.2%)	65 (2.5%)

upper and lower standard error margins calculated using Equation 4-1. N/A = not applicable, as the relationship between $\phi_s \propto Q$ (Figure 4-8) was not used for WY 2009 due to a lack of particle size data beyond 1.0 m^3/s.

4.3.4.a.2 Washload

The theoretical estimates of washload for the test period using Equation 4-4 and a constant ϕ_w (0.00125 m/s for average scarp soils < 63 μm; Table 4-2) generally matched theoretical, empirical, and measured values during peak conditions (Figure 4-10) when washload output dominated and was most important. During the test period and WY 2010, washloads during recession and baseflow conditions were underestimated as reflected in $\overline{R}$ ratios less than unity (0.78) (Table 4-3). The $\overline{R}$ ratio for the wetter year WY 2009 was in contrast above unity (1.29), but predictions were still reasonable for instantaneous concentrations. Imperfect matches are possibly due to real subtle changes in ϕ_w with Q, in contrast to a constant mean. However, ϕ_w values for material < 63 μm likely varied less than ϕ_s values (Figure 4-7), due to the definitional lack of episodic and temporary interjections of larger sand size particles from the bed material into suspension.

For the two-day test period, F_w was optimized to 0.0215 by minimizing the total load difference between empirical and theoretical values, while values for WY 2009 and 2010 were 0.0159 and 0.0214 respectively (Table 4-3). These values of F_w are smaller than corresponding F_s values (> 6%) from the comparable model setup 3.

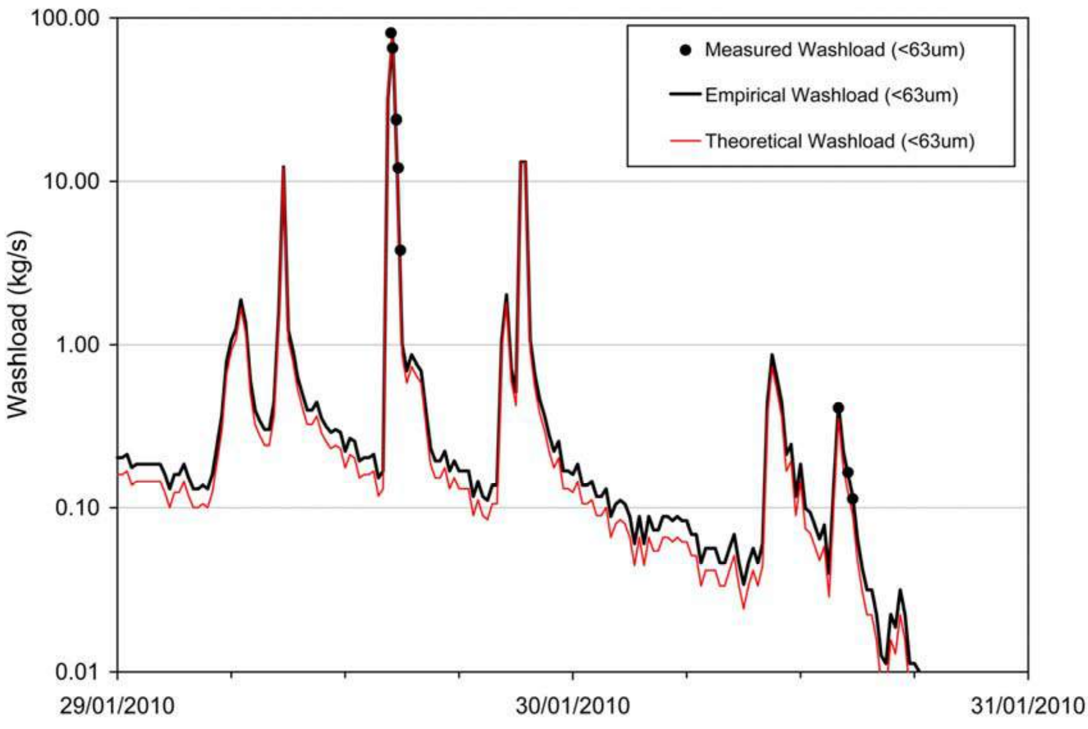


Figure 4-10 Comparison of washload (kg/s) estimates from field point measurements, empirical rating curves, and theoretical data (Equation 4-4) for the calibration period.

4.3.4.a.3 Bed material load

Estimates of total bed material load (bedload + suspended bed material) using methods of Yang (1973) and Ackers and White (1973) generally underestimated the potential total bed material load for WPGC2a. This was indicated by theoretical results for total bed material load that were less than measured and empirical estimates of suspended bed material (i.e., suspended sand > 63 μm) (Figure 4-11). These empirical suspended sand loads did not account for the unmeasured bedload and thus are a minimum (Table 4-3). The use of a median particle size (d_{50} = 220 μm) for the whole bed material load distribution (Figure 4-7) could have influenced these results. It is possible that these results are more representative of pure bedload transport of 220 μm material with little suspension. If the bed-material particle-size distribution was truncated at > 63 μm assuming the washload model accounted for material < 63 μm, this would increase the estimated median particle size and further decrease theoretical bed material load. Using the formula on multiple particle size classes and taking the weighted sum could improve estimates (Yang 1991). Regardless, these initial results provided a theoretical reference value for bed material load using equations often used in the literature for sand bed channels.

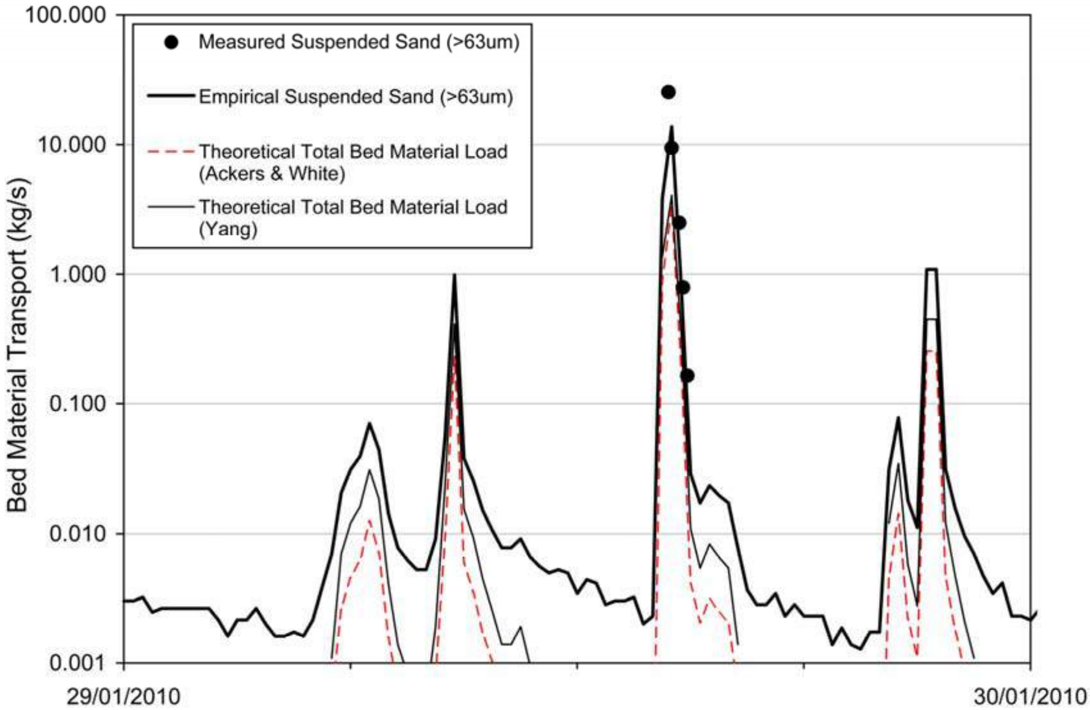


Figure 4-11 Comparison of point measurement and empirical (rating curve) estimates of suspended bed material loads (kg/s) for the first day of the calibration period, in addition to theoretical total bed material loads (Ackers and White 1973; Yang 1973).

4.3.4.a.4 Combined estimates for total load

Ideally, the total load output of all sediment from WPGC2a could be estimated using the combination of empirical washload and theoretical total bed material load. However, results suggested that theoretical bed material loads were underestimated (Figure 4-11), which was also indicated by sums of empirical washload and theoretical bed material load that were less then the empirical suspended load (Table 4-3). Therefore, an alternative load assumption was made that sums empirical suspended load with theoretical bedload, with the later taken as equal to theoretical bed material load results from Yang (1973) under the assumption that few d_{50} (220 μm) particles will travel in suspension.

Total and specific load estimates (Table 4-4) were high compared to both Australian and global data on gully erosion (see discussion). The effective specific-yields from the internal gully area (374 to 1,481 t/ha/yr) were much higher than the total catchment specific-yields (88 to 350 t/ha/yr, Table 4-4), which is expected from the extreme differences in erosion above and below the scarp. The estimated sediment input from the gully scarp (GPS surveys) was 34% of the gauged output in WY 2009 and 99% of output in WY 2010 (Table 4-4), indicating either the temporal importance of internal gully sediment sources or measurement error. Specific sediment yields estimated from historic air photos were within the same order of magnitude as the recent GPS and gauge data (Table 4-4).

Similarly, sediment budgeting at the catchment scale has estimated 154 t/ha/yr for the internal gully pixel (271m x 271m) at WPGC2a (Brooks et al. 2008; Rustomji et al. 2010), derived from the ASTER-satellite estimated gully perimeter, historic median erosion rate from air photos, 2 m scarp depth, and local bulk density of 2035 kg/m^3. These data are less than gauged specific-yields from the internal area, in addition to the internal-gully specific-yields from GPS for WY 2009 and 2010, with the later due to large differences in estimated gully perimeter and annual variation in scarp retreat (Table 4-4). However at the catchment scale, this satellite and air photo based estimate is a reasonable first-order approximation of long-term erosion rates.

Table 4-4 Summary of total load estimates, specific sediment yields, and sediment production from scarp retreat calculated for the internal gully area (7.8 ha) and catchment surface area (33 ha).

	WY 2009	WY 2010	WY 1950-1960	WY 1961-2006
Gauge Total Load (tonnes/yr) Empirical Suspended Load + Theoretical Bed Material Load	11,554 ± 63%	2,916 ± 53%	---	---
Gauge Specific Sediment Yield (t/ha/yr) Internal Gully Area = 7.8 ha	1,481 ± 63%	374 ± 53%	---	---
Gauge Specific Sediment Yield (t/ha/yr) Catchment Surface Area = 33 ha	350 ± 63%	88 ± 53%	---	---
GPS Scarp Retreat (tonnes/yr) (% of input compared to output)	3,903 (34%)	2,911 (99%)	---	---
GPS Scarp Retreat, Specific Sediment Yield (t/ha/yr) Internal Gully Area = 7.8 ha	500	373	---	---
GPS Scarp Retreat, Specific Sediment Yield (t/ha/yr) Catchment Surface Area = 33 ha	118	88	---	---
Air Photo Scarp Retreat, Specific Sediment Yield (t/ha/yr) Internal Gully Area = 7.8 ha	---	---	760	585
Air Photo Scarp Retreat, Specific Sediment Yield (t/ha/yr) Catchment Surface Area = 33 ha	---	---	180	138
Long-term Scarp Specific Sediment Yield (t/ha/yr) Brooks et al. (2008) for WPGC2a gully pixel (271 m x 271 m). ASTER perimeter x historic median erosion rate (0.34 m/yr) x scarp depth (2.0 m) x bulk density (2035 kg/m^3).	154	154	---	---

4.4 Discussion

4.4.1 Scarp retreat and sediment supply

The utilization of both GPS surveys and historic air photos provided a useful temporal measure of changes in alluvial gully area and sediment supply over long scarp distances and different time scales. However, GPS error (±50 cm) and overlap between annual surveys suggest that more accurate (but expensive and time consuming) techniques are warranted. Measurement of short-term changes in scarp location, internal gully morphology, and volumetric sediment supply could be measured from repeat surveys by airborne LiDAR, terrestrial LiDAR, large-scale photogrammetry, total station, or RTK GPS. Gaps in historic air photo time-series and erosion rate estimates could also be filled by other indirect dating techniques for gully erosion, such as tree dating and stratigraphic OSL dating (Chapter Five; Chapter Six).

Gully planform changes often follow negative exponential decay with rapid initial change followed by a longer relaxation period, due to numerous intrinsic or extrinsic factors and complex response (e.g., Graf, 1977; Schumm, 1979; Nachtergaele et al. 2002; Vandekerckhove et al. 2003; Thomas, 2004). However, one- or two-dimensional planform changes should be interpreted with caution (i.e., Graf, 1977), as three-dimensional volumetric change is the key metric from a gully evolution and sediment yield perspective. Additional historic air photo data from 18 other alluvial gully complexes across the Mitchell River megafan documented both linear and exponential decay trends in growth rates of gully area and volume [Shellberg et al. 2010; Shellberg, 2011]. Linear trends in area and volume growth at WPGC2a, as well as roughly similar specific sediment yields from the scarp and channel outlet historically and recently (Table 4-4), suggest that the sediment supply has been relatively consistent and abundant over the historic period. This is perhaps due to long relaxation times following initial disturbance, highly erodible soils, and fairly consistent monsoonal climate.

Once moisture thresholds were exceeded, 24-hr total rainfall was an important predictor of both scarp retreat and sediment yield at the outlet. Thus, rainfall could be used as an independent variable to model sediment yield from alluvial gullies using distributed catchment models, as long as some inherent geomorphic, edaphic, and hydraulic conditions are known. However, it is just a proxy measure for a whole suite of measured and unmeasured variables. The input of kinetic/momentum energy from rainfall/runoff can detach particles during rain drop impact, slake/disperse soil aggregates, erode sediment during overland flow, and dismantle fail soil blocks for onward fluvial transport, which influence scarp retreat and sediment yield. The remaining variability between rainfall and scarp retreat is likely explained by seasonal variations in vegetative cover and water runoff, and intrinsic thresholds of geotechnical stability such as near-surface pore-water pressure, tension-crack development, and antecedent conditions (Chapter Three).

Overall at the scale of the internal gully area, the highly erodible nature of these alluvial soils once exposed produced an abundant supply of sediment to the catchment outlet relative to the sediment transport capacity, which supports the concept of either a partially or fully transport-limited system. Above the scarp zone in contrast, erosion and sediment supply were limited by reduced slope and potential energy, increased soil cohesion and protection from grass cover, and soil surface sealing during intense rainfall, which resulted in the transfer of excess energy and overland flow momentum to the scarp face. Observations of relatively clear runoff above scarps compared to turbid water below (Chapter Three), suggest that gully scarps are compressed transition zones between sediment supply- and transport-limited conditions.

4.4.2 Internal erosion/deposition processes

Internal erosion and deposition processes within the gully complex below the scarp face highlight the partially or fully transport-limited nature of the sediment yield. Field and LiDAR observations indicate that scarp retreat is often incomplete spatially, with many partially eroded features remaining within the gully complex such as remnant pedestals and uneroded ridgelines (Figure 4-1). Thus scarp retreat is a minimum estimate of sediment supply. Quantitative data suggest that erosion at the scarp head does not always dominate the output of sediment during wet years (WY 2009), but can during dry years (WY 2010). Excess available energy during wet years can erode and flush remnant sediment that was incompletely eroded or transported during drier years or antecedent events within the gully complex.

Depositional features such as gully inset-floodplains develop from coarser lags of sand and ferricrete nodules, which can re-erode during bank erosion along the outlet channel. The longitudinal profile of the WPGC2a outlet channel below the active scarp zone is generally linear and appears to be at a quasi-equilibrium slope (Chapter Six). However, ongoing changes in sinuosity through bank erosion and avulsion across inset-floodplains suggest that the channel can adjust toward an equilibrium slope in response to the episodic supply of water and sediment. Therefore, internal erosional and depositional features and processes within the gully complex are important in supplying and metering sediment, which warrant further investigation.

4.4.3 Sediment yield

The modest water and sediment gauging effort at WPGC2a was essential to empirically measure the magnitude of sediment yield from a rapidly eroding alluvial gully and calibrate theoretical sediment transport models. Sediment rating curve data and particle size analysis generally supported a single Q-SSC relationship, which provided the best support for the concept of a transport limited system where sediment transport consistently responded to supplied transport capacity. However, additional SSC data on the rising and falling limbs of dozens of discharge events across seasons are needed to strengthen these observations, confirm the complete lack of hysteresis, and better define sediment supply- and transport-limiting conditions at the gully outlet.

The event variability in Q-SSC relationships in gullies and rivers channels can vary from common clockwise hysteresis loops (depletion of supply during event), to less common anticlockwise (delayed supply from distance sources) or single curve (unlimited local supply) relationships (Olive and Rieger 1985; Williams 1989; Nistor and Church 2005). In gullies, Q-SSC relationships are complicated by thresholds for specific particle size detachment or motion, seasonal influences (e.g., wetting-drying; freeze-thaw; vegetation cover), episodic or chronic land-use disturbance, antecedent flood or moisture conditions, and changes in sediment sources and erosion processes (i.e., gully-head vs. gully-side-wall vs. hillslope erosion) (Piest et al. 1975; Olive and Rieger 1985; Welch 1986; Ondieki 1995; de Boer and Campbell 1989; Oostwoud Wijdenes and Bryan 2001; Armstrong and Mackenzie 2002; Nistor and Church 2005; Fang 2008). Furthermore, the location and scale of measurement can influence determinations of sediment availability, with small hillslope catchments often being supply limited compared to larger catchments downstream that integrate sediment from the multiple sources nested upstream (Bartley et al. 2006; Bartley et al. 2010b). Thus for more detailed water and sediment yield measurements from alluvial gullies, a more robust hierarchically-nested gauging system is warranted that integrates improved infrastructure such as compound weirs, continuous stage and turbidity (or other surrogate) measurements (Gray and Gartner 2009), threshold-triggered pump-samplers for automatic event sampling, additional manual width- and depth-integrated SSC and Q measurements, and the calculation of suspended sediment load estimates at the event scale (e.g., Lewis 1996).

Measured peak suspended sediment concentrations >100 g/L at WPGC2a were higher than commonly reported for Australia (e.g., Olive and Rieger 1985; Dunkerley and Brown 1999; Armstrong and Mackenzie 2002; Bourke 2002; Bartley et al. 2006; 2010b), but these peak values are still well below non-Newtonian hyperconcentrated flow conditions (>400g/L or 40% by weight) (Beverage and Culbertson 1964). For example, measured concentration in gullied loess terrain in China can average 600g/L and peak well above 1000 g/L (e.g., Huang et al. 2003 and Fang et al. 2008). However, specific sediment yields from the WPGC2a drainage area (88-350 tons/ha/yr) are comparable to other high erosion areas of the world (Figure 4-12). The large annual rainfall and runoff volumes at WPGC2a in the monsoonal tropics, combined with modestly high SSC values, produced specific sediment yields comparable to average values in loess terrain of China, where unit rainfall and runoff volumes are at least half of those in northern Queensland (Huang et al. 2003 Chen and Cai 2006; Fang et al. 2008). The specific sediment yields from alluvial gullies in India are more directly comparable to WPGC2a, perhaps due to similar monsoonal climates and alluvial gully geomorphology (Figure 4-12; Singh and Dubey 2000).

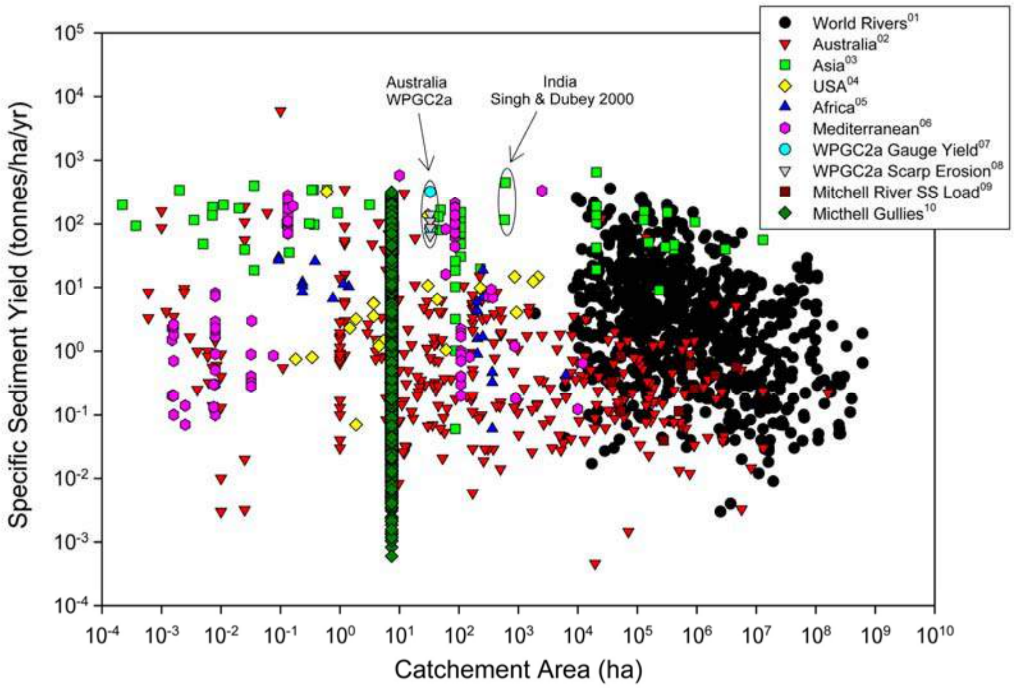


Figure 4-12 Comparison of specific sediment yields (t/ha/yr) by catchment area (ha) for hillslope erosion plots, small gully catchments, small stream catchments, and larger rivers from the following data sources.

World Rivers[01] (FAO 2010), **Australia**[02] (plot, gully, stream, river database of Wasson 1994; review by Prosser and Winchester 1996; Armstrong and Mackenzie 2002), **Asia**[03] (diCenzo and Luk 1997; Singh and Dubey 2000; Huang et al. 2003; Yu 2005; Chen and Cai 2006; Fang et al. 2008; Rustomji et al. 2008), **USA**[04] (Piest et al. 1975; Welch 1986; Thomas 2004; Nearing et al. 2007; Kuhnle et al. 2008), **Africa**[05] (Ondieki 1995; Oostwoud Wijdenes and Bryan 2001; Walling et al. 2001), **Mediterranean**[06] (Seginer 1966; Bufalo and Nahon 1992; Oostwoud Wijdenes et al. 2000; Mathys et al. 2003; Martinez-Casasnovas, et al. 2003; Martinez-Casasnovas 2003; Avni 2005; Nyssen et al. 2008), **WPGC2a Gauge Yield**[07] (this study using 33ha catchment area, Table 4-4), **WPGC2a Scarp Production**[08] (this study, production estimates using 33ha catchment area, Table 4-1), **Mitchell River SS Yield**[09] (fine suspended washload only from surface TSS data, Queensland Department of Natural Resources database), **Mitchell Gully Production**[10] [pixel(271m x 271m) based sediment production from Brooks et al. (2008, 2009; Chapter Two) across the Mitchell megafan, assumed 2.0 kg/m^3 for catchment average bulk density].

4.4.4 Theoretical modelling

Theoretical modelling of total suspended sediment (Equation 4-2) using several different model setups was able to adequately simulate sediment loads to within ± 20% of empirical loads. The most robust estimate of the average fraction of stream power used for suspended sediment transport ($\overline{F}_s$) was 1.88% for WY 2010, determined from model setup 2 by varying ϕ_s as a function of Q at each 15-minute time step. This estimate is generally similar to the 1.5% value assumed by Bagnold (1966) for suspended load. It is also generally similar to the fraction of stream power used for suspended sediment transport of 2.2% calculated by Thomas et al. (2004) for a fine-grained alluvial “valley-bottom” gully in Iowa, and 3 to 5% calculated by Rose et al. (1983) from a small planer catchment in monsoonal Arizona. If the methods of Thomas et al. (2004) are followed for calculating average stream power efficiencies for suspended sediment transport (Ω_s/Ω_w), then the corresponding average values for WPGC2a would be 1.94% for WY 2010 and 6.00% for WY 2009. The later value is similar to results using Equation 4-2 and model setup 3 (6.28%) using a constant average settling velocity for WY 2009. Additional field data on settling velocities at high discharges will be needed to improve instantaneous estimates of F_s following model setup 2. However for preliminary alluvial gully modelling purposes, a reasonable estimate of F_s from this research and the literature could be on the order of 1.5 to 2.0%.

For internally comparable model setups that assumed constant average values for settling velocity, results estimated higher F_s values (~6.6%) for suspended load than F_w values (~2.1%) for washload (<63 μm) for WY 2010, with generally similar results for WY 2009. The F_w values were smaller than F_s values as expected, but they were not as small as the washload efficiency values (1% of F_s) suggested by Bagnold (1966). He argued that once fine particles <63 μm are detached, only a small amount of total stream power is needed to maintain that washload in suspension. However, Bagnold (1966) also indicated the limitation of his theories once sediment concentrations became very high, which is a confounding factor for WPGC2a where high washload concentrations dominated total suspended sediment load (Figure 4-4; Table 4-3). Furthermore, Bagnold's (1966) methods for estimating washload efficiency were indirect.

To improve modelling results and applications, additional field data are required at the event scale and from varying gully types and sizes to further quantify 1) mean settling velocities of suspended sediment in relation to discharge, 2) actual particle size differentiation at the gully scarp for load-by-source assignment, 3) the complex interactions of sand and silt sized particles between the channel bed and water column, and 4) sediment transport efficiencies of load components. Furthermore, for the more complex field situation where river backwater and overbank flooding are major erosional drivers of alluvial gully erosion (Chapter Three), future field-based empirical data collection and theoretical modelling efforts will need to be modified and newly formulated respectively.

4.4.5 Conclusions

Alluvial gullies in the lower Mitchell catchment are major concentrated sources of sediment to the aquatic environments, with sediment yields comparable to erosional hotspots on the world scale. The gully studied here is a partially to fully transport-limited erosional system along its outlet channel that is supplied with sediment from de-vegetated dispersible soils and responsive to rapid inputs of rainfall and runoff energy. The transport-limited equations of Rose (1993) and Bagnold (1966) are useful in modelling washload and suspended load in these systems. However model calibration needs to be based on field measurements of key parameters, specifically mean settling velocity and sediment transport efficiency. Future modelling of alluvial gully erosion across northern Australia and beyond must be founded on improved field collection of key parameters and empirically measured sediment yield, including bedload, at a variety of spatial and temporal scales. Otherwise, attempts at modelling this type of erosion at the landscape scale for sediment budget purposes will be at best, works of art (Rustomji et al. 2010).

Chapter Five: Quantification of Alluvial Gully Erosion Rates Using Radium-226/228 and Carbon-14 Radionuclide Dating of *Eucalyptus microtheca* Tree Ages

5.1 Introduction

As alluvial gully fronts migrate away from mainstem river channels through riparian vegetation and woodlands (Brooks et al. 2009; Chapter Two; Chapter Three; Chapter Four), they leave in their wake dead trees, live trees that have survived gully erosion (Figure 5-1a), and new alluvial surfaces such as gully inset-floodplains that are colonized by various tree species (Figure 5-1b). In the woodlands of the lower Mitchell River on the Cape York Peninsula in northern Queensland, Coolibah trees (*Eucalyptus microtheca*) grow on river floodplains in massive sodic soils and are hardy trees that can survive gully erosion and re-colonize the eroded landscape. In different global environments, trees and tree roots have been successfully utilized to age gully erosion rates (e.g., Gonzalez 2001; Vandekerckhove 2001; Gartner 2007; Malik 2006; 2008). If Eucalyptus trees can be aged via ring counting and independent radionuclide dating in these Australian gullies, live trees that have survived the passage of the gully front could provide a maximum date of erosion passage (Figure 5-1a). In contrast, live trees that have re-colonized the inset-floodplains of gully floors could provide a minimum age for the passage of the gully front (Figure 5-1b). The objective of this chapter is to determine whether trees growing in and around an alluvial gully pilot site have the potential to define the rates and timing of gully erosion, through ring counting and age dating of rings using independent methods.

a) b)

Figure 5-1 Examples of Coolibah trees (*Eucalyptus microtheca*) at KWGC2 showing a) exposed roots of a tree that was established before gully erosion and survived the passage of the gully front and lowering of the land surface by 1.5 m, and b) a tree that has colonized the surface of a gully inset-floodplain after the passage of the gully front. Note location of root flares relative to the ground surface.

Trees in Australia such as *Eucalyptus spp.* are difficult to date using traditional dendrochronology methods due to the inconsistency in laying down *visible* and *annual* growth rings as a result of highly episodic growth following unpredictable rainfall (e.g., Ogden 1978; 1981; Pearson and Searson 2002; Argent et al. 2004; Hancock et al. 2006). However, *non-annual* tree ring patterns and growth of *Eucalyptus spp.* have been correlated to rainfall, soil moisture and river discharge in climates with unpredictable moisture inputs (Downs et al. 1999; Leal et al. 2004; Argent et al. 2004), which provides hope for climate analysis. More importantly in strongly-seasonal monsoon-climates of tropical Australia, it has been found that tree growth during the predicable summer wet season dominates the production of growth rings each year, resulting in near annual growth rings in *Eucalyptus* species (Mucha 1979; Odgen 1981; Hancock et al. 2006) and *Callitris* species (Baker et al. 2008, Pearson et al. 2011). However, the assumption of annual growth rings at a specific location can not be made without independent confirmation of tree age or growth from other dating techniques (direct observations, photographs, radionuclide dating). If growth rings are not perfectly annual but consistently identifiable, then correction factors are needed from independent dating such as radionuclide analysis to determine, on average, how many rings per year are laid down. Subsequently, these correction factors could be applied to tree ring counts from undated trees to estimate tree age.

Bomb-pulse radiocarbon dating is a well established tool to independently verify the age of carbon in tree rings for the last ~60 yrs (Fichtler et al. 2003; Hua and Barbetti 2004; Biondi et al. 2007; Hua 2009; Pearson et al. 2011). During photosynthesis, trees uptake CO_2 and store that carbon in xylem at similar relative contributions of carbon species (^{12}C, ^{13}C, ^{14}C) present in the atmosphere at the time of growth. Natural radiocarbon is produced continuously in the atmosphere by the interaction of the secondary neutron flux from cosmic rays with atmospheric ^{14}N. Human activity can also contribute to the production of radiocarbon. A significant amount of ^{14}C was artificially produced when hundreds of nuclear weapons were detonated in the atmosphere mostly during the late 1950s and early 1960s. The varying atmospheric ^{14}C levels after 1955 offer the possibility of dating recent organic materials by bomb-pulse ^{14}C with a variable resolution of one to a few years (Hua and Barbetti, 2004). The measured ^{14}C content in two or more adjacent tree-ring samples can be converted to calendar ages by comparing them against known regional atmospheric bomb curves of ^{14}C concentration that fluctuate over time (Hua and Barbetti 2004; Hua 2009).

Radium radionuclide dating of tree rings also has recently proven to be an independent tree aging technique for Australian trees (Hancock et al. 2006), which utilizes radium radionuclide concentrations in tree xylem tissues to determine temporal growth of tree rings. Radionuclides of radium (^{226}Ra and ^{228}Ra) are mobile in soil- and ground-water, while their thorium parents (^{230}Th and ^{232}Th) are relatively immobile. Radium can become incorporated into tree xylem tissue and tree rings following initial soil water uptake during photosynthesis. After uptake, radium becomes immobile in tree *heartwood* where it begins to decay in a closed system (tree ring) at known half-lives. The half life of ^{228}Ra is 5.8 years and thus decays quickly, whereas ^{226}Ra has a half-life of 1600 years, and thus is stable over the life of a tree. Following Hancock et al. (2006), the tree age at any distance or ring t_x across the tree radius within the *heartwood* can be calculated from:

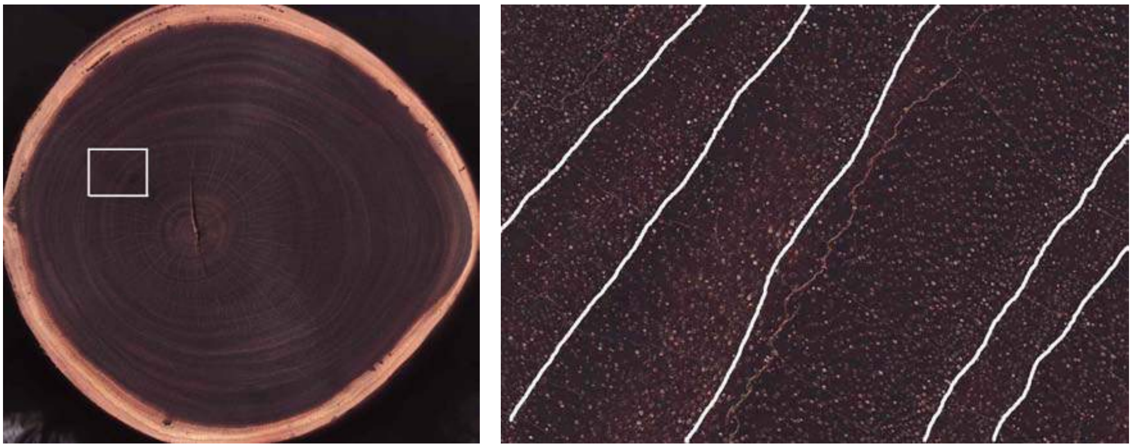
$$t_x = -\frac{1}{\lambda_{228}} \ln\left[\frac{R_x}{R_0}\right] \qquad (5\text{-}1)$$

where λ_{228} is the radioactive decay constant of ^{228}Ra (ln2/half-life) and R_0 is the initial versus final R_x activity ratio of ^{228}Ra/^{226}Ra. Values of the initial (R_0) activity ratio can be measured from either outer sapwood, used here, or live foliage or local groundwater, assuming that ^{228}Ra/^{226}Ra ratios do not change considerably over time (Hancock et al. 2006).

5.2 Methods

For initial testing of both carbon and radium radionuclide tree ring dating techniques (i.e., Hancock et al. 2006; Hua 2009) in relation to gully erosion, one gully complex (KWGC2) near Kowanyama in the lower Mitchell River catchment, Cape York, northern Australia was selected as a pilot site. During November 2008, wood samples for tree ring analysis were collected at KWGC2, with the permission of aboriginal Traditional Owners'. In total, forty-two (42) Coolibah trees (*Eucalyptus microtheca*) were sampled that had either survived during (20) or re-established after (22) the passage of the gully head cut front (e.g., Figure 5-1ab). Due to difficulty in tree coring due to hardness and irregularity, all trees were felled with a chainsaw to obtain cross-section samples (disks) of xylem and growth rings. A majority of trees resprouted from cut stumps the following wet season. The diameter of each tree was measured at the cut location at the base of tree just above the root flare. The tree height was also measured after felling. Each tree was geo-referenced on the landscape with GPS. Using standard surveying techniques, the elevation of each tree was measured at the 1) root flare location, 2) ground surface below the tree, and 3) cut location, to determine the trees' pre- and post-gully growing position and age relative to the gully. Overall, these trees represented a small percentage of trees growing in the poor habitat across the gully floor.

Cut disks at least 100 mm in length were sanded sequentially with a belt sander and disk sander (sandpaper range 50, 200, 500, 1200 grit) and polished with a fine cloth. Tree rings were then analysed using a 40x dissecting scope. Tree ring boundaries were identified using a combination of 1) transitions from seasonal light wood to dark wood and 2) where vessel size and density changes from dense vessels to sparse vessels (Figure 5-2b), following methods of Argent et al. (2004) and Hancock et al. (2006). For all forty-two (42) Coolibah trees felled at the gully site, tree rings were counted onto tracing paper in four radial directions, producing an average and standard deviation for analysis.



a) b)

Figure 5-2 a) Example of a polished tree cross-section showing rings, and b) detail of the inset white rectangle in a) showing light and dark bands and variations in vessel size and density used to locate ring boundaries.

5.2.1 Radium analysis

For radium-226/288 analysis, eight (8) trees were selected to analyse the relationship between tree age and tree ring production. As above, initial tree ring counts were conducted in four radial directions away from zero at the tree center, producing an average and standard deviation for analysis. In addition for these eight trees, ring boundaries were delineated around the tree circumference from initial radial marks. False rings were identified as rings that did not continuously circumnavigate the tree. These more precise rings counts were then compared to the average number from radial counts, which were usually within one or two rings. The total full ring count was then divided into grouped ring bands, starting at zero at the center of the tree. The number of rings per band was varied across the radius to ensure that a minimal mass of 0.2 grams of ash was obtained as recommended by Hancock et al. (2006). Thus, the smallest band in the center of the trees contained 5 rings, while this number decreased to 2 toward the edge of the tree due to increasing wood mass per ring. The tree disk was then cut into concentric bands of rings using a band saw. After cutting subsamples, the wood was pre-weighted and ashed at 500 °C for 24-hrs, to obtain at least 0.5 grams of ash per band.

The tree ash was analysed chemically at the Australian Nuclear Science and Technology Organization (ANSTO) environmental radiochemistry laboratory. Known activities of the laboratory tracers ^{133}Be and ^{229}Th were added to each ashed sample before analysis, to determine the % recovery following chemical separation. Chemical separation of the radium and thorium radioisotopes was initiated by nitric acid digestion of the ash, followed by conversion via evaporation to a solution of hydrochloric acid. This solution was then passed sequentially through different pre-conditioned (HCl or HNO_3) resins in ion exchange columns, to isolate the radium and thorium from each other and other contaminants. Finally, radium was co-precipitated using $PbSO_4$ before source preparation onto a filter dish. Thorium was similarly co-precipitated using a cerium carrier onto filter paper. The % recovery of ^{133}Be (and Ra) was first determined using gamma-spectrometry, before later α-particle counting on an alpha spectrometer. Recovery of ^{229}Th was measured on an alpha spectrometer, in addition to the other naturally occurring thorium radioisotopes. Since ^{228}Ra is a beta-emitter, it is best determined by measuring its alpha-emitting daughter, ^{228}Th, after a 6 to 12 month in-growth period. After a 7 month in-growth period, the original radium sources were again chemically treated to separate in-grown thorium from radium following the methods above. The in-growth thorium activities were again measured on an alpha spectrometer, and ^{228}Ra activities were assumed to be in secular equilibrium with ^{228}Th activities.

5.2.2 Carbon analysis

For carbon-14 analysis, four (4) trees were selected to determine the relationship between tree age and tree ring production. Unfortunately, different trees were used for carbon analysis than for radium analysis, due to the full consumption of wood during radium analysis. After ring counting, tree disks were sliced radially to expose the tree center. Two wood samples (>100 mg) per tree were chiselled and scalped from near the tree center (ring 1 or 2) and several rings away from the center. Samples were ground up using a cutting mill and the >500 μm portion was kept via sieving for chemical treatment. Chemical pre-treatment to extract alpha-cellulose from the sample involved cyclohexane/ethanol extraction followed by ethanol and water reflux to remove unwanted mobile material (resins, wax, oil, etc.), extraction of holo-cellulose to remove lignin, and finally alpha-cellulose extraction with sodium hydroxide under nitrogen gas. The extracted alpha-cellulose was treated with dilute HCl, and then washed thoroughly with water and dried. The alpha-cellulose was combusted to CO_2 and then reduced to graphite over a Fe catalyst (Hua et al. 2001; Hua et al. 2004) for accelerator mass spectrometry (AMS) measurements at ANSTO (Fink et al. 2004). Carbon-14 content in percent modern carbon (pMC) was converted to calendar ages using the Southern Hemisphere bomb curve (Hua and Barbetti 2004) and the CALIBomb calibration program (Reimer et al. 2004).

5.3 Results

5.3.1 Geomorphic and vegetative patterns

While trees surviving gully erosion are important geomorphic indicators (Figure 5-1a; Figure 5-3), determination of erosion rates at KWGC2 focused on the analysis of those Coolibah trees that had re-established *after* the passage of the gully head cut front (e.g., Figure 5-1b). These colonizing trees were well distributed across the floor of the alluvial gully complex (Figure 5-3), where they predominantly established along the new channels of inset-floodplains that drained the new gully complex. It was initially hypothesized that the growth of the gully network developed predominantly in a linear progression away from its confluence point with the main channel (Sandy Creek lower section of Figure 5-3). This is supported by analysis of historic air photos that indicates elongation was the predominant growth direction, followed by widening (see Figure 5-9 below). Thus, the channel thalweg distance and straight line valley distance upstream from the gully outlet were used as location references for the evolution of the gully and adjacent inset-floodplain germination points for Coolibah trees.

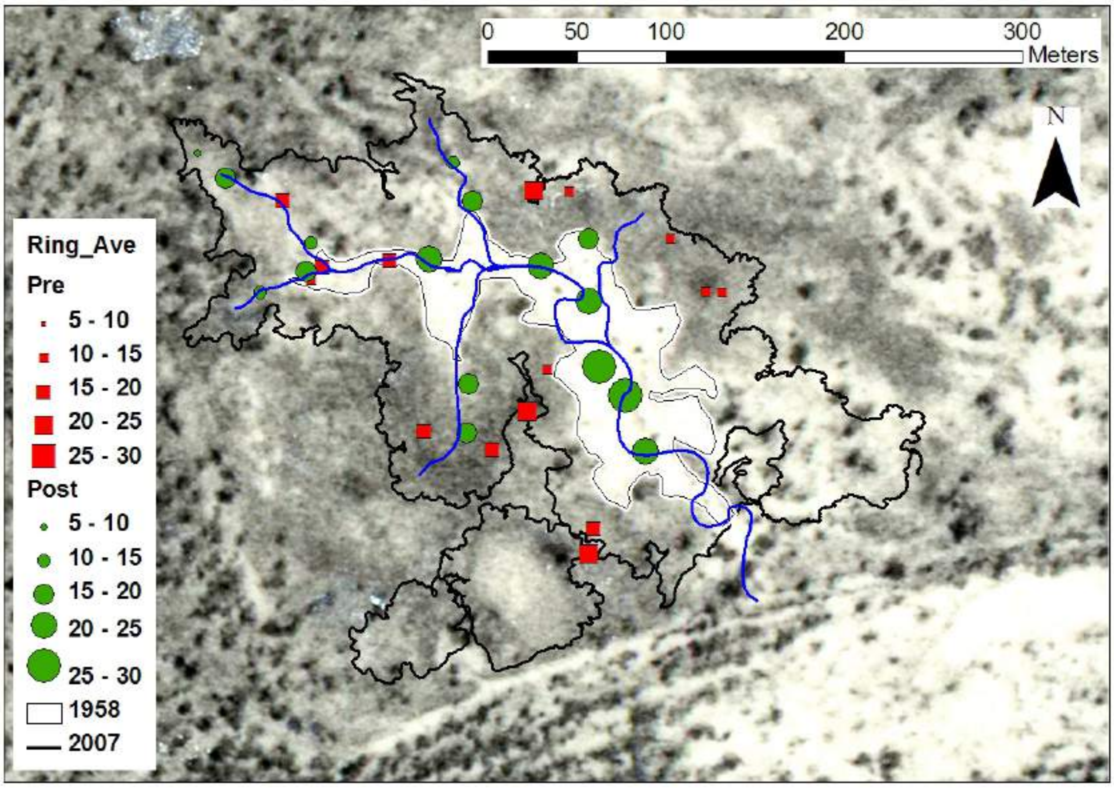


Figure 5-3 Locations and average ring counts of Coolibah trees that germinated *before* (red) and *after* (green) gully erosion, in addition to the 2007 scarp lines and 1958 air photograph.

Initial analysis of diameter and height indicated that the largest diameter trees were located near the bottom of the gully closest to the outlet (Figure 5-3). Tree diameter decreased significantly upstream, while the decrease in tree height upstream had a weaker relationship (Figure 5-4).

Based on tree diameter alone, it would appear that the trees lower in the gully were older, and thus had established on new inset-floodplain surfaces that had been exposed for longer. The opposite could be true for the smaller trees upstream, which had more recently colonized newly created gully bottom surfaces. After ring counting analyses of these same trees in the laboratory, the average ring counts along four radii confirmed that the oldest trees (highest ring count) were indeed located toward the bottom of the gully channel, and that tree age (ring count) decreased upstream (Figure 5-5). The oldest and largest diameter trees had between 25 and 30 rings, while the youngest and smallest diameter trees had approximately 10 rings. The youngest saplings in the gully complex were not sampled.

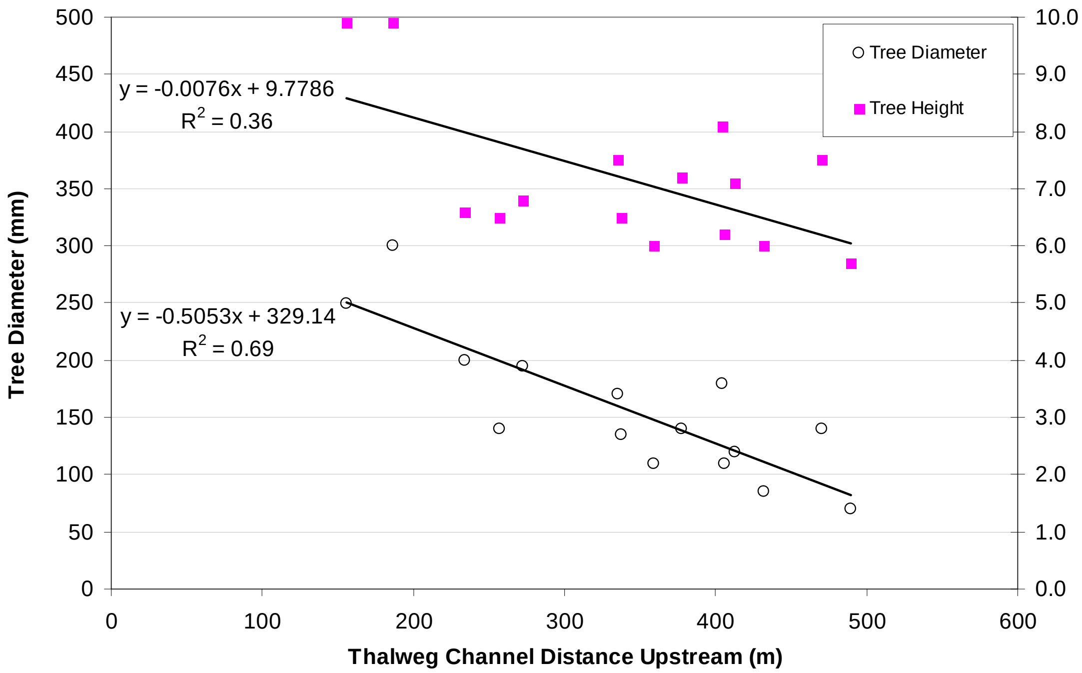


Figure 5-4 Relationships between tree location upstream from the gully outlet and the tree diameter and height.

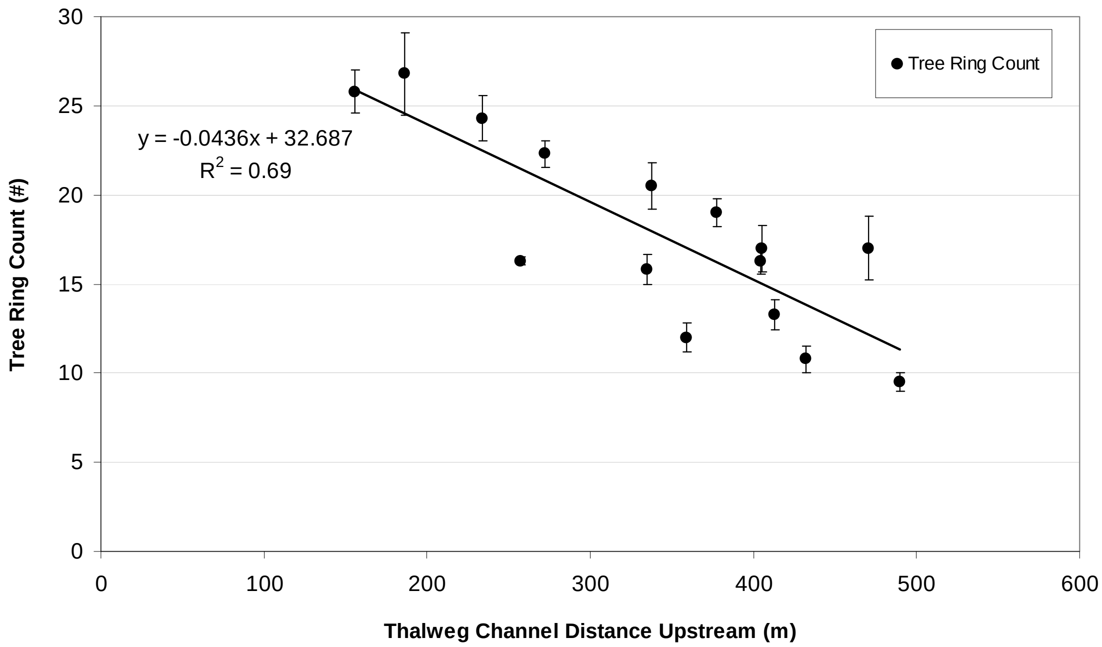


Figure 5-5 Relationship between thalweg channel distance upstream from the outlet of the gully and the average ring count for Coolibah trees that have re-colonized onto the inset-floodplain after the passage of the gully front (i.e., see trees in Figure 5-1a and Figure 5-3).

These data in mass do not support a null hypothesis that tree colonization is completely random and uniform regardless of local edaphic or microclimate conditions along the catena associated with gully evolution. Tree size and ring count are associated with provision of newly available tree habitat in the gully floor (Figure 5-3; Figure 5-4; Figure 5-5). The remaining variability between gully position and diameter or ring count could be related to the combination of 1) episodic recruitment cycles due to seasonal or decadal climatic variability 2) the recruitment success at any given micro-site and/or 3) the use of thalweg channel distance as a correlation variable. Overall however, there does not appear to be any major clusters of diameters or ring counts that would signify major pulsed recruitment or survival, which is likely due to the fairly predicable monsoonal climate in this location (Chapter Three).

The trend line through the ring count vs. thalweg distance plot (Figure 5-5) suggests that Coolibah trees colonized the gully inset-floodplains at a rate of 23 m per ring, or 20 m per ring if the straight line valley distance is utilized. Geomorphically, if the headward retreat of the gully created inset-floodplain habitat post-erosion that was colonized by trees and was commensurate (i.e., without lag times) with the rates of retreat at the gully head (i.e., geomorphic equilibrium during evolution), then the gully head retreat along the main gully channel(s) would have occurred at a rate of ~20 m per ring. However, equilibrium between scarp erosion and inset-floodplain formation remains unknown (see below). Furthermore, the biggest question still remains: are the tree rings counted annual rings?

5.3.2 Radium dating results

After a 7 month in-growth period of ^{228}Ra decaying into ^{228}Th, ^{228}Th activities were measured on an alpha spectrometer. It soon became apparent that the activities of most sources were below the detection limit for ^{228}Th, and thus ^{228}Ra. Several independent but cumulative reasons could have resulted in these poor detection results. First, radium activities in the ambient environment (soil, water) around trees could be inherently low, resulting in low levels of uptake by trees. However, ^{226}Ra activities in sapwood were generally similar to results of Hancock et al. (2006) (0.8 to 8.9 Bq/kg dry wood). Thus radium availability is likely not limiting, unless ^{228}Ra activities and thus ^{228}Ra/^{226}Ra ratios are inherently low, as seen in some environments (Hancock et al. 2006). Second, ^{228}Ra and ^{228}Th activities below the detection limit were likely influenced by the actual age of many heartwood samples that were older than several decades, as confirmed by ^{14}C dating below, and thus beyond the detection limit due to the short half-lives of ^{228}Ra and ^{228}Th. Third, the use of less than 1 gram of ash for most of the samples (range 0.1 to 3 grams) put the mass close to or slightly below recommendations by Hancock et al. (2006) of a minimum mass of 0.2 grams of ash. Since the detection of ^{228}Ra following in-growth is poorer than for direct ^{226}Ra or ^{228}Th measurement, this method is especially sensitive to both initial mass utilized and the percent recovery of tracers following chemical separation. Forth, initial tracer yields of ^{133}Ba ranged from 22% to 98% with an average of 72%. However, the subsequent chemical separation process after ^{228}Th in-growth yielded between 70-80% of the ^{229}Th tracer activity, thus further reducing the final detectable activities of ^{228}Th, and thus ^{228}Ra. Finally, longer in-growth periods up to 12 months or greater could have increased the detectability and measurement of ^{228}Th and ^{228}Ra.

Despite these poor results, one tree (#35, pre-erosion, ring count = 15.3, dia = 115 mm) had enough consistent, detectible data to calculate tree ages and ring growth rates using the model of Hancock et al. (2006). Two additional trees (# 32 and # 41, pre-erosion, ring count = 17.0 and 17.0, dia = 110 and 140mm, respectively) also had data suitable for fairly coarse age estimates by combining radium data from the cores of these trees with ambient radium data from the sapwood of other nearby trees. Figure 5-6 displays the changes in radium activity ratios (^{228}Ra/^{226}Ra) across two samples of heartwood and one sapwood sample of Tree 35. Activity ratios increased with ring number toward the heartwood/sapwood boundary, where the sapwood sample represents the initial (R_0) activity ratio used in Equation 5-1. Using this sapwood R_0 value, the ^{228}Th radioactive decay constant, and the heartwood activity ratios, the time since xylem transition from sapwood to heartwood (t_x) was calculated using Equation 5-1 for different heartwood ring positions. Using this exponential model, it was estimate that on average across the heartwood that 0.74 ± 0.15 rings/yr were produced. The large error margins largely represent the influence of the number of rings (four) used to produce sufficient wood mass in the tree center, in addition to activity measurement errors. Two additional trees (#32 and #41) yielded less reliable estimates of 0.72 and 0.86 rings/yr. Hancock et al. (2006) found that a *Eucalyptus microtheca* tree growing in the wet-dry tropics of the Ord River had a growth rate of 0.80 ± 0.08 rings/yr. Similar to north-western Australia, the wet-dry monsoonal savannas of the lower Mitchell catchment in northern Queensland have periodic lower annual rainfall totals (600 mm vs. 1200 mm average) every 5 to 10 years, largely associated with ENSO-PDO cycles (see Chapter Six; Figure 6-13; Lough 1991; Heinrich et al. 2008; Risbey et al. 2009). These dry years appear to have less than optimal growth conditions, possibly leading to the yield of less than 1 ring/yr.

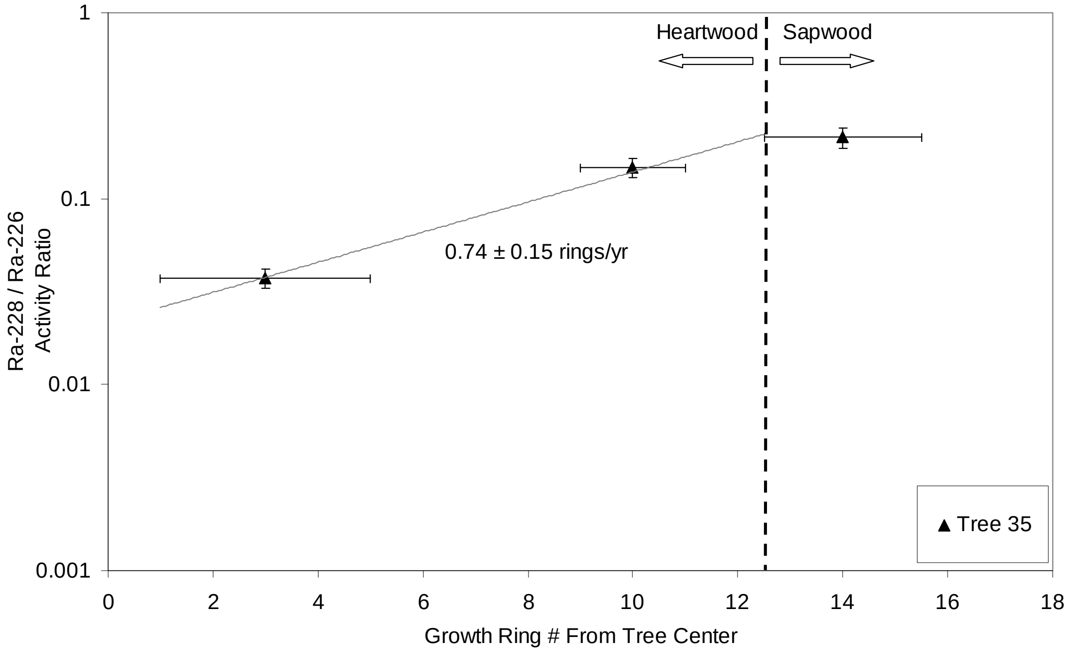


Figure 5-6 $^{228}Ra/^{226}Ra$ activity ratios versus ring number from tree 35 center.

5.3.3 Carbon dating results

Of the four trees analyzed for radiocarbon, two trees returned firm dates on the age of initiation of growth from just two samples per tree. The two other trees had age ranges of tree centers that were before the post-1955 bomb pulse curve for the Southern Hemisphere (Table 5-1). These trees will require two additional ^{14}C measurements per tree from rings further away from the center, in order to anchor some ring ages in the bomb pulse period and match pre-1955 measurements to the earlier calibration curve. Air photo evidence and trends in gully area (see below) can help constrain the establishment dates of these older trees growing within the gully, which suggested establishment dates between 1940 and 1954 when the gully was initiating. For all trees, average ring counts for each tree were used with estimated initiation dates to interpret the results in terms of average rings per year growth. Trees were also grouped and analyzed depending on their general growing environment: 1) on small, young, gully inset-floodplains, or 2) on the uneroded river high-floodplain surface.

Table 5-1 Percent modern carbon and calibrated mean calendar ages for trees at KWGC2.

					percent modern carbon		Calibrated Ages at 2σ (cal AD)			Interpretation	
Tree ID	Location	Lab ID	Ring #	δ ^{13}C (‰)	Value	1σ error	Lower cal	Upper cal	Prob.	Mean AD	2 σ
KWGC2 Tree 22	River High-Floodplain	OZM 699	1	-24.9	123.95	0.31	1962.47 1982.09	1963.25 1984.65	0.050 0.950	1983.37	1.28
		OZM 700	6	-22.9	118.01	0.29	1959.67 1985.45	1963.17 1992.29	0.305 0.695	1988.87	3.42
KWGC2 Tree 23	Gully Inset-Floodplain	OZM 701	2	-25.4	98.78	0.33	1683 1951.02	1928 1955.83	0.979 0.021	1953.43	2.40
		OZM 701	6	-24.1	103.38	0.27	1956.31	1957.50	1.000	1956.91	0.60
KWGC2 Tree 01	Gully Inset-Floodplain	OZM 703	3	-24.9	97.88	0.28	1662 1918	1865 1955.77	0.785 0.215	<1956	---
		OZM 704	7	-24.9	97.78	0.28	1661 1924	1810 1954.1	0.792 0.208	<1954	---
KWGC2 Tree 10	Gully Inset-Floodplain	OZM 705	2	-24.5	98.02	0.27	1666 1916	1876 1955.77	0.787 0.213	<1956	---
		OZM 706	6	-24.4	97.61	0.32	1654 1927	1807 1953.07	0.806 0.194	<1954	---

5.3.3.a.1 Trees growing on river high-floodplain surfaces

From carbon analysis, tree 22 had an estimated start date of 1982 and average ring count of 23.5 producing an estimated growth rate of 0.89 ± 0.07 rings/yr (Table 5-2). These rates are comparable within error margins to the growth rate of tree 35 determined by radium analysis (0.74 ± 0.15 rings/yr) (Table 5-2; Figure 5-6). It is also similar to the growth rate of 0.80 ± 0.08 rings/yr measured by Hancock et al. (2006) for a *Eucalyptus microtheca* tree growing on an uneroded terrace (high-floodplain) in the wet-dry tropics of the Ord River. It is unknown whether these variations in ring production are related to natural variability, ring identification and age error, or the specific growing conditions of micro-sites. For example, tree 35 experienced but was not killed by gully scarp retreat over the latter decade of its two decade life (as determined from air photos), while tree 22 was only slightly influenced by gully erosion.

5.3.3.a.2 Trees growing on gully inset-floodplain surfaces

Tree 23 had an estimated start date of 1952 and average ring count of 22.3 produced an estimate of 0.40 ± 0.03 rings/yr of growth (Table 5-2). If trees 01 and 10 established at a minimum age or maximum date of 1954, their ring production would be 0.40 and 0.47 rings/yr respectively. Additional samples for ^{14}C analysis from these trees will likely reduce this ring production estimate. For example if they both initiated in 1940 when the air photos suggest the gully started, they would have produced 0.32 and 0.38 rings/yr respectively. These rates are less than half of those for tree growing on the river high-floodplain. These older trees (23, 01, & 10) established early in the evolution of the KWGC2 gully, and thus would have experienced much different environmental growing conditions than trees 22, 14, and 35 growing on the high uneroded floodplain.

Table 5-2 Calculations of average tree rings per year estimated by radiocarbon (white) and radium (grey) using estimated tree ages and average ring counts per tree.

Tree ID	Location	Diameter (mm)	Height (m)	Ring Count Mean	Ring Count 1σ	Dating Method	Life Average Estimated Start Date	Life Average Rings/yr	Life Average 1σ	Early Life Average Rings/yr	Early Life Average 1σ
KWGC2 Tree 35	River High-Floodplain	115	6.7	15.3	2.2	Radium	1987.72	0.74	0.15	N/A	N/A
KWGC2 Tree 22	River High-Floodplain	170	8.7	23.5	1.9	Carbon	1962.01	0.89	0.07	0.91	0.07
KWGC2 Tree 23	Gully Inset-Floodplain	195	6.8	23.3	1.5	Carbon	1952.01	0.40	0.03	1.15	0.08
KWGC2 Tree 01	Gully Inset-Floodplain	232	7.9	22	2.2	Carbon	~~1954 youngest	~~0.40	---	---	---
KWGC2 Tree 10	Gully Inset-Floodplain	250	9.9	25.8	2.4	Carbon	~~1954 youngest	~~0.47	---	---	---

5.3.4 Tree colonization rates and scarp retreat rates

Due to the uncertainty in average ring production per year from these preliminary data, two different ring production estimates were used to highlight the influences on tree age estimation and subsequent gully erosion rates. First, from the radium results that estimated the rate of heartwood production from sapwood of a tree growing on the river high-floodplain, a ring production rate of **0.74 ± 0.15 rings/yr** was used. This is generally comparable to the rate measured from another river high-floodplain tree by carbon-14 dating, 0.89 ± 0.07 rings/yr, and results from Hancock et al. (2006), 0.80 ± 0.08 rings/yr. Second, since we are more interested in the ring production rate of trees growing on gully inset-floodplains, a production rate of **0.40 ± 0.03 rings/yr** was also utilized as a lower end member, which was estimated from carbon-14 dating of trees growing within the gully.

Using these two above ring production estimates, the average ring counts for the fifteen (15) Coolibah trees growing within KWGC2 on the gully inset-floodplain (Figure 5-3; Figure 5-5) were converted to tree ages (Figure 5-7), while propagating 1σ of error in both ring count and ring production rate. These ages were regressed against channel thalweg distance upstream (Figure 5-7) and straight line valley distance upstream (Figure 5-8). These regressions represent potential colonization rates of trees re-establishing within the gully inset-floodplain. Using the thalweg distance as a reference, trees colonized the gully on average 17 m/yr when the rate 0.74 ± 0.15 rings/yr was used, while colonizing at 9.2 m/yr when the rate 0.40 ± 0.05 rings/yr was used (Figure 5-7). When the upstream straight line valley distance was used rather than thalweg distance, the rate of tree colonization onto gully inset-floodplains was 13.5 m/yr (0.74 ± 0.15 rings/yr) and 7.3 m/yr (0.40 ± 0.05 rings/yr) respectively (Figure 5-8).

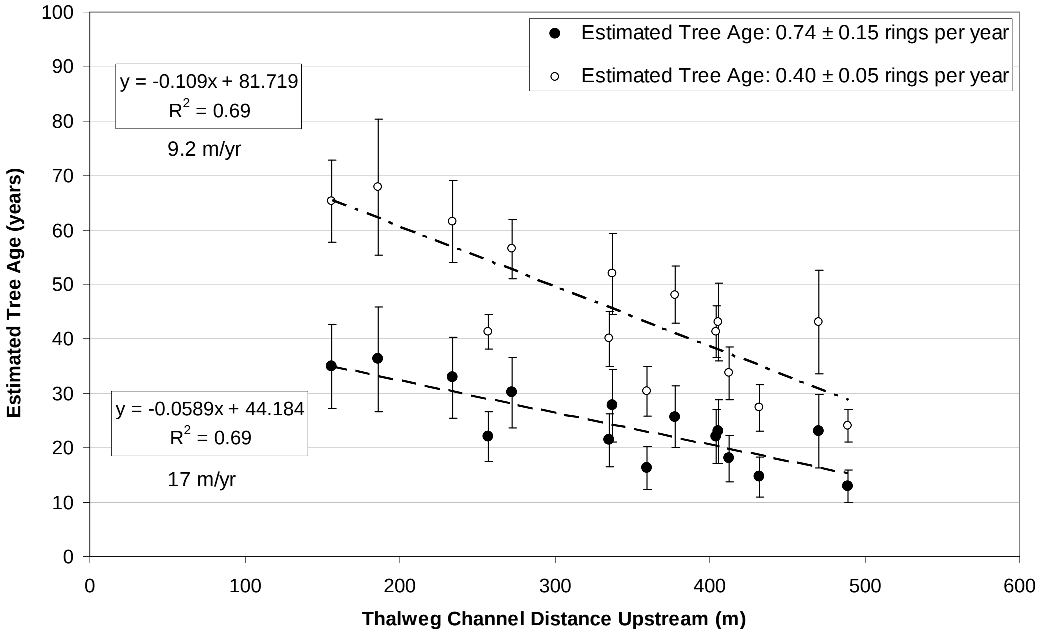


Figure 5-7 Relationship between thalweg channel distance upstream from the outlet of the gully and estimated Coolibah tree age on the gully inset-floodplain after the passage of the gully front. Error bars are 1 standard deviation around the mean propagated from respective errors in ring count and age errors.

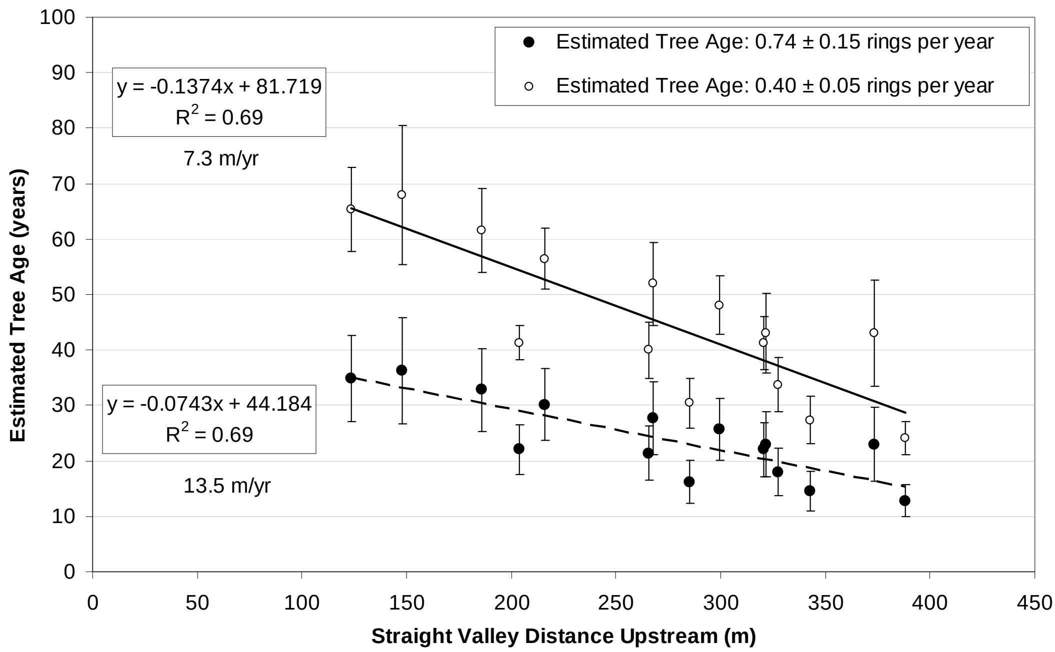


Figure 5-8 Relationship between the straight-line valley-distance upstream from the outlet of the gully and estimated Coolibah tree age on the gully inset-floodplain after the passage of the gully front. Error bars are 1 standard deviation around the mean propagated from respective errors in ring count and age errors.

These different estimates of tree ages from radium radionuclide and radiocarbon analyses, along with subsequent estimates of tree colonization rates onto gully inset-floodplains, were compared to the progression of gully scarp erosion delineated from air photographs between 1958 and 2007 (Figure 5-9). Both gully area and gully volume data (estimated from LiDAR) demonstrate that area and volume increased linearly over time at this site (Figure 5-10). Back trending changes in gully area and volume suggest that gully initiation occurred between 1940 and 1950. Therefore, all trees that have colonized gully inset-floodplains (post-erosion features) should be younger than a maximum of 67 years (i.e., 1940-2007).

Many of these gully inset-floodplains were not present in 1958, 49 years before 2007 (Figure 5-3; Figure 5-9). However by 1958 the gully had already progressed past the locations of trees 23, 01, and 10, so these trees could have established before 1958. Alternatively, they also could have established after 1958 due to a time lag of colonization. Therefore, the air photo evidence of exact dates of tree colonization remains unclear due to photo resolution. The black points within the gully floor area in 1958 (Figure 5-3; Figure 5-9), could be either 1) live trees that survived the initial wave of gully erosion via root buttressing (Figure 5-1a), 2) live trees that temporarily survived erosion on soil pedestals, 3) live tree that began recolonizing the gully floor after erosion (Figure 5-1b), or 4) wood of dead trees post-erosion.

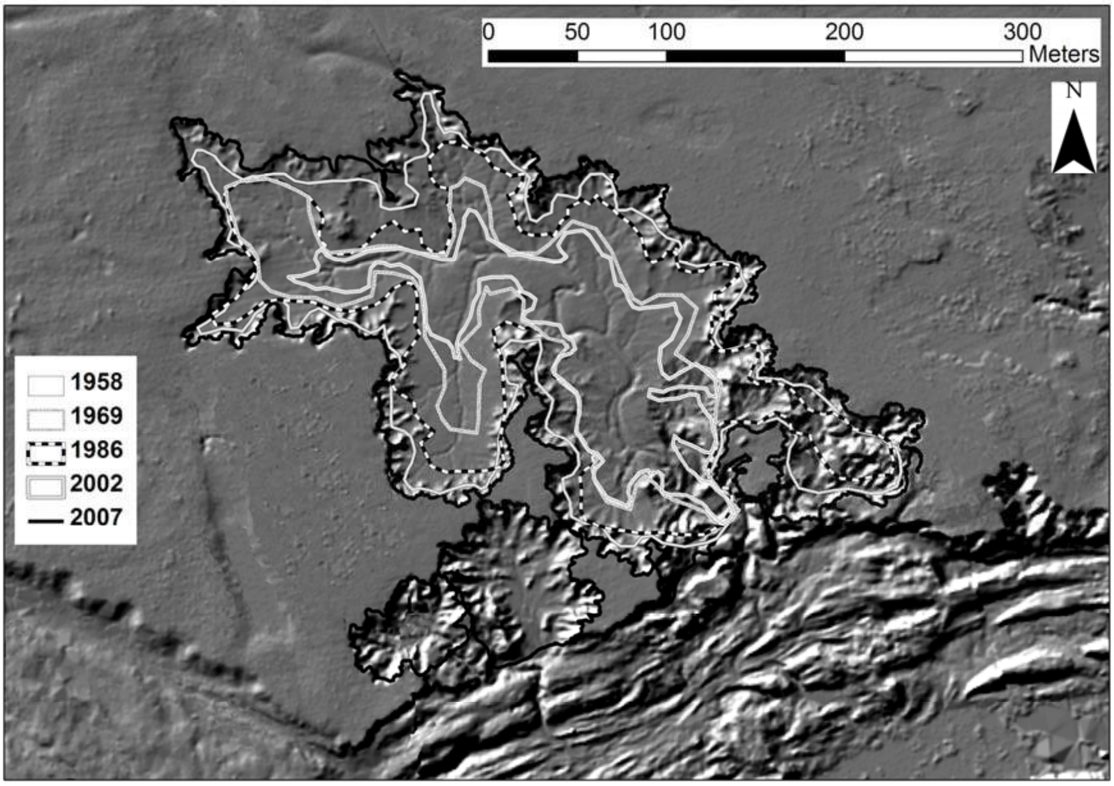


Figure 5-9 Locations of the gully head scarp at KWGC2, delineated from air photographs between 1958 and 2007, with 2008 LiDAR hillshade in background.

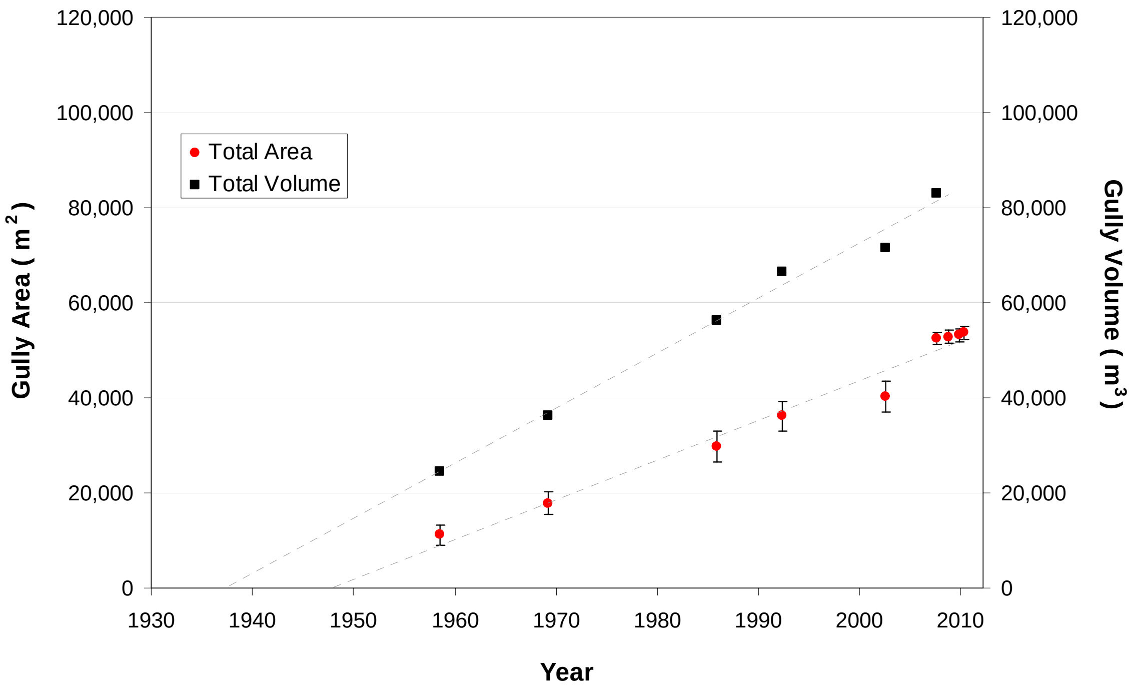


Figure 5-10 Gully area and volume changes over time at near KWGC2, Sandy Creek.

A further comparison was made between average and maximum linear erosion rates from air photographs and linear colonization rates of *Eucalyptus microtheca.* For all air photos between 1958 and 2007, average linear erosion rates (change area / perimeter) varied between 0.25 and 0.90 m/yr. Maximum rates did not exceed 6 m/yr and averaged 2 m/yr. These maximum rates are less than the 13 to 17 m/yr average tree colonization rates calculated using a ring production rate of 0.74 ± 0.15 rings/yr. They are also lower than 7 to 10 m/yr average tree colonization rates calculated using a ring production rate of 0.40 ± 0.03 rings/yr. Arguably, the colonization rate data obtained from the later and lower ring production rate of 0.40 ± 0.03 rings/yr relates better than the maximum rates of scarp retreat of 2 to 6 m/yr. In addition, the maximum rates of headward retreat could have been higher during early stages of gully development before the 1958 photograph. Indeed, the extension of gully heads can follow a negative exponential decay function, with rapid initial change followed by a longer relaxation period towards stability (e.g., Graf 1977), which could have been the case in KWGC2 pre-1958 (Figure 5-10).

5.4 Discussion

5.4.1 Dating techniques

Radium results in this study and the more detailed results from Hancock et al. (2006) confirm that radium activities across *Eucalyptus* heartwood and sapwood can be used to independently determine tree age and growth rates. However, numerous pitfalls in these techniques were highlighted that need to be addressed in more detail during future efforts. These include 1) waiting for a longer in-growth period of 12 or more months for ^{228}Ra decay into ^{228}Th before alpha spectrometry, 2) more careful laboratory procedures to maximize the percent recovery of radium and tracer activities, 3) starting with additional dry wood and ash mass to ensure detectable activities of radionuclides, and 4) accepting the constraint of a maximum dateable tree ring age using this radium technique due to the short half-lives of ^{228}Ra and ^{228}Th and their detection limits. Long in-growth periods could be avoided in the future by the use of liquid scintillation counting techniques to measure Actinium-228 activities from beta (electron) emission during the decay of ^{228}Ra to ^{228}Ac to ^{228}Th.

The most important improvement could be in obtaining sufficient mass from tree rings. This could be achieved by combining the mass of the same ring(s) from multiple tree sections of the same tree. Since ring boundaries are often not perpendicular to cut surfaces, increasing the disk thickness is not an option due to the potential for cross-contamination with other non-target rings. However, multiple narrow tree sections could all be analysed for tree ring boundaries and counts and the mass from the same rings sections added together to obtain a larger sample size. Due to a degree of subjectivity in ring identification, counts, and sample locations in these

Eucalyptus microtheca trees, future efforts should take advantage of new technologies to quantitatively identify seasonal or annual ring boundaries and patterns. For example, wood growth boundaries can be located by automated non-destructive measurements of wood density by x-ray radiography and densitometry (Croudace et al. 2006; Helama et al. 2008) or trace element chemistry by X-ray fluorescence (Croudace et al. 2006) or synchrotron radiation induced X-ray emission (Poussart et al. 2006).

Carbon-14 analysis of tree wood was more straightforward than radium radionuclide analysis, mostly due to the more developed and standardized analysis techniques for trees and the small sample mass required. However both dating techniques required significant laboratory labour inputs per sample and both are likely equally valid. For trees younger than 1955, the ^{14}C techniques has the advantage that only two samples are needed to determine the tree age from the bomb-pulse curve. However, for trees older than 1955, additional samples are required for age determination, increasing labour and costs.

5.4.2 Geomorphic implications

Measured tree ring growth rates varied in this study depending on micro-site growing environment (gully inset- or river high-floodplain) and possibly climatic variability over different time scales. Thus, extrapolation of tree ring growth rates to other nearby or regional environments should be used with caution until additional data on local growth variability is determined by species. However overall for geomorphic purposes in northern Australia, dating *Eucalyptus* trees using radium-228/226 and carbon-14 radionuclide activities remains promising and does provide some age constraints on the timing of gully erosion.

Without more data on initial erosion rates and tree ages, the relationship between tree colonization rates and headward erosion rates remains unclear. If the air photo data are representative of early maximum erosion rates (< 6m/yr), and trees colonized at a rate between 7 and 17 m/yr, then these rate data support the concept of a time lag between the onset of erosion and the development of conditions suitable for tree colonization. Early in the erosion cycle, tree mortality of pre-existing trees would dominate on pre-erosion surfaces being affected by gully expansion, and conditions within the gully would be rapidly changing and unsuitable for vegetation colonization. However as erosion scarps migrated headward, new gully channels would evolve with fresh material supplied from upstream, creating small gully inset-floodplains with more suitable soil and water conditions. Once developed into suitable habitat, these surfaces would be colonized by Eucalyptus seedlings supplied from the surrounding intact woodlands. In conclusion, gully inset-floodplain formation and tree colonization occurs over a shorter and more recent time span than the total cycle of gully erosion. Dating trees that have colonized gully inset-floodplains post-erosion provides a minimum age of the development of the gully at any particular point, due to this disequilibrium.

The use of trees that originally colonized onto the river high-floodplain surface deserves more attention. The age of these trees could provide for a maximum age of erosion, and thus constrain the rates of colonization of trees on the gully floor. However the maximum potential age of a given tree species could limit their potential use backward in time. For example, Mucha (1979) hypothesized that trees in monsoonal savanna environments in northern Australia would rarely surpass 100-years of age. Furthermore at KWGC2, most pre-erosion trees only exist along the margins of the current or past gully scarps. No large pre-erosion trees exist near the bottom origin of the gully, as most were eroded away or have decayed. Several standing dead trees exist on remaining soil pedestals partially extending into the gully, which if also dated may provide insight into the maximum age of gully erosion

5.5 Conclusions

Overall, this study demonstrated that *Eucalyptus microtheca* trees surviving the passage of an alluvial gully head cut or re-colonizing gully inset-floodplains can be dated with radium-226/228 and carbon-14 radionuclides, but that wood analysis, sampling and laboratory techniques could be improved upon for enhanced precision. As confirmed by independent air photographs, tree ages on gully inset-floodplains can used to define the minimum time of gully initiation. Due to lag times between scarp retreat, gully inset-floodplain development, and tree colonization, tree ages along the longitudinal gully continuum can only estimate maximum rates of gully expansion. Additional dating of trees growing in the river high-floodplain that survived gully retreat could be useful in constraining the maximum time of gully initiation.

Chapter Six: Alluvial Gully Erosion Rates Across the Mitchell River Fluvial Megafan

6.1 Introduction

Gully erosion is a global phenomenon, a major cause of severe land degradation, and an important source of sediment pollution that reduces water quality and degrades aquatic ecosystems (Oldeman et al. 1990; Lal 1992; Poesen et al. 2003; Valentin et al. 2005). Catchments across northern Australian have undergone major land-use changes from traditional Aboriginal management to widespread cattle grazing on unimproved rangeland since European settlement. Numerous studies in northern Australia rangelands have documented irreversible changes in vegetation conditions from the introduction of cattle grazing, changes in fire regimes, and spread of exotic species (Fensham and Skull 1999; Crowley and Garnett 1998, 2000; Sharp and Whittaker 2003; Bowman et al. 2004; Sharp and Bowman 2004). However, relatively few studies have quantified the pre- and post-European changes in gully erosion and sediment yield as a result of rangeland cattle grazing impacts in northern Australia, despite numerous assessments suggesting likely changes (e.g., Medcalff 1944; Payne et al. 1979; Condon 1986; Wasson 2002; McCloskey 2010). In south-eastern Australia in contrast, dramatically increased sediment yields from soil, gully, and channel erosion post-European settlement have been well documented, which was a result of the introduction of hard-hoofed cattle and sheep grazing, in addition to tree clearing on hillslopes and along channels (e.g., Eyles 1977; Prosser et al. 1994; Prosser and Winchester 1996; Brooks and Brierley 1997; Wasson et al. 1998; Brooks et al. 2003; Olley and Wasson, 2003; Rustomji and Pietsch 2007). Rangeland degradation leading to extensive gully erosion and increased sediment yields has also been well documented in more remote arid regions of Australia (Condon et al. 1969; Wasson and Galloway 1986; Pickup 1991; Fanning et al. 1999; McKeon et al. 2004; Pringle et al. 2006; Stafford Smith et al. 2007).

On Cape York in northern Queensland, detailed remote sensing mapping within the 31,000 km^2 Mitchell River fluvial megafan has identified that alluvial gullying into near-river, highly-dispersible floodplain soils occupies a minimum of 0.4% (129 km^2) of the land area, with an estimated active front length of around 5,560 km (Brooks et al. 2009; Chapter Two). It is estimated that these gullies erode > 5 Mt/yr of alluvial soil (Brooks et al. 2008). The degree to which these recent erosion rates represent natural background rates has been unquantified until now. Understanding rates of gully erosion pre- and post-European settlement is essential to defining past human land-use impacts and the sensitivity of the landscape to further development. The erosion of these soils presents a major threat to the local pastoral industry and sustainable cattle production, as well as to downstream aquatic ecosystems and the cultural use of water bodies.

The objective of this chapter was to quantify how gully erosion rates (linear and volumetric) have changed over different time scales, potentially as a result of the European settlement and cattle introduction. Erosion rates were estimated using recent GPS surveys, historic air photo delineation, geomorphic analysis using LiDAR, and field observations. These data were supplemented with optical stimulated luminescent (OSL) dating of stratigraphic deposits within gully inset-floodplains to constrain the timing of pre- and post-European erosion. Historic explorer accounts of earlier gully types and archival records of cattle numbers and land management were also reviewed. The results are summarized into a conceptual model of the evolution of alluvial gully erosion in the Mitchell River, and a process-based understanding of the stability of landforms and a threshold response to disturbance.

6.2 Methods

6.2.1 Study sites

The study area is located in the Mitchell River catchment (71,630 km^2) in tropical northern Queensland, Australia and is concentrated in the lower half of the catchment where vast savanna woodlands and alluvial plains of the Mitchell fluvial megafan cover 31,000 km^2 (Figure 6-1). A representative subset of alluvial gullies was selected based on the overall population of gullies distributed across the Mitchell River megafan (Brooks et al. 2008; Brooks et al. 2009; Chapter Two) (Figure 6-1). Road induced gullying and rilling is an additional land-use impact not addressed in this paper, despite it being widely observed across the lower Mitchell catchment. More specific details on the geomorphology, hydrology, soils, vegetation, and erosion dynamics of the gully study sites and Mitchell fluvial megafan can be found in Brooks et al. (2008; 2009; Chapter Two, Chapter Three, Chapter Four, and Chapter Five).

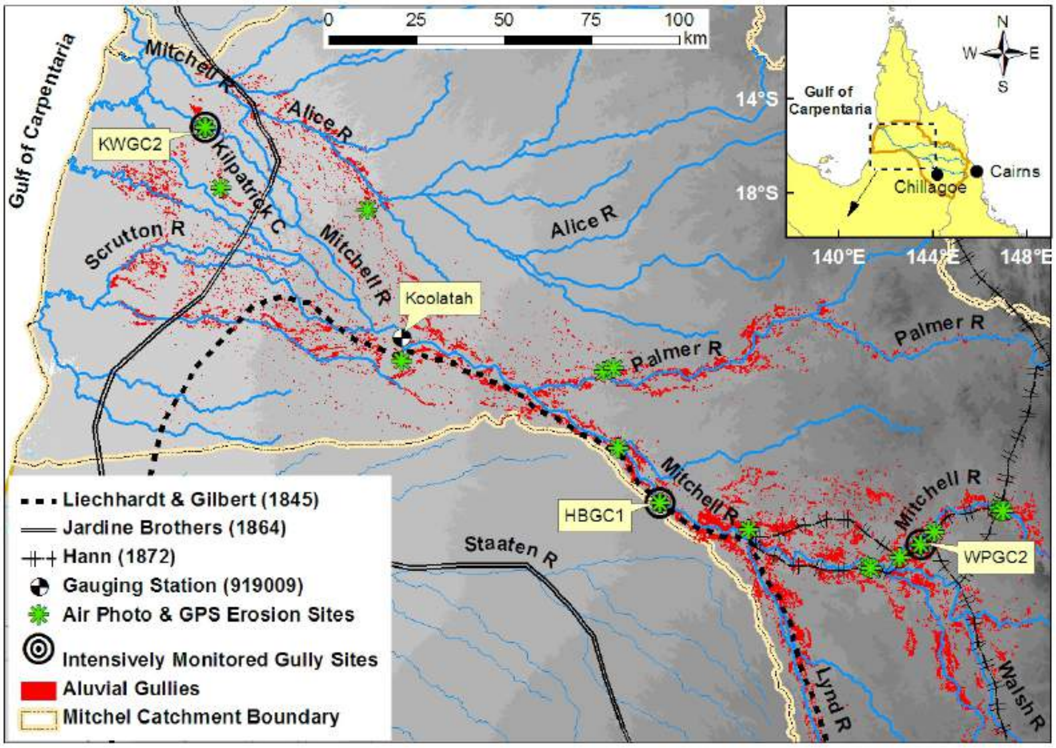


Figure 6-1 Study area along the lower Mitchell River fluvial megafan, locations of study sites, main Mitchell River gauging station at Koolatah, ASTER derived distribution of alluvial gullies, and *approximate* tracks of early European explorers. The greyscale background represents 30m elevation bands derived from the 1-sec SRTM DEM.

6.2.2 Recent erosion rates at gully fronts from GPS surveys

Annual surveys (2005-2010) of selected alluvial gully fronts (scarps) in the Mitchell megafan were conducted using differential GPS with sub-meter accuracy (Trimble with Omnistar High Precision). Accuracy depended on signal strength and vegetation cover, but was typically below 0.5 m for repeat surveys. GPS surveys were conducted at 18 sites across the alluvial megafan (Figure 6-1), totalling 50,040 m of gully front. Gully expansion measured by average scarp retreat rate was determined from annual surveys in 2005 (partial), 2006 (partial), 2007, 2008, and 2009, and 2010 (partial). The average linear erosion rate (m/yr) was calculated as the total area of change (m^2) between any two survey-years divided by the total common survey length (m) of active gully perimeter. Error margins of gully area for a given survey year were calculated by buffering each survey line by ± 0.50 m (1 m total buffer width). Maximum linear rates were calculated for individual lobes of headwater extension.

6.2.3 Historic erosion rates at gully fronts from air photos

Historical air photographs (1949-2006) were obtained for the same 18 study sites (Figure 6-1) to assess the historic location and rates of gully front erosion. The earliest air photographs were from either 1949 or 1955, with repeat photographs taken approximately every decade. The availability of air photos for each gully site differed, with the average number of photos between

1949-2006 being 4.8 and ranging from 3 to 7. The photo scale ranged from 1:20,000 to 1:85,000, with the first (1949, 1:23,900) and last photos (2006, 1:20,000) being of the highest resolution.

Digital copies of photos were scanned from either Queensland State archives or the Australian National Library by either 1) a desktop scanner at 2400 dpi for photo hardcopies, or 2) a Leica film negative scanner down to the grain size of the photo (15um) for photo negatives. Recent photos (2000's) were obtained in 2006 and 2008 during the collection of LiDAR (Light Detection and Ranging) laser altimetry data used to create 1 m^2 DEMs (Digital Elevation Models). Thus, the air photograph analysis covered a typical period of 57 years (1949 to 2006) with ground GPS surveys and LiDAR extending the scarp location coverage to 2010 (61 years).

Digital files clipped to the general gully area of interest were then imported into a Geographic Information System (ArcMap 9.3). Georeferencing was conducted backward through time starting with recent air photos and LiDAR, GPS surveys of current gully locations, and ASTER satellite imagery. Historic air photos were georeferenced to this recent information using ground control points consistently identifiable between photos, which were most often large trees, but also fence lines, roads, and stable fluvial features.

Once rectified, the location of the gully head scarp was digitized and the total area occupied by the eroded area was calculated and compared between years. A total of 43,163m of common gully front was repeatedly measured. Annual average linear erosion rates (m/yr) were calculated by dividing the area change (m^2) over two consecutive time periods (years) by the scarp perimeter (m) measured at the later timer period. Error margins of gully area for a given survey year were calculated by buffering each survey line by ± 2 m (4 m total buffer width).

The zero area or starting point for each gully was located at either 1) the confluence of the gully channel with the mainstem river or lagoon water body, 2) the confluence of the gully with a much larger well vegetated tributary creek, or 3) the transition between bare amphitheatre gully complexes and their very narrow outlet channels (creeks) that traverse well vegetated riparian zones. In the later case, these vegetated channels and their initial *linear* erosion and elongation over time are un-mappable from air photos, and thus not quantified in this analysis.

6.2.4 Alluvial gully sediment production across the Mitchell megafan

Brooks et al. (2008; 2009; Chapter Two) mapped the distribution and density of alluvial gullies across the Mitchell megafan (Figure 6-1) and estimated that > 5 Mt/yr of alluvial sediment (sand/silt/clay) are eroded from these gullies. This estimate was based on a combination of preliminary GPS measurements of linear retreat, estimates of scarp heights from LiDAR, field measurements and floodplain elevation, assumptions of average bulk density, and estimates of gully distribution and scarp front length from remote sensing using ASTER and Quickbird.

Here, new estimates of alluvial sediment production are given based on new data on scarp retreat rates from historic air photos (1949-2006) and GPS (2005-2010), in addition to field measurements of bulk density. Similar data sets to Brooks et al. (2008; 2009; Chapter Two) are used for estimating the scarp heights across the megafan, and the length of gully scarp perimeter in 1 km^2 grid cells. However, the later was slightly modified to exclude some initially misclassified gullies on the Lynd and Walsh Rivers (Figure 6-1) due to errors in the geologic mapping of true alluvial units. The median (50^{th} percentile) scarp retreat rates from either historic air photos or GPS were used uniformly across the Mitchell megafan, but the $25^{th}/75^{th}$ percentile values were again used to calculate error margins around sediment production estimates.

For comparative sediment budget purposes, the measured fine sediment load at the lowest river gauge on the Mitchell (Koolatah, 919009; Figure 3-1; Figure 6-1;) was compared to the estimated sediment production from alluvial gullies upstream of the gauge. Gauge load estimates were based on water discharge data from 1973 to 2009, along with 80 measurements of surface total suspended solids (TSS) concentration over the same period (QDERM 2011). Sediment concentration samples were collected via non-isokinetic grab samples at the water surface, which are not representative of average depth-integrated concentrations during flood (Edwards and Glysson 1998; Shellberg and Brooks, unpublished data from Koolatah gauge, 2009 flood). The samples were also analysed using the TSS protocol rather than the SSC protocol, with the former known to bias against sand sized particles during subsampling (Gray et al. 2000). Thus, surface TSS samples were assumed to be representative of washload <63 μm dominated by silt and clay. These surface washload concentrations were used with instantaneous discharge data to construct a rating curve for the period of record, from which the median annual washload was calculated along with the $25^{th}/75^{th}$ percentile annual washload. For comparison to this gauged washload, sediment production from alluvial gullies upstream of the Koolatah gauge was adjusted downward by 40%, to account for the coarser 40% of the alluvial soil particle size distribution (i.e. > 63 μm) that becomes part of the bed material load (Chapter Four).

6.2.5 Analysis of gully expansion over time

The change in exposed gully area over time (1949-2010) was determined for different sites using the combination of historic photo and recent GPS data. Trends were analysed by fitting exponential, linear, and logarithmic functions to the data and evaluated for goodness of fit by the coefficient of determination (r^2). According to disturbance and relaxation theory (e.g., Schumm 1977), it was initially hypothesized that trends in gully area would follow a negative exponential function describing the non-linear rates of change in unstable channels that often have declining rates of growth (or incision) over time (e.g., Graf 1977; Simon 1992; Rutherfurd et al. 1997; Whitford et al. 2010). A slightly modified version was adopted here for analysing increases in gully planform area over time:

$$\frac{A}{A_0} = a + be^{(-kt)} \qquad (6\text{-}1)$$

where A is the exposed gully area at time *t*, A_0 is the initial gully area at $t_0 = 0$, *a* and *b* are dimensionless coefficients determined by regression, *k* is a coefficient determined by regression that defines the rate of change in gully area over time, and *t* is the time (years) since the initial starting point or the first air photograph. When *k* is very small, the equation approaches linearity. Since gully area always increases with time (regardless of rate), *a* in this case is always positive ($a>0$).

As a comparison to this negative exponential function and hypothesis, more simplistic linear and logarithmic functions were also fitted to the data using:

$$\frac{A}{A_0} = (a \times t) - b \qquad (6\text{-}2)$$

$$\frac{A}{A_0} = a \times \ln(t) - b \qquad (6\text{-}3)$$

where A/A_0 is a normalized measure of relative gully area, A is the exposed gully area at time *t*, A_0 is the initial gully area at $t_0 = 0$ at the first air photograph, *a* and *b* are dimensionless coefficients determined by regression, and *t* is the time (years) since the initial starting point or the first air photograph.

6.2.6 LiDAR volumetric erosion estimates over time

Changes in gully area are only a surrogate for sediment yield over time, with estimates of sediment volume or mass over time being more useful for evolutionary growth analysis and sediment budgets. At the three intensively monitored gully sites (Figure 6-1; WPGC2, HBGC1, KWGC2), LiDAR DEM data (1 m^2) collected in 2008 were used in conjunction with historic scarp locations to analyse the changes in gully volume and mass over time. To estimate the pre-gully erosion surface topography, an inverse distance weighted (IDW) algorithm (power 2; 500

point search radius) was used to interpolate across the eroded gully from elevation data at uneroded points around the perimeter of the gully and uneroded pedestals remaining within the gully, similar to Perroy et al. (2010). Elevation data from uneroded pedestals and surfaces were important in defining the subtle slope and swale forms of pre-existing surfaces. The 2008 gully volume was calculated by subtracting the LiDAR DEM elevations from the interpolated pre-gully surface elevations. Historic gully volume estimates were calculated in a similar way, but the DEMs were clipped to gully area extent defined from historic air photos for those periods. This method assumes a vertical head scarp at the scarp line and complete export of sediment from the gully network, which are first order assumptions for a gully eroding into dispersible silts and clays. Additional volume changes into 2009 and 2010 were estimated from GPS measured area change times the average scarp depth measured from longitudinal profiles. Measurement of soil bulk density at each site allowed for the conversion of these volume changes into mass changes over time.

6.2.7 Past gully erosion chronologies from OSL dating

To quantify erosion timing and rates before the first 1949 air photos, alluvial sediment deposits from gully walls and gully inset-floodplains at two gully complexes (WPGC2; HBGC1, Figure 6-1) were dated using single-grain optically stimulated luminescence (OSL) (Aitken 1998; Olley et al. 2004; Pietsch 2009). Sample sites were chosen toward the middle of the gully complexes to ensure that the sedimentary units were dominated by gully outwash sediment, and not sediment deposited from river backwater conditions. Sediment profiles were exposed at natural cut banks and enhanced by shovel. Major stratigraphic breaks were defined and sampled for OSL, such as the contact between uneroded sediment (pre-gully material) and more recent deposition following gully retreat. Ten (11) discrete sediment samples at WPGC2 and four (4) at HBGC1 were collected for OSL dating.

When quartz grains are buried within a sediment profile, they begin to accumulate a trapped charge in the mineral imperfections of quartz, due to stimulating radiation energy in the surrounding soil and atmospheric environment. Over burial time, they accumulate an electron charge in a predicable fashion. This charge can be measured from the luminescence signal of a grain(s) when stimulated with light (typically green) in a laboratory environment (Aitken 1998). In the natural environment, exposure to sunlight will also release the trapped charge within seconds and reset or “bleach” the OSL signal. The burial age (years) can be determined from the equivalent dose (D_e, Grays) the grain(s) received cumulatively over time and the dose rate (D_r, Grays/year) received from radiation in the surrounding environment (Aitken 1998).

$$Age_{Burial} = \frac{D_e}{D_r} \quad (6\text{-}4)$$

To obtain samples that were not exposed to sunlight, stainless steel tubes were driven horizontally into vertical profiles. Sealed samples were reopened in a red-light (non-UV) laboratory environment. The potentially field-contaminated end-sediments of the tubes were used for both water content determination and dose rate determination. The latter was calculated from soil radionuclide activities measured using gamma spectrometry (Murray et al. 1987), conversion factors from Stokes et al. (2003), and beta-dose attenuation factors from Mejdahl (1979). Sediment in the center of the sample tube was used for OSL analysis following methods in Olley et al. (2004) and Pietsch (2009). Samples were sieved to the 180–212um size class, both heavy (zircon) and light (feldspar) minerals were separated from quartz using heavy-liquid density-separation, and quartz grains were then etched in 40% hydrofluoric acid for 50 min to remove the outer 10 um rind and to completely remove any feldspar. OSL measurements were made on a Risø TL/OSL DA-15 reader using a green (532 nm) laser for optical stimulation, and the ultraviolet emissions were detected by an Electron Tubes 9235QA photomultiplier tube fitted with 7.5 mm of Hoya U-340 filter. Laboratory irradiations were conducted using a calibrated 90Sr/90Y beta source mounted on the reader.

A modified single-aliquot regenerative-dose (SAR) protocol was used (Olley et al. 2004), to determine the full dose response curve for each aliquot (grain). For each OSL sample, 1000 single-grain aliquots were typically analysed for their OSL signal and the equivalent doses were determined from dose-response curves. Grains that responded poorly to test doses with a resulting poorly developed dose-response curve were rejected from further analysis, which often was > 95% of the grains. The remaining grains and data were used as a representative sample of the D_e values of the overall population of grains.

Olley et al. (2004) and others have found that for fluvial sediment, partial bleaching and partial exposure to sunlight during sediment transport can incompletely reset the OSL signal for a percentage of grains, which can lead to an overestimation of age due to retained earlier dose. Single-grain analysis circumvents the averaging of D_e values from multiple-grain aliquots. However, positively-skewed asymmetric-distributions of D_e from single grains are still common due to the mixture of fully and partially bleached grains (see Appendix). To address this skew, Olley et al. (2004) demonstrated that a “minimum age model” targeting the “leading edge” of the D_e distribution developed by Galbraith et al. (1999) was a rigorous way to determine the true burial dose, rather than using the central tendency of the skewed D_e data. Subsequently, Pietsch (2009) analysed several methodologies and determined that fitting a “single Gaussian curve to the peak of a multi-Gaussian summed probability distribution" was a robust method for determining the true burial dose for young fluvial sediment. This method was also adopted here.

6.2.8 Historic European Explorers in the Mitchell

Only a few European explorers traversed the lower Mitchell River pre-1880 before extensive cattle grazing and mining. The most notable was the journey of Ludwig Leichhardt, accompanied by the ornithologist John Gilbert, who in 1845 travelled down the Lynd River to the Mitchell River junction and then downstream along the Mitchell toward the upper delta (Figure 6-1). Journal entries by Gilbert along this leg of the trip would be his last, as he was killed by Aboriginal people on 28 June 1845 near the bottom of the Mitchell catchment (Leichhardt 1847, Chisholm 1940). Transcripts of the independent but parallel diaries of Ludwig Leichhardt and John Gilbert (Gilbert 1845, Leichhardt 1847) were analysed for location and description information in relation to soil erosion, gullies, creeks, rivers, and fluvial processes. The subsequent journals of the 1864 expedition of the Jardine Brothers (Jardine and Jardine, 1867) and the 1872 mineral exploration of William Hann (Hann 1872) were also analysed. The Jardine Brothers crossed the lower Mitchell River delta in an area down river of that explored by Leichhardt and Gilbert. William Hann explored the Mitchell catchment upstream of the Lynd/Mitchell confluence in an area also not observed by Leichhardt and Gilbert (Figure 6-1).

6.2.9 Historic land use and cattle statistics

Historical data post-European settlement (~1870) on land use, land condition, and introduced cattle numbers for specific cattle stations or "runs" were obtained from the Queensland State Archives, as an indicator of land-use change over time. For each cattle station leased from the public Commonwealth or State government, a "run file" was kept by the Public Lands Office. For most stations, these files documented the establishment of the run and lease, transfers and lease renewal, and most importantly cattle stocking rates, general land use and condition, and "improvement" infrastructure (fencing and water development). Fairly diligent records were kept up to the 1960's, after which non-archived public records ironically become less detailed. The run files for the following stations in the lower Mitchell catchment were obtained from the State Achieves to assess the information they contained: Mount Mulgrave, Frome #2, Wrotham Park, Gamboola, Gamboola South, Highbury, and Drumduff. For much of this period, all of the above except Mulgrave and Frome were managed as one large aggregated cattle station (Arnold 1997). Cattle numbers over time for this Wrotham Park Aggregation were used as representative data for the study area, with cattle numbers post-disaggregation of stations added back into this one unit. These pre-1960's data were supplemented by additional published data on cattle numbers for the aggregation (Edye and Gillard 1985; Arnold 1997), in addition to personal communications with station managers. These regional data were also compared to historic beef-cattle numbers in Queensland from the Australian Bureau of Statistics.

6.2.10 Historic rainfall

Historic monthly rainfall totals for the periods of record at measurement stations in the Mitchell catchment were obtained from the Australian Bureau of Meteorology (ABOM 2011). Analysis focused on the continuous stations with the longest records from pre-1900 to 2011. Additional interpolated monthly rainfall data from water years (WY, Oct-Sept) 1901-2011 were obtained from the ABOM's interpolated 5-km (0.05°) gridded dataset for Australia, created following methods in Jones et al. (2009). These gridded monthly data were used to generate interpolated monthly datasets at key gully erosion sites to 1) analyse trends in rainfall and 2) correlate to gully scarp retreat measurements from the historic air photo record.

6.2.11 Future gully extent from profile and rate extrapolation

For future land-use management purposes, the ultimate extent of alluvial gully growth is a primary concern due to loss of productive land and infrastructure damage. From initial gully longitudinal profile analysis (e.g., Figure 2-8 in Brooks et al. 2009; Chapter Two) and measurements of scarp reteat and water and sediment yield (Chapter Three; Chapter Four), it was hypothesized that sand-bed gully-outlet channels would be at an equilibrium slope or grade, due to the regular water discharge from annual monsoonal rains and consistent sand bed-material supplied from gully scarp failure. A graded channel has a slope that is adjusted to the available water discharge and sediment supply (Mackin 1948; Lane 1955). The graded nature of the sinuous main channel should be in stark contrast to the degrading nature of the immediate gully scarp front. Over-steepened profiles actively incising into the floodplain landscape should flatten over time until the new equilibrium slope of the gully channel outlet is reached.

At each of the three intensively monitored gully sites (Figure 6-1; WPGC2, HBGC1, KWGC2), over fifty longitudinal profiles of the channel thalweg elevation were extracted from each LiDAR DEM. Each profile radiated out from the main channel along individual dendritic tributaries and extended through the gully scarp zone onto the flat terrain of the river high-floodplain. Future projections of the spatial expansion of gully area were made by forward trending the equilibrium slope of the outlet channel, common to all tributaries, through the scarp zone and into the uneroded alluvial plain. The ultimate erosion extent of the gully was located where this slope intersected the elevation of the relatively flat uneroded floodplain or the surface of another topographic feature. However, since the channel-slope within each gully was a sinuous thalweg slope rather than a straight-line valley-slope, the calculated straight distance from the current scarp edge to the future estimated scarp endpoint was adjusted to a straight-line valley distance by dividing this distance by the sinuosity of the outlet channel. Temporal estimates of when the gully scarp would reach a graded profile in all directions were made by projecting the 1949-2010 linear trends in gully area change into the future, until the relative gully area (A/A_0) spatially predicted by the profile extensions was reached.

6.3 Results

6.3.1 Erosion rates from recent GPS and historic air photos

From recent GPS measurements (2005-2010), the median rate of annual average scarp retreat (area change / scarp perimeter) was 0.23 m per year, which was calculated from 18 gully sites and 41 annual time steps across 50,040m of gully front. Measurements of erosion rates along surveyed gully fronts varied by site and by year (Figure 6-3). Similar to preliminary data in Brooks et al. (2009; Chapter Two) within individual gullies on any given year, scarp retreat was highest at active erosion lobes or alcoves (in planform) (Figure 6-2; Brooks et al. 2009; Chapter Two). Measurement of retreat rates along less-active inter-lobe zones (in planform) was less certain due to lower retreat rates and GPS error (± 50 cm). This resulted in error margin overlap between consecutive survey years (Figure 6-2; Brooks et al. 2009; Chapter Two), suggesting the GPS equipment utilized was close to its limits of usefulness for measuring annual change. Other techniques (e.g., RTK GPS, total station, terrestrial laser scanning) might be better suited to measure more subtle changes, otherwise reduced GPS survey frequency (e.g., every other year) could also be warranted if only general change was needed.

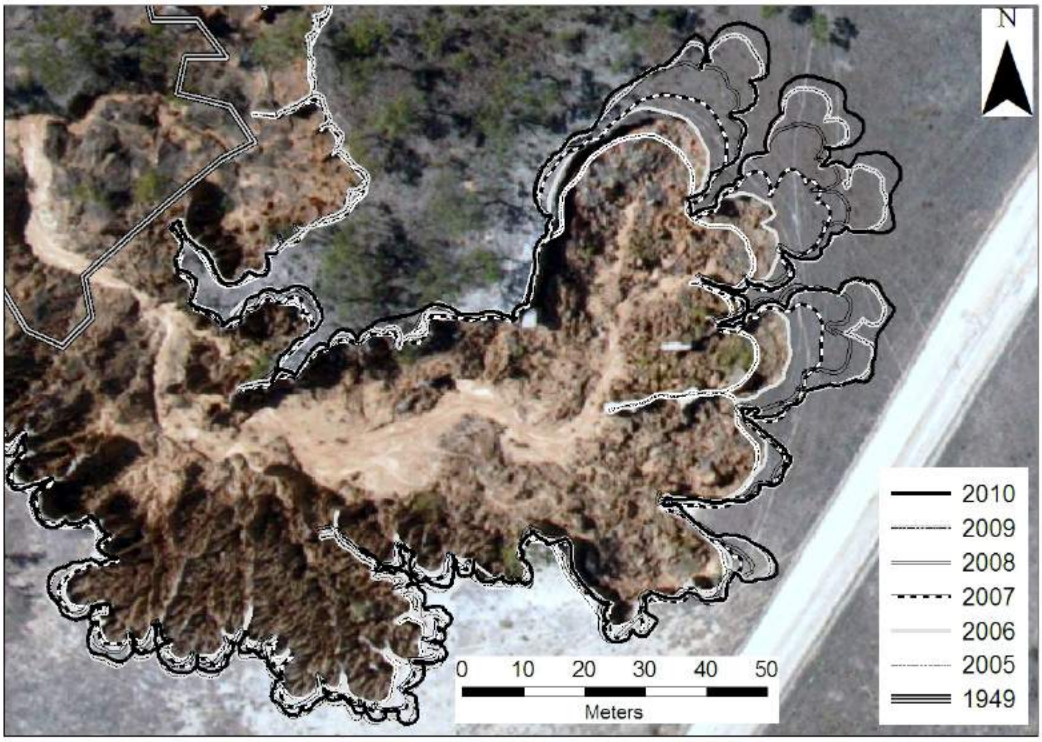


Figure 6-2 Annual gully scarp location between 2005 and 2010 at WPGC3 measured using GPS, with approximate 1949 position from historic air photo.

From historic air photos (1949-2006), the median rate of annual average scarp retreat (area change / scarp perimeter) was 0.37 m per year, which was calculated from 18 gully sites and 58 annual time steps across 43,163 m of gully front. Historic vs. recent data are within the same order of magnitude with median values between 0.2 and 0.4 m/yr, and maximum values less than ~1 m/yr (Figure 6-3). However, the two distributions (historic vs. recent) were significantly different from each other ($p=0.001$, $\alpha=0.1$; non-parametric Kruskal-Wallis one-way analysis of variance). When the historic rate data from air photos was split into two groups (1949-1975 and 1975-2006) excluding the GPS data, these groups were also significantly different from each other ($p=0.058$, $\alpha=0.1$), although less strongly. Comparing all three groups (1949-1975; 1975-2006; 2005-2010) using both photo and GPS data also showed strong statistical difference ($p<0.001$; $\alpha=0.1$).

These data suggests that either 1) average erosion rates have been decreasing slightly over time, as suggested by negative exponential decay (Graf 1977) or logarithmic trends, 2) variability in rainfall or other driving or resisting factors have changed through time, and/or 3) different measurement methods and measurement time scales are not directly comparable. Regarding the first point, only some gullies displayed declining aerial growth rates over time, while others followed linear rates of aerial growth (see Figure 6-5; Figure 6-6; Figure 6-7), which on average could have influenced these declining rate trends. On the second point, there was only a 76 mm average difference in annual WY rainfall between the two periods as influenced by the wet period in the early 1970's and the drought in the late 1980's (pre/post-1975, Figure 6-13b). The embedded daily, seasonal, annual, and decadal variation in rainfall during these two coarse time periods could have influenced the observed erosion rate differences (Figure 6-3), which will be analysed further below. On the third point above, it is possible that the more detailed GPS measurements at annual time steps capture different ratios of annual gully area change to perimeter length, as compared to ratios calculated by coarser air photographs and GIS digitized scarp perimeters at decadal time steps. This could also be the case for air photo derived rates calculated early in the life cycle of a gully when total perimeter lengths were relatively small compared to later lengths, which were often more convoluted for a given area. Furthermore, average linear erosion rates might differ from actual erosion volume, as a slower rate across a longer perimeter and shallower scarp might produce the same sediment volume as a faster rate over shorter perimeter and deeper scarp.

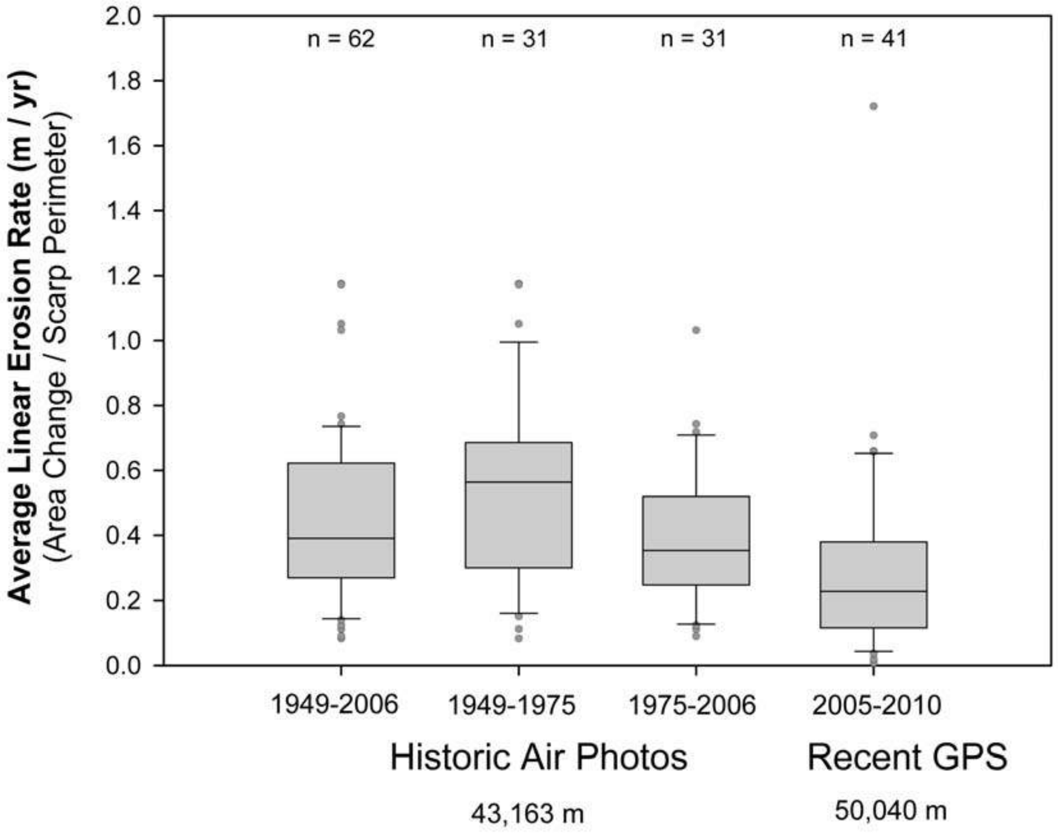


Figure 6-3 Comparison of annual average linear erosion rates (area change / scarp perimeter, m/year) measured from historic air photos and recent GPS surveys. Boxes represent 25th, 50th, 75th percentiles, whiskers represent 5th and 95th percentiles, and points represent outliers.

6.3.2 Alluvial gully sediment production across the Mitchell megafan

Updated estimates of sediment production from mapped alluvial gullies across the Mitchell megafan suggest that ~ 6.3 Mt/yr were eroded historically, compared to ~3.9 Mt/yr recently (Table 6-1). However there is still substantial uncertainty in these data due to the spatial and temporal variability in scarp retreat rates and the accuracy of mapping the density of all gullies at the landscape scale (Table 6-1; Brooks et al. 2008). The comparison of the median annual gauged washload at the Koolatah gauge (Figure 3-1; Figure 6-1) to the meadian annual fine sediment (<63 μm) inputs from alluvial gullies above the gauge suggests that a large percentage of the fine sediment delivered to the Mitchell River and tributaries from alluvial gully erosion is deposited into storage between the gully sources and gauge outlet (Table 6-1). This is supported by preliminary data of sedimentation rates on artificial tuff mats regularly exceeding 2 kg/m^2 on river inset-floodplains, benches and bars, measured in the main Mitchell River near WPGC2, HBGC1, Koolatah, and KWGC2 (Figure 6-1, Shellberg unpublished data). However, gauged washload at Koolatah should also be taken as minimum, as a considerable amount of water and fine sediment can bypass the gauge on the floodplain and in distributaries during annual flood recurrence intervals greater than 3 to 5 years (Chapter Three; Figure 3-4; Figure 3-5; Figure 3-7c).

The additional course bed material load (>63 μm) eroded from alluvial gullies (~40% of total) undoubtably contributes to the large stores of sand in the Mitchell mainstem (e.g., Brooks et al. 2008), in addition to total bed material loads. One recent hydrographic survey trip down the Mitchell in 2009 during flood conditions measured that 30 to 70% of the daily total load (washload + total bed material load) was sand bed material load (Brooks and Shellberg, unpublished data). If the median annual bed material load at the Koolatah gauge was taken to be the same relative magnitude as the median washload from gauge records (Table 6-1), then the historic median sediment production of sand (>63 μm) from alluvial gullies above Koolatah (~2,166,000 t/yr) would still be considerably larger than the output yield of sand.

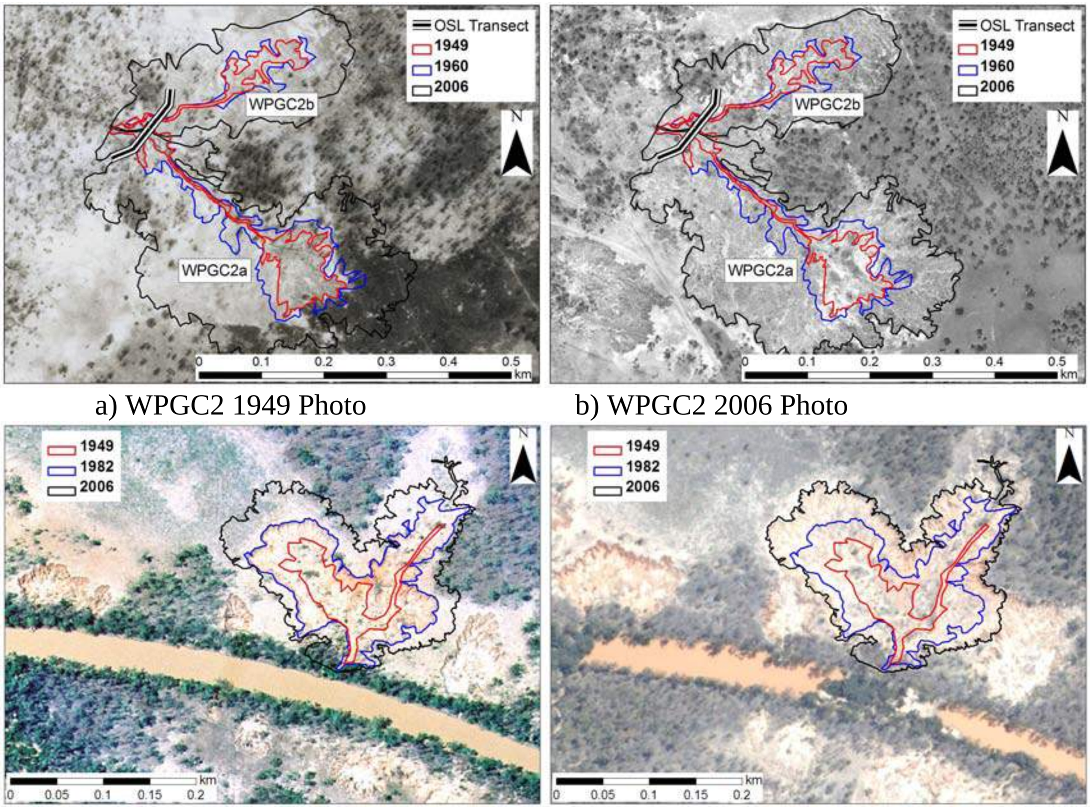
In total these data suggest that alluvial gullies along the floodplains of the Mitchell megafan are a major source of sediment at the catchment scale, regardless of the magnitudes of other upstream catchment sources. However, fine and coarse sediment storage in channels, floodplain water bodies, and floodplain surfaces appears to be large (e.g., Figure 6-4c-d; Table 6-1). Additional field data are needed to quantify the fate of the alluvial gully sediments once they are re-entrained back into the channel network after their initial storage period from the Pleistocene to Holocene.

Table 6-1 Sediment production from alluvial gully erosion (updated from Brooks et al. 2008).

Parameter	Median	25%	75%
Recent scarp retreat rate (2005-2010, GPS) (m/yr) (Figure 6-3)	0.23	0.12	0.37
Historic scarp retreat rate (1949-2006, Air Photo) (m/yr) (Figure 6-3)	0.37	0.22	0.59
Recent gully erosion, total for Mitchell megafan (t/yr) Bulk density 2000 kg/m^3	3,823,000	223,000	18,986,000
Historic gully erosion, total for Mitchell megafan (t/yr) Bulk density 2000 kg/m^3	6,150,000	447,000	28,722,000
Washload at Koolatah Gauge (919009) (1973-2009) (t/yr) (Mean annual washload = 1,633,000 t/yr)	796,000	239,000	2,188,000
Recent gully erosion, washload sediment, above Koolatah (t/yr) 60% < 63 µm, bulk density 2000 kg/m^3 (Percent % median gauged output / gully input)	2,020,000 (32%)	118,000 (104%)	10,032,000 (14%)
Historic gully erosion, washload sediment, above Koolatah (t/yr) 60% < 63 µm, bulk density 2000 kg/m^3 (Percent % median gauged output / gully input)	3,250,000 (20%)	236,000 (52%)	15,177,000 (9%)

6.3.3 Analysis of gully expansion over time

Georeferenced historic air photos, digitized gully head scarp locations, and GPS surveys of scarp locations showed progressive growth of all 18 gully complexes over the period 1949-2010 (e.g., Figure 6-4). These patterns of change from a variety of different alluvial gully environments across the Mitchell fluvial megafan demonstrate the non-static nature of gully scarps, the types of savanna woodland landscapes they consume, and the aquatic ecosystems they degrade by infilling with fine and coarse sediment.



a) WPGC2 1949 Photo b) WPGC2 2006 Photo

c) HBGC2 1982 Photo d) 2006 Photo

Figure 6-4 Changes in gully scarp location from a) 1949 to b) 2006 at Wrotham Park (WPGC2) with OSL transect location at bottom of gully complex, and c) 1982 to d) 2006 at Highbury (HBGC2) with 1949 area for reference. Note how the floodplain lagoon has in-filled from sediment derived from the expanding alluvial gullies.

Trends in relative gully area over time (A/A_0) from both historic photo and recent GPS data at gully sites displayed area increases 1.25 to 10 times the initial 1949 area (Figure 6-5). Fitting the initially hypothesized negative exponential function to these data (Equation 6-1) indicated that erosion rates were generally linear over time, with values of the coefficient k between 0.0007 to 0.0028. Sites with the highest average linear erosion rates (m/yr) and greatest relative expansion ($A/A_0 > 2$) had the smallest *k*-values, suggesting near linear areal expansion. Field observations indicated that these gully fronts had fairly constant annual expansion at their head scarps from undercutting and mass failure of soil blocks (e.g., Figure 2-11a in Chapter Two; Brooks et al. 2009). In contrast, other gully complexes with the low average linear erosion rates (m/yr) and small relative expansion ($A/A_0 < 2$) had larger k-values, suggesting non-linear trends with rapid initial growth and slower growth over time. Field observations indicated that these gully fronts were less influenced by undercutting and mass failure, and that erosion was dominated by direct rainfall and fluting and carving of the gully front face (e.g., Figure 2-11b in Chapter Two; Brooks et al. 2009). All but one of the gully sites had high r^2 values (>0.95) when fitting the exponential decay function (Equation 6-1).

Extrapolation of gully area growth trends backward in time towards a small initial relative gully area (A/A_0<<1) suggested that the gully initiation time period was evident for some gullies and less clear for others. For the fastest growing gullies (A/A_0 >2) with near linear rates, the time frame for initiation was between 1910 and 1950, which is within the period since cattle introduction (Figure 6-5). Often these gullies had the most identifiable staring points near the banks of rivers or lagoons. In contrast, slower growing gullies (A/A_0 <2) had less identifiable starting points and indeterminate initiation times around 1900 or before (Figure 6-5). However, the lack of air photo data before 1949 makes large extrapolations backward in time less certain for these slower growing gullies, in addition to the uncertainly due to choice of mathematical model for trend analysis.

For comparative purposes, linear (Equation 6-2) and logarithmic (Equation 6-3) models were also fitted to the data. Gully sites were split into two groups that had either: 1) apparent linear trends and fast growth rates (A/A_0 >2; Figure 6-6), or 2) apparent logarithmic trends and slower growth rates (A/A_0 <2; Figure 6-7). The linear group had an average r^2 value of 0.990 for the linear function (Figure 6-6), with comparable values of 0.985 and 0.975 for negative exponential and logarithmic functions, respectively, fit to the same sites. The logarithmic group had an average r^2 value of 0.978 for the logarithmic function (Figure 6-7), with comparable values of 0.976 and 0.969 for negative exponential and linear functions, respectively, fit to the same sites.

These data suggest that all models fit the existing data generally well, largely due to the small sample sizes, with only slight preferences for model type between sites. For all cases, it is possible that the available data over a short period might bias the trend toward a more linear form, and mask any rapid erosion rates early in the evolutionary cycle. The preference for a logarithmic or negative exponential trend for the slowest growing gullies (A/A_0 <2) suggests that erosion rates for these sites could have been higher earlier in the evolutionary cycle, with initiation around 1900 (Figure 6-7). Insight supporting this hypothesis will come further below from OSL dating of gully inset-floodplains and the timing of gully initiation, LiDAR topographic analysis, and historic accounts.

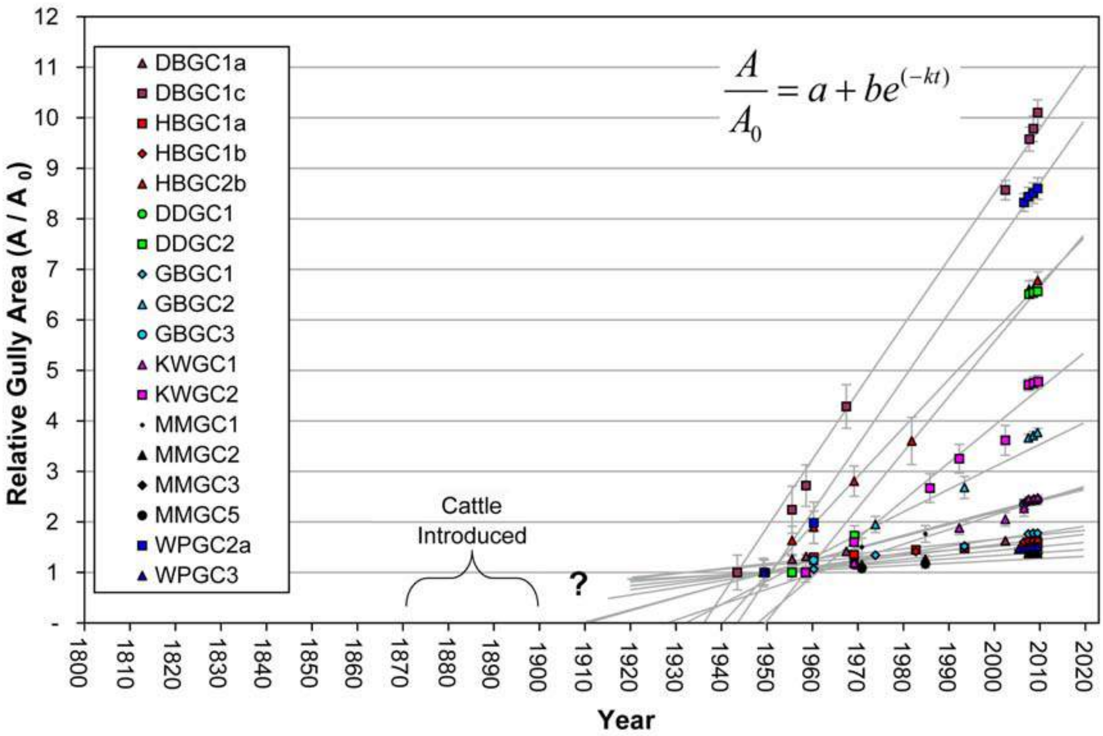


Figure 6-5 Relative changes in gully area (A/A_0) over time at all 18 gully sites fitted with a negative exponential function. Error bars ± 2m historic photos; ±50 cm for recent GPS.

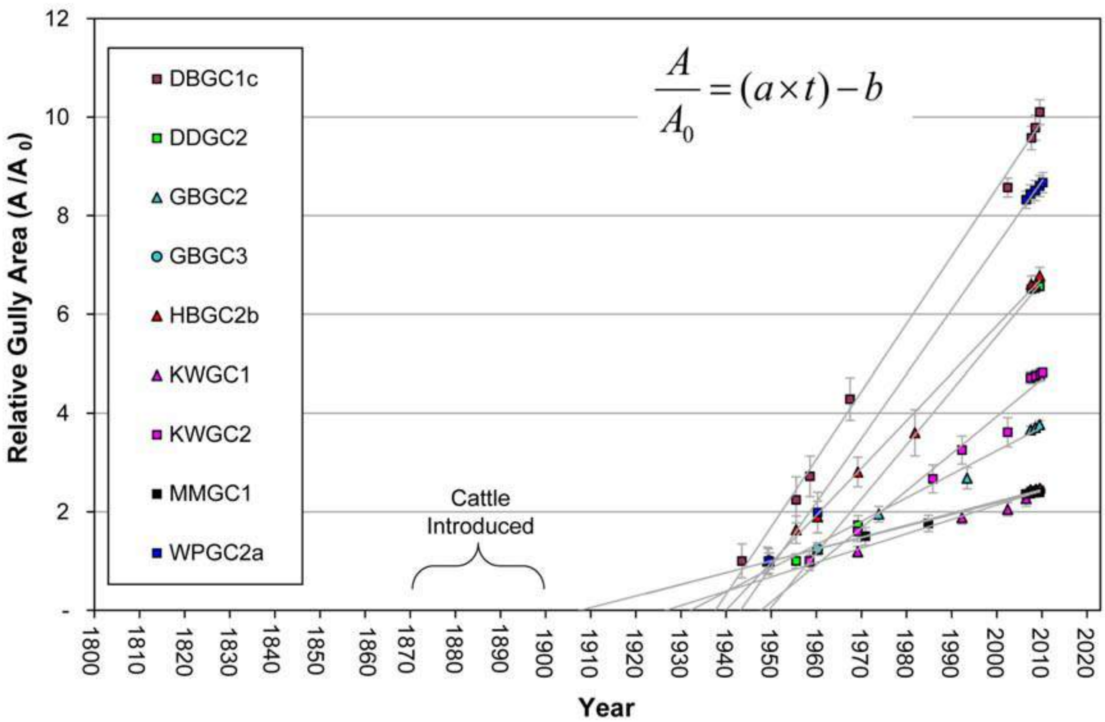


Figure 6-6 Sub-sets of study sites showing linear trends of gully area over time. Error bars ± 2m historic photos; ±50 cm for recent GPS.

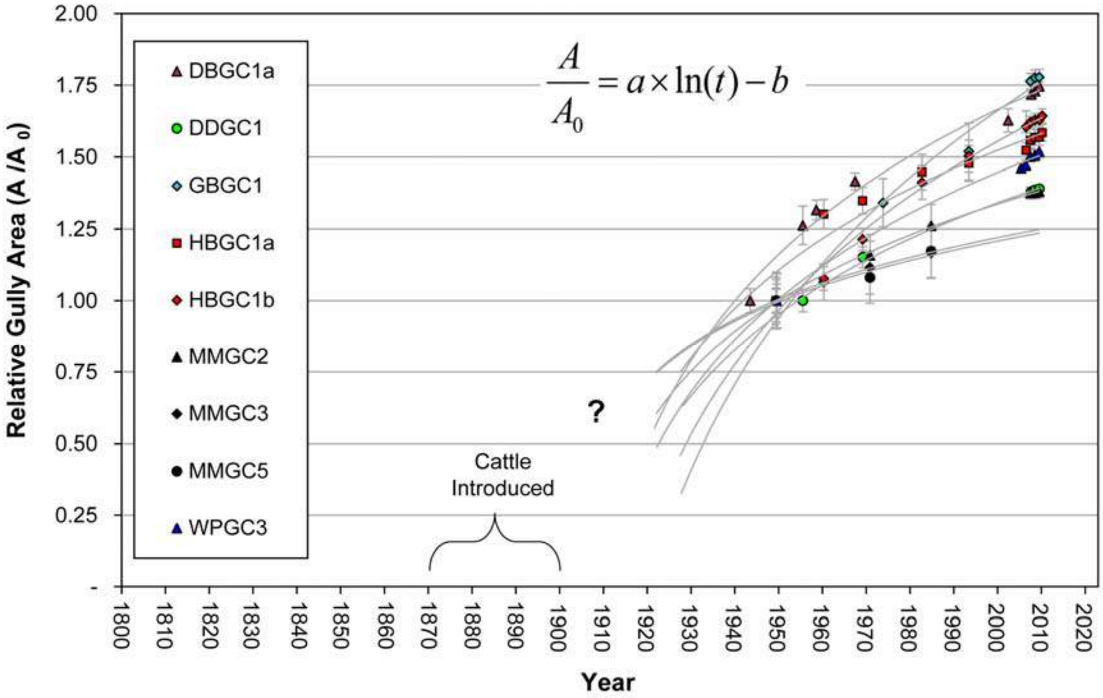


Figure 6-7 Sub-sets of study sites showing logarithmic trends of gully area over time. Error bars ± 2m historic photos; ±50 cm for recent GPS.

6.3.4 LiDAR volumetric erosion estimates over time

Estimated gully volumes over time at the three intensively monitored gully sites (Figure 6-1; WPGC2, HBGC1, KWGC2) displayed similar patterns to change in area (Figure 6-8). These data suggest that gully area is a decent surrogate for estimating changes in gully volume or mass over time. However these initial volume estimates are highly dependent on a number of assumptions: 1) accurate interpolation of the pre-gully erosion surface (flat floodplain or subtle swale); 2) a vertical head scarp at discrete historic time steps; 3) complete export of sediment from the gully network; 4) no changes in gully floor sediment storage; and 5) no progressive incision of the gully channel outlet. Analysis of longitudinal profiles of these gullies (Figure 6-16a-c) supports the general concept of near vertical head scarps, but field observations indicate that retreat is not 100% complete with many pedestals and interfluves remaining after initial erosion. More detailed analysis from sediment gauging within WPGC2 suggests that internal erosion processes can be important in addition to scarp retreat (Chapter Four). In the future, more accurate methods will be needed to measure annual or decadal change in gully volume in comparison to areal changes, such as by using repeat LiDAR differencing.

As a rough estimate of sediment yield from these three gullies over the period of record, the difference between the beginning (1949) and end (2008) volumes was multiplied by the soil bulk densities (WPGC2 = 2035 kg/m^3; HBGC1 = 2057 kg/m^3; KWGC1 = 1859 kg/m^3) and divided by the total number of years. For specific sediment yields, data were normalized to the

2008 internal gully area or effective catchment area. However, this area is a minimum due to the difficulty in defining surface water catchment boundaries on flat floodplains with changing inundation conditions. Over this period, WPGC2 yielded an average of 6,147 tonnes/yr (544 t/ha/yr), HBGC1 yielded 2,792 t/yr (295 t/ha/yr) and KWGC2 yielded 2,218 t/yr (423 t/ha/yr). These specific sediment yields are comparable to gauged sediment yields from WPGC2a (Chapter Four; Table 4-3; Table 4-4), and other high erosion areas of the world (Chapter Four; Figure 4-12).

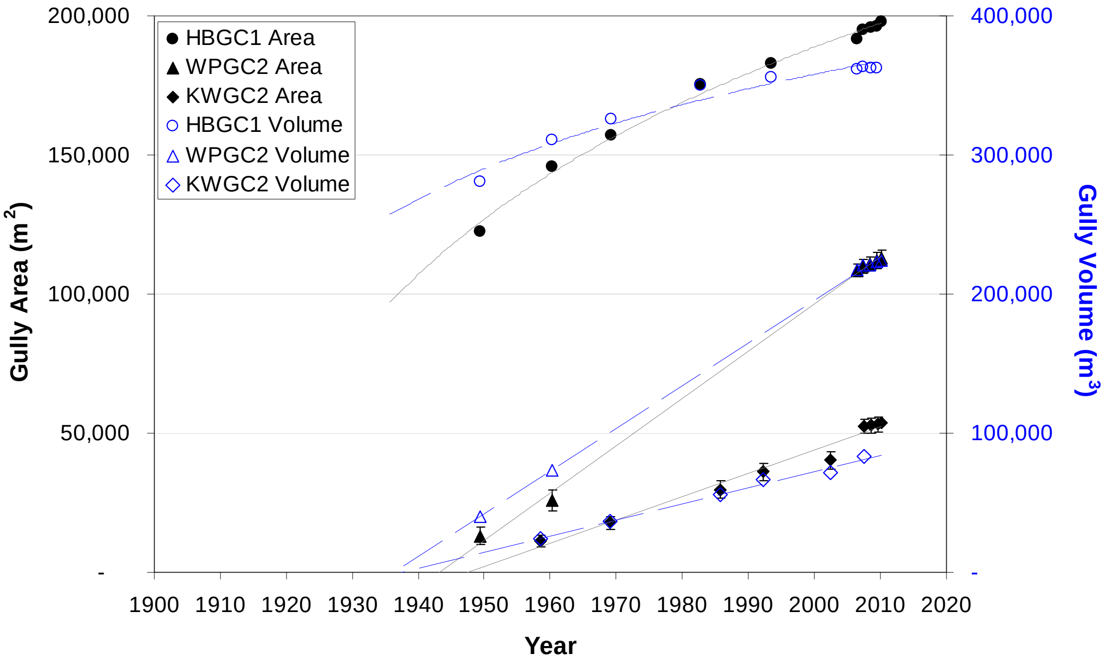


Figure 6-8 Gully area and volume changes over time at the three detailed study sites.

6.3.5 Gully erosion chronologies from OSL dating

At WPGC2, OSL sample locations were surveyed into a common datum for interpretation at 3 vertical gully profiles along a cross-section transect through the main channel (Figure 6-4ab; Figure 6-9), in addition to one other profile further upstream. Gully inset-floodplain deposits at profiles 2 and 3 in WPGCa (Figure 6-9) were unconsolidated and had ages that were less than ~130 years since the 1880 European settlement of the area (Table 6-2; Appendix). A major unconformity existed at the base of profile 3 (Figure 6-10), where recent unconsolidated gully units Aa-Ac overlayed an indurated river-floodplain unit C dated to the Pleistocene (Table 6-2; Appendix), which the gully eroded into post-European settlement.

At profile 5 in WPGC2b, the pre-European soil surface (> 130 years) remained in situ (unit B) (Figure 6-11), and consisted of indurated silty-clay within a depression or swale similar to nearby un-eroded swales (Figure 6-16, top right corner). An in situ tree growing on the surface of this swale unit B pre-European settlement (Figure 6-11a) was buried by the post-European unit A, which eroded from sheet and/or shallow gully erosion within catchment until ~ 50 years ago or less. Additional data from the same but thinner post-European fill unit A upstream (WP-19, profile 7) confirmed that deposition of unit A initiated ~ 120 years ago, compared to the older silty-clay swale unit B immediately underneath (WP-20) (Table 6-2; Appendix). Subsequently or simultaneously, gully incision downcut through profile 5 of WPGC2b exposing the underlying Pleistocene river-floodplain unit (C) (Figure 6-11). Generally across the majority of the gully complex, head scarp retreat is eroding directly into similar Pleistocene river-floodplain soils like unit C. Holocene soils like unit B were likely restricted to the bottoms of swale depressions or proximal river inset-floodplains. Older channel features like these are generally rarely present in gully walls across the Mitchell megafan due to typical incision into massive, unstructured Pleistocene deposits.

Both air photo evidence (Figure 6-4ab) and OSL dates of inset floodplains from profiles 2 and 3 indicated that gully incision in WPGC2 was underway earlier than 1949, while the younger OSL date (WP-10) from unit A of profile 5 suggested that this unit was still aggrading after this initial incision. These differences could be a result of OSL dating error of very young sediments (see Appendix), different degrees of incision and timing of erosion for tributary WPGCa (profiles 2, 3) versus tributary WPGCb (profiles 5, 7) (Figure 6-9), different sources of sediment (i.e., sheet vs. gully erosion) from the gully complex contributing to deposition, and/or the complex response of multiple cycles of cut and fill during net incision over the last 130 years. Additional OSL analysis and dating will be needed to uncover this complexity, in addition to the exact extent of the unconformity between the Holocene unit B (WP-12) and the Pleistocene unit C (WP-13). However, these data in whole support the hypothesis of a major shift in erosion processes and rates circa 1880 likely associated with land-use change. For example, post-European deposition rates of unit A ranged from 4.3 ± 0.4 mm/yr (profile 7) to 10 ± 2.1 mm/yr (Profile 5). Comparatively, pre-European deposition rates of unit B at profile 5 between samples WP-11 and WP-12 were 1.3 ± 0.4 mm/yr, up to an order of magnitude less than unit A.

At HBGC1, OSL dating was conducted at one profile at an exposed cut bank into a gully inset-floodplain, which was located just upstream from an indurated knickpoint controlling the profile of the gully (Figure 6-14; Figure 6-16b). The upper unconsolidated to partially indurated units A-D were of recent age (Figure 6-12; Table 6-2; Appendix). These units overlayed a massive indurated silt/clay unit E that was similar in character to the resistant material of the indurated knickpoint just downstream. OSL dating suggested that this unit was last exposed ~ 70 years ago, when the gully cut down to this surface before inset-floodplain aggradation occurred at an average rate of 6.4 ± 0.9 mm/yr. Additional machine excavation will be needed to expose and date older underlying material and confirm the full nature of any additional unconformities. Further dating at HBGC1 of river floodplain soils at gully scarps and exposed large cut banks below the knickpoint in the gully could also help uncover the timing of river floodplain construction and later gully evolution.

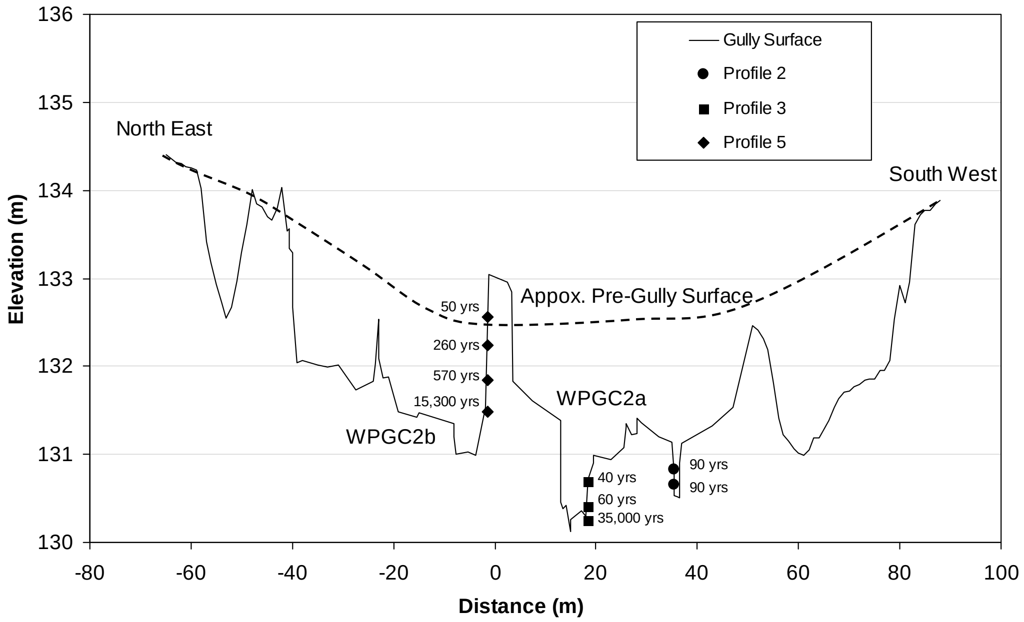


Figure 6-9 Cross-sectional transect through the center of WPGC2 with locations of OSL samples and their ages. See Figure 6-4ab for location.

Table 6-2 OSL sample ages (years before 2009) from WPGC2 and HBGC1

Site	Code	Profile	Unit	Depth (cm)	D_e (Gy)	D_r ($Gy \cdot ka^{-1}$)	Age (a)
WPGC2	WP-03	2	Ab	45	0.32 ± 0.02	3.67 ± 0.35	90 ± 10
WPGC2	WP-04	2	Ac	65	0.33 ± 0.02	3.66 ± 0.35	90 ± 10
WPGC2	WP-05	3	Ab	30	0.16 ± 0.03	3.95 ± 0.39	40 ± 10
WPGC2	WP-06	3	Ac	60	0.22 ± 0.03	3.85 ± 0.36	60 ± 10
WPGC2	WP-07	3	C	75	154.0 ± 9.59	4.38 ± 0.41	35,000 ± 4,000
WPGC2	WP-10	5	A	50	0.20 ± 0.03	3.79 ± 0.36	50 ± 10
WPGC2	WP-11	5	B	80	0.95 ± 0.06	3.71 ± 0.35	260 ± 20
WPGC2	WP-12	5	B	120	2.20 ± 0.06	3.88 ± 0.36	570 ± 60
WPGC2	WP-13	5	C	160	60.2 ± 3.50	3.94 ± 0.37	15,300 ± 1,700
WPGC2	WP-19	7	A	51	0.56 ± 0.02	4.79 ± 0.47	120 ± 10
WPGC2	WP-20	7	B	67	0.57 ± 0.02	3.68 ± 0.35	150 ± 20
HBGC1	HB-01	1	A	6	0.03 ± 0.01	3.64 ± 0.38	10 ± 10
HBGC1	HB-02	1	B	20	0.10 ± 0.01	3.48 ± 0.37	30 ± 10
HBGC1	HB-04	1	D	35	0.08 ± 0.01	2.17 ± 0.21	40 ± 10
HBGC1	HB-05	1	E	45	0.18 ± 0.01	2.57 ± 0.26	70 ± 10

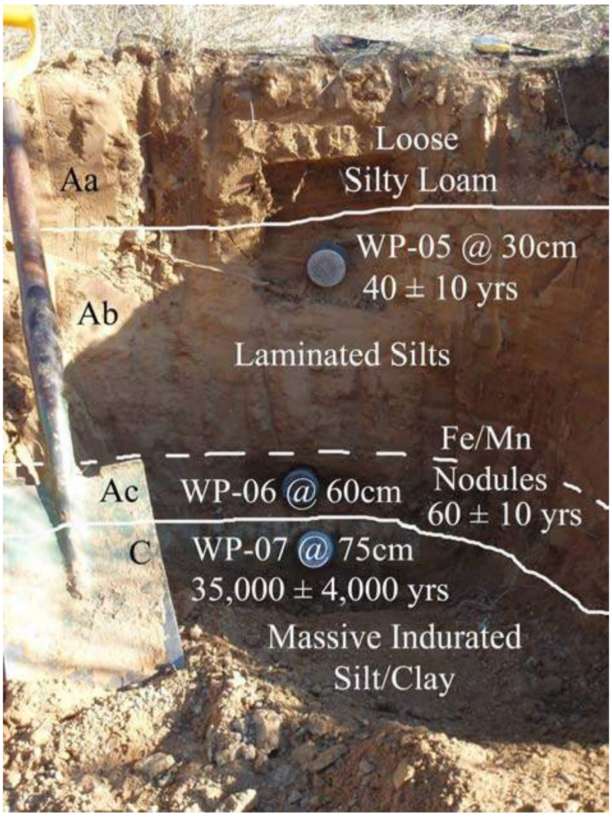


Figure 6-10 Profile 3 at WPGC2 showing stratigraphic units, OSL sample locations, and measured ages.

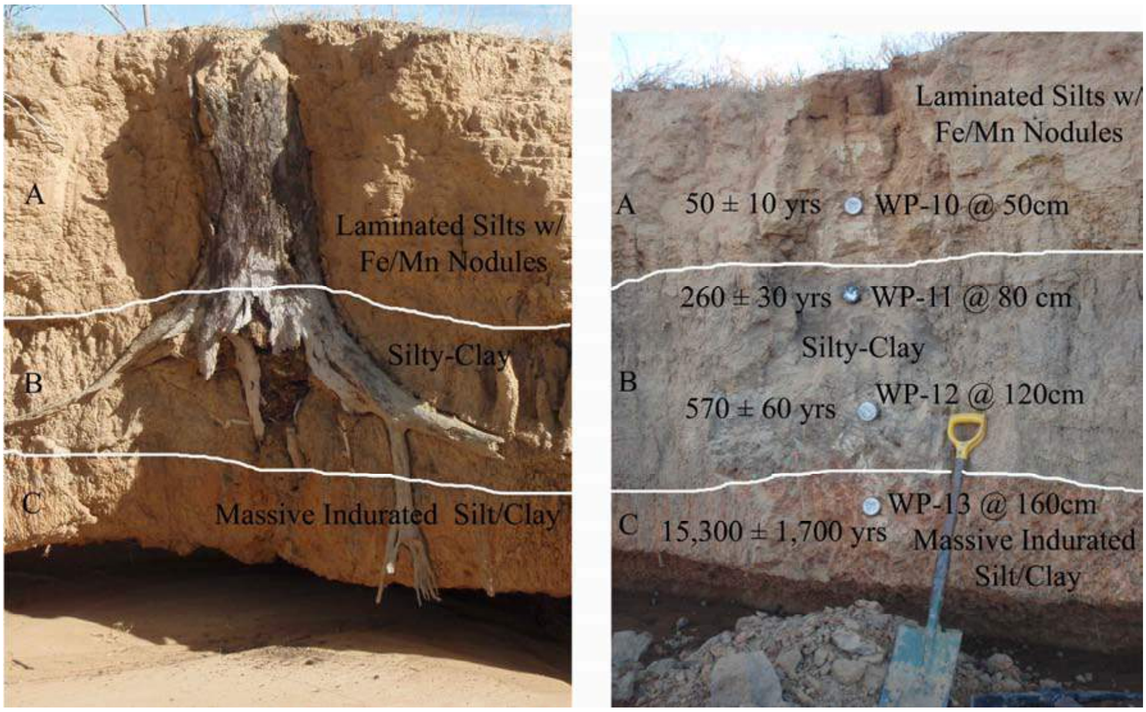


Figure 6-11 Profile 5 at WPGC2 showing a) stratigraphic units and a buried tree looking left and upstream, and b) stratigraphic units, OSL sample locations, and measured ages looking right and downstream.

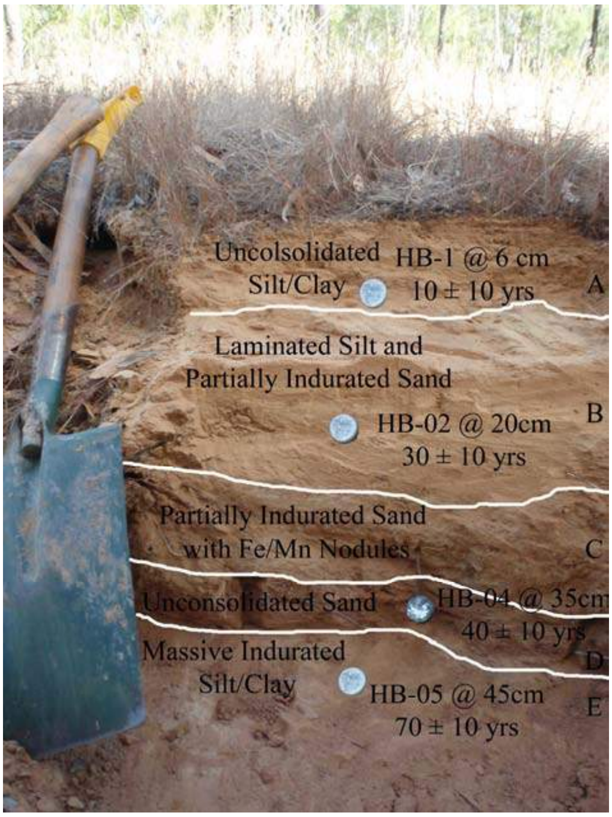


Figure 6-12 Profile 1 at HBGC1 showing stratigraphic units, OSL sample locations, and measured ages.

6.3.6 Historical explorers

6.3.6.a.1 Leichardt and Gilbert 1845

After reaching the Mitchell-Lynd confluence and the floodplains of the Mitchell on the 15th of June 1845, Leichhardt, Gilbert, and crew travelled for two weeks downstream parallel to the Mitchell River (Gilbert 1845; Leichhardt 1846), where they described the nature of some of the fluvial features along the floodplains. These early observations confirm that the Mitchell floodplain and river banks were periodically dissected by fluvial features such as flood drainage "*hollows*", "*gullies*" and "*creeks*", and that the river banks were indeed steep (Table 6-3).

The exact geomorphic definition of these terms however, was left open to interpretation. Often they combined terms confusing meaning, such as "*gullies [coming from] small creeks*" (Gilbert 1845) or "*gullies were gently sloping hollows, filled with a rich black soil*" (Leichhardt 1846). Their use of adjectives clarified meaning, such as "*grassy hollow*" or "*rocky gully*". From a complete analysis of their journals, hollows were often defined as sloped drainage depressions "*along river banks*", "*densely grassed*", "*generally without trees*", that "*fill with water by the thunder-storms*" (Leichhardt 1846). The terms "*gullies*", "*ravines*", and "*creeks*" were used more interchangeably and generally. Gullies were often described as "*little creek[s] and watercourse[s]*" that were "*deep*", on hill "*slopes*", "*filled with boulders and shingles*" and generally harder to navigate on horse than hollows (Leichhardt 1846). "*Creeks*" were often described as more permanent water courses that were "*large*", "*good-sized*", "*sandy bed*", "*running*", "*dry*", "*deep*", "*broad*", "*rocky*", with "*clayey flats*", and at times with flowing water and vegetated banks (Leichhardt 1846). Despite this confusing terminology, it is important to note that Leichhardt (1846) or Gilbert (1845) never used terms such as *erosion, eroded, bare, stripped, de-vegetated, dissected, unstable, incised, head cut, scarp, drop-off, break-away, badland, or wasteland.*

It can be observed today in comparison to Table 6-3 that the Mitchell River indeed has very steep banks, caused by progressive river incision into the fluvial megafan during and since the Pleistocene (Grimes and Doutch 1978; Brooks et al. 2009; Chapter Two). "*Gullies frequent on the immediate banks of the river*" (Table 6-3) can also be observed downstream of the Lynd junction, as well as unchanneled "*hollows*" further back from the river banks (see Figure 6-14 below). However, the highly eroded alluvial gully landscape observed today near HBGC1 (Figure 6-1; Figure 6-8; Figure 6-14), with 100's of hectares of completely denuded soil surfaces, were apparently not mentioned or observed by Leichhardt or Gilbert as they passed this location. Historic air photo evidence suggests that these large gully complexes were likely not present in 1845 (Figure 6-5; Figure 6-8), which is also supported by young OSL dates of small floodplains inset within HBGC1 (Figure 6-12; Table 6-2; Appendix). It is possible that Leichhardt and Gilbert observed the precursor unchanneled hollows, bank gullies, and deep creeks that subsequently eroded into the massive alluvial gully complexes observable today.

Table 6-3 Journal entries by Leichhardt (1847) and Gilbert (1845)

Date and Location	Leichhardt (1847)	Gilbert (1845)
16th June 1845 ~ Boundary Creek	"….the [floodplain] was interrupted by *gullies*, and occasionally by deep *creeks*, which [were] the outlets of the waters collecting on the [floodplain]"	"…we mostly kept back from the river bank to avoid deep *gullies*, which so frequently came into the river from *small creeks*, several of which we could not avoid, and two of which were as bad as any *gully* we had to cross from the first setting out of the expedition."
19th June 1845 16˚ 22' 16" ~ 10-mile Lagoon	"The soil of the flat round the lagoon, was very stiff and suitable for making bricks."	"The river was parallel with us most of the route, becoming necessary for us to keep well back to avoid the deep gullies frequent on the *immediate* banks of the river."
20th June 1845 ~ 20-mile Lagoon	"We…..avoided the *gullies* by keeping at a distance from the river. The banks of the river were so steep, that the access to its water was difficult."	"The bed and banks of the river were *broken* instead of excellent travelling; we as usual had very distant *gullies* and *hollows* to cross; the banks of the river being very steep with very indifferent camping places"

6.3.6.a.2 Jardine 1864

Jardine and Jardine (1867) noted several "*gullies*" as they crossed the distributaries of the lower Mitchell River Delta (Figure 6-1). They observed that "*many gullies were crossed filled with the screw-palm* (*Pandanus Spirilas)*" (14 Dec). One creek or distributary "*came from the eastward, was tolerably watered, and presented some bad broken sandstone country on its north bank. Its shady appearance suggested the appropriate name of 'Arbor Creek'. For three miles the route lay over gullies, spurs, and walls of broken sandstone. The country beyond opened agreeably into flats, which might almost be called plains….*" (15 Dec). After crossing the Mitchell River, they observed a "*complete network of anabranches, gullies, and vine scrubs to another branch*" (18 Dec). They also observed that "*during the floods the stream must be eight or ten miles wide, for, two miles back from it, a fish weir was seen in a small gully*" (19 Dec).

From these observations, it is again unclear of the exact definition and usage of the term "*gully*". Depression channels or small creeks with vegetation or fish were termed "*gullies*". However, their description of "*broken sandstone country*" and "*gullies, spurs, and walls of broken sandstone*" suggest that they might have observed alluvial gully complexes or, more likely, the indurated ironstone alluvium and lateritic surfaces perhaps near present day Kilpatrick Creek (Figure 6-1). The rivers and distributaries draining into the Gulf of Carpentaria are known for their unique indurated alluvium formations along water courses (e.g., Nanson et al. 2005).

6.3.6.a.3 Hann 1872

Hann's (1872) exploration along the Mitchell and Walsh River upstream of the Lynd took him passed the epicentre of major alluvial gully erosion today (Figure 6-1). Hann described the wedge of land between the Mitchell and Walsh River upstream of their confluence as the "*best country I have seen in northern Queensland*". He was also impressed by the quantity of the water running in the Walsh River and the "*dense scrub*" that was confined on outside bends (Table 6-4). However, he did not mention the presence of gullies on the high banks of the lower Walsh River, nor earlier along Elizabeth and Louisa Creeks, all of which have extensive alluvial gullies today (Figure 6-1).

Below the Walsh along the left bank of the Mitchell, Hann (1872) described the rough conglomerate and sandstone country where the Tertiary Wyaaba Beds of the Holroyd Plain inter-finger with the Quaternary Alluvium immediately adjacent to the river (Table 6-4; Grimes and Doutch 1978). His mention of "*very broken gullies or ravines*" that got "*scrubby before joining the river*" suggests that he observed either gullies or hollows near the river bank and the numerous creeks (Brown, Sandy, Dead Cow, Dinner, Bull Camp) that drain from the Pliocene Holroyd Plain into the Mitchell. On his return trip back upstream on the north side of the river, Hann (1872) did not describe the presence of gullies or ravines, despite their commonality today in the Lagoon and Reid Creek sub-catchments (Figure 6-1). However, upon reaching the Mitchell again upstream of the Walsh, he did observe the spectacular river cut banks near the present day Wrotham Park Resort and noted the "*many gullies and broken country*" along the banks of the river.

Similar to Leichhardt and Gilbert, Hann (1872) did not describe gullies as *eroded, bare, de-vegetated, or unstable badlands or wastelands*. However his use of the word "*broken*" to describe the country does suggest that numerous fluvial drainage features on the river high-floodplain made travel by horseback difficult. The historical air photo data and recent LiDAR topography from large gullies of the Wrotham Park area, which Hann appears to have passed in 1872 (Figure 6-1), suggest that many of the large alluvial gully complexes seen today were likely not present in 1872. However bank gullies and hollows along the immediate banks were present as suggested by LiDAR (see Chapter Three; Figure 3-3a), and thus Hann (1872) likely observed these pre-cursing near bank gullies and hollows.

Table 6-4 Journal entries by Hann (1872)

Date and Location	Hann (1872)
17th-19th July 1872 Wrotham Park • Elizabeth Creek • Louisa Creek • Walsh River	"….[we travelled] over very first class cattle county. This certainly is as good cattle county as I have seen in northern Queensland, being covered with fine thick grass about 2 feet high." "The banks [of Elizabeth Creek]….were very steep. One of the pack horses fell getting up the bank…". "The bank of the [Walsh] river is always lined with dense scrub which is confined to the side the river flows, the other is generally open with gentle sandy slopes."
20th July 1872 Gamboola • Left Bank Mitchell • Between the Walsh and Lynd Junctions	"Started down the [Mitchell] River still keeping on its left bank. After crossing the river the formation changed. We got into conglomerate, sometimes overlain by sandstone which was generally sandy country, timbered with stingy bark and bloodwood with very little grass which was of the wiry, poor description. In some places the sandstone extends into the river but generally only went within one mile of the river, and *ended in very broken gullies or ravines* which made it very difficult travelling near the river as *most all the gullies got scrubby before joining the river*".
24th July 1872 Wrotham Park • Wrotham Park Resort	"…on the right bank of the river…about one mile from the camp we came on the river where the plane come right on to the river with a perpendicular bank of about 100 feet overlooking a magnificent sheet of water. This is, without exception, the prettiest river scenery I ever saw. I intended on keeping on the bank of the river but I found this impossible as *the many gullies and broken country* made it impossible to travel."

6.3.7 Historic land use

The total number of introduced cattle on the Wrotham Park Aggregation in the lower Mitchell River and in the State of Queensland as a whole has steadily increased over the last 140-years (Figure 6-13)(BoS 2008; Queensland State Archives). The initial stocking of cattle into the lower Mitchell occurred in the 1870's, with an initial peak of cattle between 1910 and 1920 (Figure 6-13a). Subsequent fluctuations in cattle numbers both locally and regionally were strongly influenced by cattle prices, episodic climate fluctuations, and the increased use of Brahman cattle (*Bos indicus*) in the early 1970's. Cattle numbers have continued to generally increase on these properties to present (Edye and Gillard 1985; Arnold 1997; Ian Rush, personal communication) (Figure 6-13a).

For the first 100 years in the lower Mitchell, cattle were generally allowed free run of the landscape, with little length of fences to control movement, no protection of sensitive areas such as water courses, riparian zones, and wetlands, and limited off channel water development to reduce cattle concentrating in riparian zones and watercourses. Often but not always, the basic development requirements outlined in pastoral run leases were rarely met, with mismanagement widespread (Table 6-5). Additional management conflicts arose from the use of seasonal stock routes for bringing cattle to market, which crossed through multiple properties along the watered Mitchell River and enhanced degradation in riparian zones.

As a consequence of cattle grazing and European settlement in the catchment, the distribution of exotic plant and animal species rapidly expanded, such as the thick infestation of noogoora burr (*Xanthium pungens*) and rubber vine (*Cryptostegia grandiflora*) in riparian zones of the lower Mitchell River starting in the 1930's and continuing today (Figure 6-13a). Major changes to the fire regime of the savanna and riparian woodlands also occurred, with a switch from early dry-season fires managed by traditional aboriginal owners (e.g., July fires observed by Hann 1872) towards a regime of fire suppression in the early dry-season and fire ignition in the early wet-season (i.e., storm burning) by pastoralists to maximize cattle forage. Change from cattle, weeds, and fire resulted in major alterations to the native grass understory of the fringing woodlands along major water bodies.

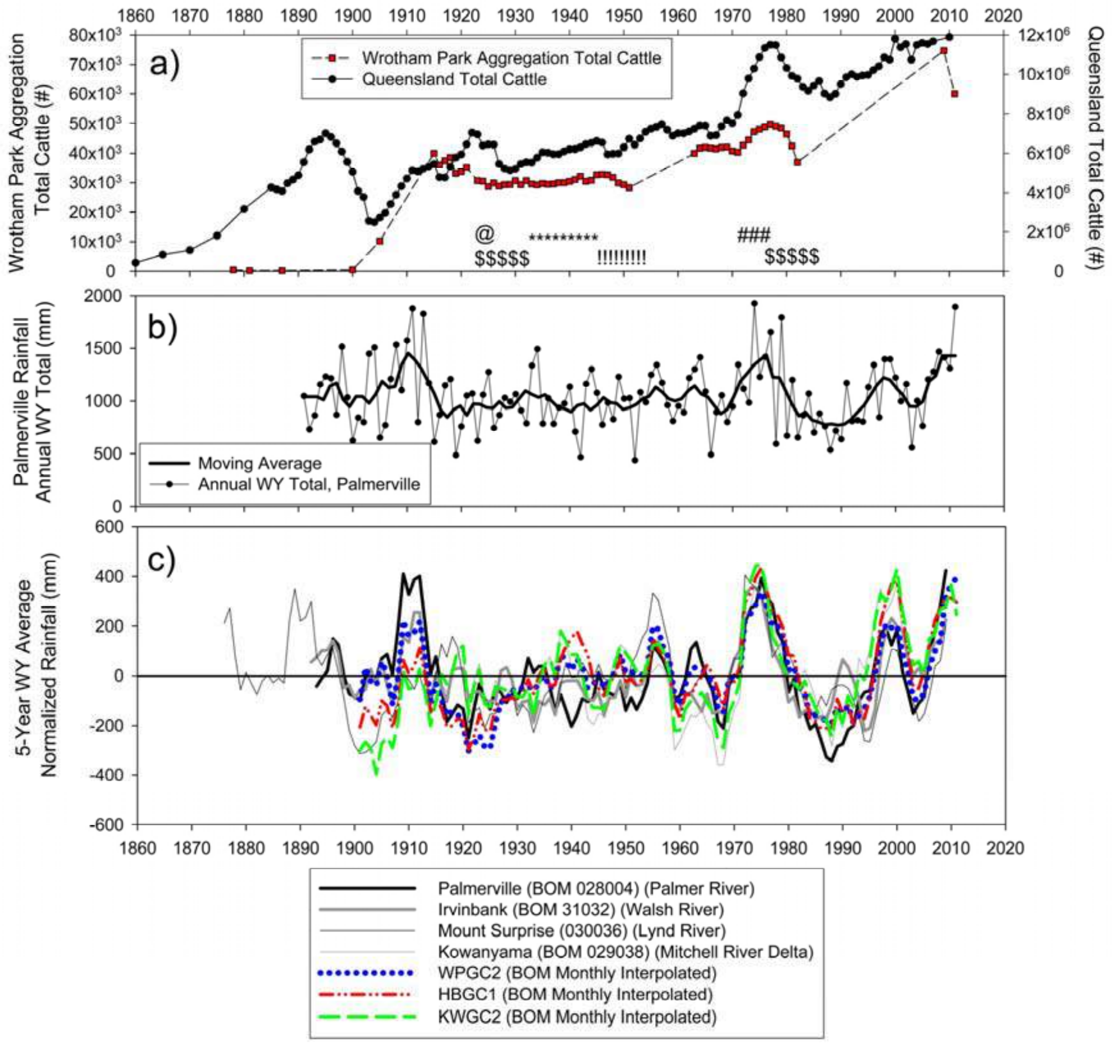


Figure 6-13 Historic trends in a) cattle numbers on the Wrotham Park Aggregation cattle station (Wrotham Park, Gamboola, Gamboola South, Highbury, Drumduff) and in the State of Queensland, b) water year (WY, Oct to Sept) rainfall totals and trends from Palmerville Station (028004), 60km from WPGC2, and c) normalized rainfall (5-year moving average divided by mean) for distributed rainfall stations in the Mitchell catchment and interpolated data (ABOM monthly data, 1900-2011) for key gully sites.

Cattle and land-use data sources are from Historic Lease Application "run files" from the Queensland State Archives, Edye and Gillard (1985), Arnold (1997), and recent cattle estimates at Wrotham Park Station (Ian Rush personal communication), adjusted to include Highbury and Drumduff using a conservative estimate of 30 hectares per beast. Changes in land-use conditions recorded in the "run files" are denoted in a) by the symbols $$$ (slumps in cattle prices), @ (first increase in wild pigs), *** (first infestation of noogoora burr in riparian zone), !!! (first infestation of rubber vine in the riparian zone), ### (first introduction of Brahman and Santa Gertrudis cross cattle), and ^^^^[first introduction of Lucerne (Stylosanthes spp.) on <0.5% of the land area Arnold 1997].

Table 6-5 Comments on mismanagement of the Wrotham Park Aggregation noted in early "run files" located in the Queensland State Archives.

Date	Wrotham Park
21st May 1941	"Driving rates are very high on this property as small mobs are railed each week from Mungana to Cairns". *Station Manager*
21st May 1952	"The lessees…..are described as particularly backward tenants of the Crown, who have done little more than exploit the natural advantages of these holdings and any vacant land adjacent thereto". *The Minister of Lands.*
3rd February 1955	"I would also point out that the [lessees] hold an aggregate area of 5625 square miles of Pastoral Leases with a cattle capacity in excess of 47,000 head. The general standard of improvement and management of these properties was poor and on much of the country improvement and development has occurred only as a result of firm action by this department." *The Minister of Lands.*
3rd December 1963	"…..no property in the North has been maintained or cared for worse, and this includes the quality of cattle and horses, together with plant and improvements". *W. Reid Queensland Primary Producers Co-op*

6.3.8 Historic rainfall

Inter-annual rainfall totals are quite variable in the Mitchell (Figure 6-13b), as are intra-annual storm rainfall and intensity (Chapter Three; Chapter Four). Over the last century, annual rainfall patterns in the Mitchell catchment have cycled through distinct wet and dry phases (Figure 6-13c) and this decadal variability is common but not spatially or temporarily synchronous across Queensland (Lough 1991) and elsewhere in Australia (Nicholls and Lavery 1992; Gallant et al. 2007). Several major wet phases in the Mitchell have centered around 1889, 1911, 1955, 1974, 1999, and 2011, with interspersed dry or neutral phases (Figure 6-13c). However rainfall anomaly signals are variable across the catchment, such as with the 1911 wet phase being strongest at Palmerville Station and weaker at other stations and interpolated at gully sites. In contrast, other anomalies were spatially widespread in the Mitchell and beyond, such as the 1970's wet phase.

The rapid increase of cattle into the lower Mitchell after 1900 (Figure 6-13a) was partially coincident with several years of above average rainfall at Palmerville and to a lesser extent at other locations (Figure 6-13b-c). Additionally, new established cattle numbers remained relatively high into the subsequent dry phase in the late 1910's. These climate variations could have exacerbated the erosional impacts of major land-use changes and cattle introduction, similar to elsewhere in Australia (McKeon et al. 2004; Henry et al. 2007; Stafford Smith et al. 2007). However as will be discussed below, these decadal variations in rainfall are an inherent component of this moonsonal landscape (Nott et al. 2007), and preceding wet and dry phases during earlier centuries did not trigger widespread gully erosion in the style observed today.

From Chapter Three it was determined that average annual scarp retreat was positively correlated to annual rainfall total ($r^2 \sim 0.6$) if scarp retreat was measured locally and precisely using time-lapse cameras or other methods, but weakly and negatively correlated ($r^2 \sim 0.1$) if scarp retreat was measured from coarser GPS measurements across longer scarp distances with a mixture of both active and inactive fronts (Chapter Three; Table 3-4). At longer decadal time scales, the annual variation in erosion and rainfall is averaged out between available air photos at a site. Unfortunately, the differing acquisition dates of air photos between sites and lack of frequent photo dates coincidence with climate regime shift boundaries limits the ability for robust multi-site comparison of regional gully change to decadal climatic variation. However as some coarse examples from several individual gully sites with near decadal photo records, the correlations between period-average erosion rates and period-average, -maximum- or -minimum annual WY rainfall (ABOM interpolated) were generally inconsistent (Table 6-6). Statistical power was low due to the small sample size, which prohibits any firm conclusions from these data. Positive or negative correlations with annual rainfall metrics could be a results of direct changes in the driving forces such as rainfall total or intensity, indirect climatic influences on resisting forces such as vegetation cover and soil moisture, other factors such as intrinsic geomorphic factors or extrinsic land use, and/or errors in scarp retreat data or ABOM interpolated rainfall.

Table 6-6 Correlation coefficients (r) between the dependent variable (period-average annual scarp retreat) and independent daily variables (period-average, -maximum, or -minimum annual WY rainfall, ABOM interpolated).

	Period-Average Annual Scarp Retreat (m/yr) versus		
	Period-Average Annual WY Rainfall	Period-Maximum Annual WY Rainfall	Period-Minimum Annual WY Rainfall
KWGC1	-0.31 (n=4)	+0.12 (n=4)	-0.14 (n=4)
KWGC2	-0.54 (n=5)	-0.32 (n=5)	-0.57 (n=5)
HBGC1a	+0.08 (n=5)	-0.23 (n=5)	-0.21 (n=5)
HBGC1b	+0.15 (n=5)	+0.08 (n=5)	+0.47 (n=5)
HBGC2	-0.67 (n=5)	-0.58 (n=5)	-0.65 (n=5)
GBGC2	+0.56 (n=4)	+0.83 (n=4)	+0.83 (n=4)

6.3.9 Reconciling quantitative data and explorer observations

How do we reconcile the contrasting information that 1) early explorers noted gullies on the banks of the Mitchell River and 2) empirical evidence from historic air photos and OSL dating suggest large alluvial gully complexes seen today were not present in the mid-1800's ? Were these the same gullies and gully types or different features all together?

Topographic analysis using LiDAR can provide information on the likely pre- and post-European settlement morphology of gullies. An example is provided from a floodplain area that Leichhardt and Gilbert directly passed in 1845, which is currently eroded by a large alluvial gully (HBGC1; Figure 6-1). Trends in gully area from historical air photos (Figure 6-5; Figure 6-7) suggested that the upper part of HBGC1 outlined in Figure 6-14 was not present in 1845, which is also supported by OSL dating of gully inset-floodplain deposits less than 100 years old (Figure 6-12; Table 6-2). The current incised morphology of HBGC1 can be seen outlined in LIDAR planform (Figure 6-14) and cross-section (C-C', Figure 6-15). In comparison, several adjacent large (A-A') and small (B-B') hollows are still undergoing erosional transformation from shallow hollow to gully complex (Figure 6-14; Figure 6-15). These adjacent gullies provide a location-for-time substitution of gully evolution.

Air photo analysis was unable to map the progressive erosion of the larger gully outlet channel below the indurated knickpoint (Figure 6-14), due to the dense canopy of riparian vegetation. From LiDAR and field observations it is likely that these lower portions of the channel network were present in 1845 in some form, hollow or gully. While many of these proximal bank gullies are undergoing rejuvenation today, there still are some sections of these gullies that retain their earlier hollow morphology (HBGC99; Figure 6-14). The longitudinal profiles of these bank gullies without connections to upstream hollows (e.g., HBGC99; Figure 6-16b) are much steeper than profiles draining well developed gully complexes (e.g., HBGC1; Figure 6-16b).

In summary, the historic explorer accounts and erosion rate data from historical photos are not necessarily in contradiction. Remnants of the "*deep gullies frequent on the immediate banks of the river*" described by Leichhardt/ Gilbert can still be observed today, as can the "*hollows*" mentioned by Gilbert (Table 6-3; Figure 6-14; Figure 6-15). These features have subsequently evolved together rapidly over time into the much larger alluvial gully complexes seen today, which have incised into generally massive, unstructured Pleistocene/Holocene river deposits. Completely new gully features also are eroding directly into previously uneroded floodplain surfaces, as initiated from disturbances on steep river banks (~10 m high) or existing drainage channels (Figure 6-14, Brooks et al. 2009; Chapter Two).

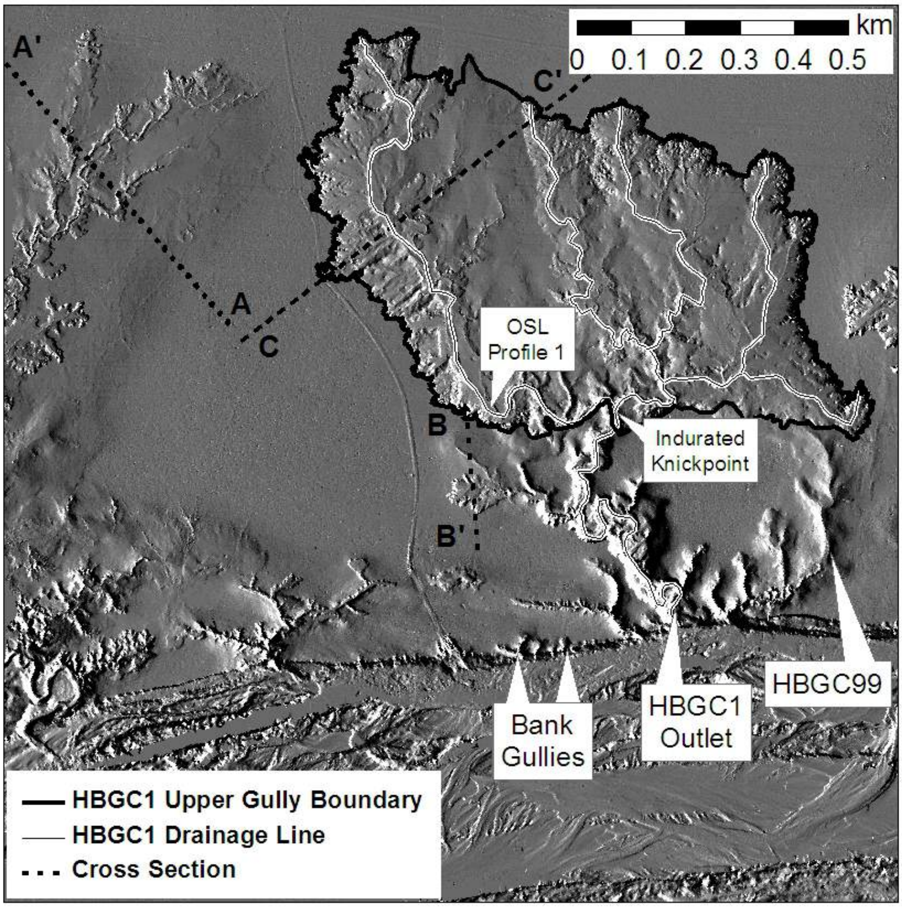


Figure 6-14 LiDAR hillshade map of the left bank of the Mitchell River at HBGC1, with locations of cross-sections (Figure 6-15) and the upper scarp boundary of HBGC1 above the indurated knickpoint and main outlet channel, which is confluent with the Mitchell River at bottom.

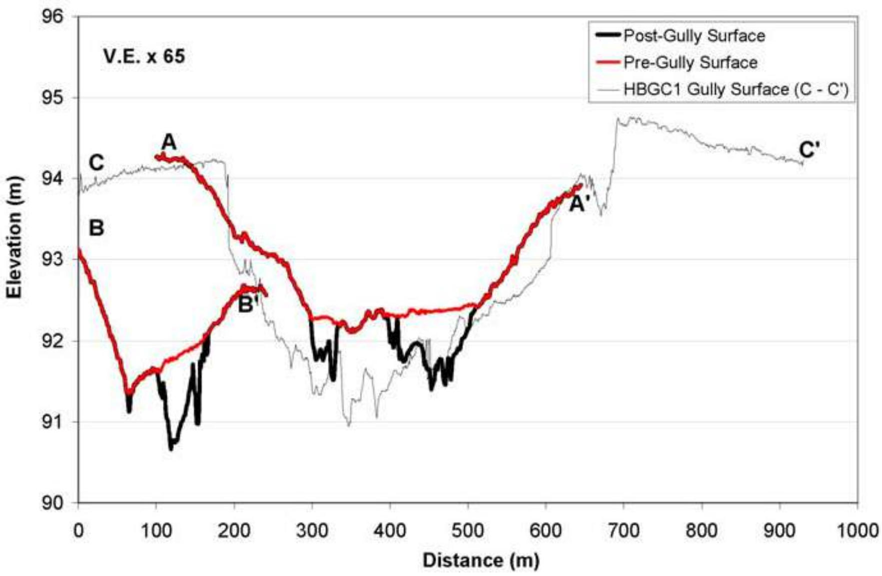


Figure 6-15 Cross-sections from A to A’ and B to B’ (hollow adjacent to HBGC1) and C to C’ (HBGC1) in Figure 6-14. Note that y-axis scale is exaggerated 65-times compared to x-axis.

6.3.10 Future gully extent from profile and rate extrapolation

Gully-thalweg longitudinal-profiles extracted from LiDAR DEM’s (e.g., WPGC2, Figure 6-16d) generally displayed graded thalweg slopes over finite distances up to the immediate scarp zone where the profiles were over-steepened (Figure 6-16a-c). However in the cases of HBGC1 and KWGC2 (Figure 6-16b-c), the channel profiles were interrupted by resistant indurated-alluvium at depth. For HBGC1 (Figure 6-16b), the lower channel slope above the knickpoint was used because 1) the knickpoint was a permanent feature influencing the upstream channel grade and scarp retreat, decoupling the upper reach from the lower, and 2) the over-steepened convex profile below the knickpoint was not in equilibrium due to cut and fill processes associated with both river backwater and upstream gully sedimentation. For KWGC2 (Figure 6-16c), the steeper channel slope below the knickpoint was used for profile extension because 1) the indurated knickpoint was actively failing and temporary, and 2) the slope of the profile below the knick point matched the channel slope a few hundred meters below the scarp.

Temporal estimates of when the gully scarp would reach a graded profile in all directions differed between study sites. The fastest observed rates of gully area expansion were at WPGC2 (Figure 6-5; Figure 6-6), where linear rates projected into the future until a graded profile was reached suggested that the gully would continue to erode until the year 2277 AD with an ultimate size 42 times its 1949 size (Figure 6-17). Linear projections at KWGC2 suggested that the gully would erode until 2271 AD with an ultimate size 24 times its 1958 size. In contrast, the HBGC1 site was predicted to erode until 3248 AD but only reach 13 times its 1949 size (Figure 6-17). The later estimate is influenced both by the lower slope used to project profiles into the floodplain (Figure 6-16b), but also the comparatively low rates of area expansion at this site post-1949 (A/A_0 <2; Figure 6-5; Figure 6-7). If logarithmic or negative exponential trends were used for future prediction, the time till stabilization with a graded profile would be in excess of 2000 years.

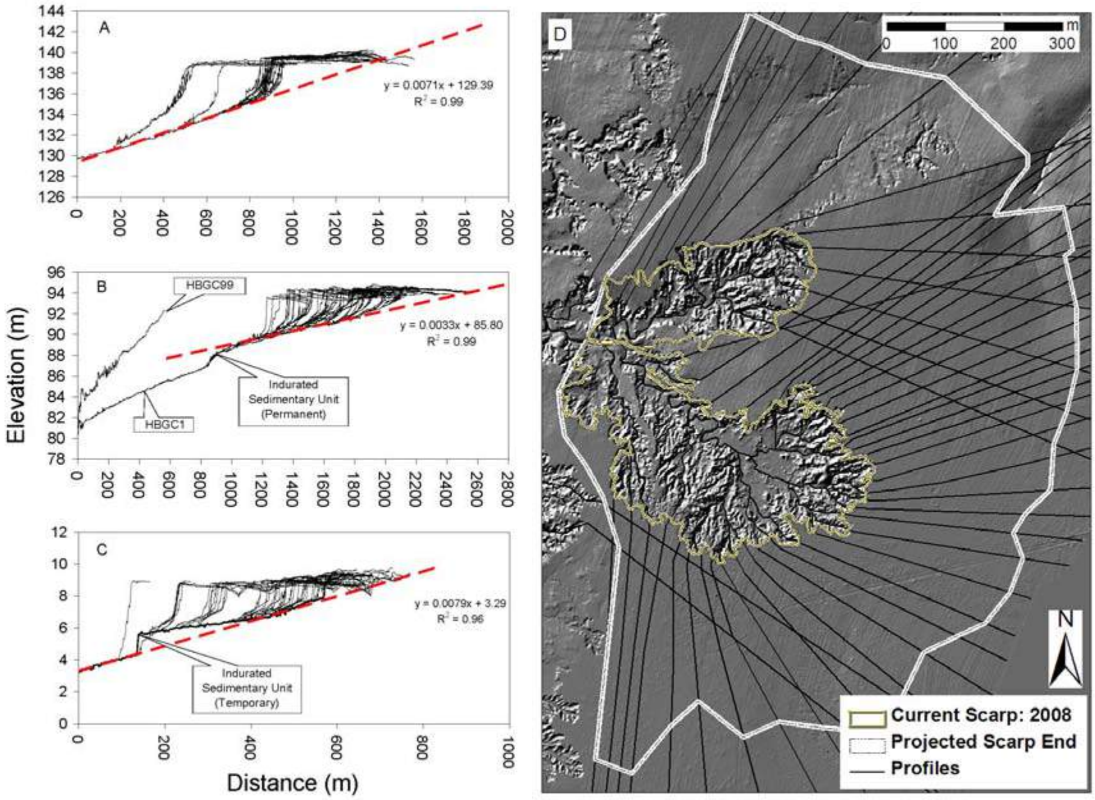


Figure 6-16 Longitudinal profiles of channel thalwegs extracted from LiDAR for a) WPGC2, b) HBGC1 (and HBGC99), and c) KWGC2, with trend lines of thalweg slopes extended beyond the scarp zone to intersection points with the river high-floodplain surface. d) WPGC2 LiDAR hillshade DEM, longitudinal profile (thalweg) extraction lines, current gully extent, and future projection of gully extent.

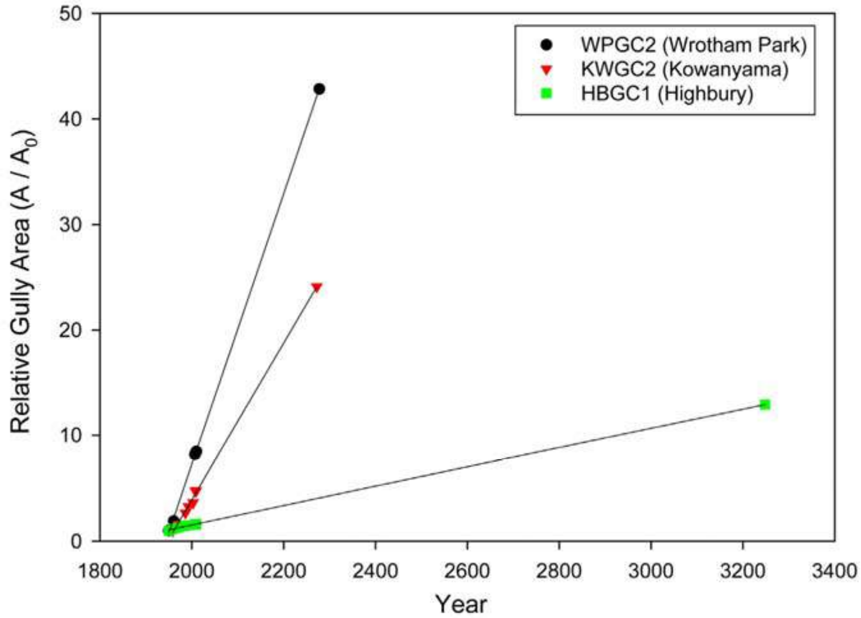


Figure 6-17 Linear trends of relative gully area (A/A_0) extended beyond 2010 until a point in space and time when thalweg longitudinal profile trends intersect the river high-floodplain and the gully profile grades into equilibrium.

6.4 Discussion

6.4.1 Rates of gully erosion

This study used a 'multiple lines of evidence' approach to determine past, current and future rates of alluvial gully erosion. Historic and recent trends in alluvial gully area defined the progressive degradation of the Mitchell megafan during modern times. Extrapolation of area trends back in time suggests that many alluvial gullies are post-European features, which is supported by OSL dating, LiDAR data, and historical records, along with tree age analysis from Chapter Five. However, uncertainly remains in defining the exact mechanisms for initiation, which are discussed below from an evolutionary and geomorphic threshold viewpoint. Regardless, estimates of sediment production from these gullies in sum demonstrate that they are massive sources of sediment (3.9 Mt/yr recently, ~ 6.3 Mt/yr historically) and important in the overall catchment sediment budget. Unit area sediment yields > 100 t/ha/yr are high compared to Australian and world standards (Chapter Four). Pre-European sediment yield is less certain, but there is little geomorphic evidence from the massive, relatively homogenous, Pleistocene/Holocene floodplain units along the Mitchell River that this scale and type of erosion has been a consistent process operating on the landscape over geologic-geomorphic time. Even the presence of smaller, earlier forms of gullying on steep river banks perhaps seen by earlier explorers, could not have supported the sheer magnitude of erosion seen today. The landscape has transitioned from unknown, but reduced, background erosion rates pre-European settlement, to accelerated rates historically and recently.

The future spatial and temporal projections of gully area growth – using the concept of a graded equilibrium profile and constant average linear retreat rates – represent a minimum in space and time for equilibrium to be reached. True growth rates into the future are unknown (i.e., linear, logarithmic, exponential), as are the factors required for full stabilization discussed below. For immediate land management purposes using minimum estimates of growth extent, it is clear that the alluvial gullies in the lower Mitchell catchment will continue to erode and degrade the near river riparian zone and associated floodplain savanna. These gullies will remain chronic erosion features on the landscape for hundreds, if not thousands, of years unless existing erosion is mitigated by land management intervention and future gully initiation is reduced by best management practices (Chapter Seven).

6.4.2 Alluvial gully evolution

A preliminary conceptual model of alluvial gully evolution was provided by Brooks et al. (2009; Chapter Two), which was developed from initial field observations and a location-time substitution (Huggett 2004). These initial ideas of the evolution of alluvial gullies in the

Mitchell are still valid, but are updated and summarized here with new insight from historic air photos, recent LiDAR data, and early explorer observations. Gully erosion typically goes through several stages during evolution: from initiation to expansion to stabilization to possibly accretion (Schumm 1973; 1979).

6.4.2.a.1 Initiation

The ultimate initiation point of alluvial gullies is the over-steepened banks of rivers, lagoons, creeks and other water bodies (e.g., Figure 6-4c-d; Brooks et al. 2009; Chapter Two). Initial bank profiles are typically sinusoidal in form with the steepest slopes at convex sections of the profile. These slopes are conditionally unstable, subject to disturbance, and intrinsically prone to erosion due to available potential and kinetic energy. However, erosion is mediated by the resistive influence of vegetative cover and surface soil condition. Small incipient gullies on channel banks can initiate from disturbances such as rilling and channel scour after rainfall-runoff and flood drawdown, bank seepage points, bank slumps, bank erosion, animal tracks, and roads. The later two mechanisms have increased ubiquitously with European land use, given the previous absence of vehicle traffic and hard-hoofed animals such as cattle. Positive feedback mechanisms tend to concentrate both surface and subsurface flow into these new drainage features (Dunne 1980; 1990). Over time, incipient gullies develop further as they incise into dispersible sub-soils of alluvial banks and cut back into adjacent flat floodplains or pre-existing topography (e.g., Figure 6-16a-c).

6.4.2.a.2 Expansion

Once initiated, gullies become less influenced by their initiation mechanism (i.e., soil and bank disturbance). Factors driving or resisting their propagation include available surface and subsurface water sources as influenced by natural and anthropogenic factors, relative relief and potential energy, the depth and volume of dispersive sub-soils, soil resistance and indurated layers at depth, channel and gully roughness from vegetation, drainage capture by adjacent gullies (e.g., Figure 6-14; HBGC99), and the ultimate equilibrium slope or grade needed for stabilization (Figure 6-16a-c). A degree of chance is involved in propagation, due to the heterogeneity of alluvial material composition and the subtle differences in antecedent topography, such as hollows or swales, proto-gullies, and alluvial ridgelines. Due to the importance of sub-surface soil dispersion and large slope imbalances, even seemingly influential surface topography such as alluvial ridges or negative floodplain slopes (away from the river) can be breached or overcome by gully erosion. These unbounded gullies can subsequently evolve into very large gully complexes and creek drainages systems (Brooks et al. 2009; Chapter Two).

Brooks et al. (2009; Chapter Two) hypothesized that during gully initiation the dominant sources of water for erosion were from rainfall-runoff and floodwater drawdown, with a switch towards subsurface groundwater seepage erosion and soil piping during propagation. However, empirical pore-water pressure data at a propagating scarp (WPGC2) indicated that negative pore-water pressures were common in deeper sub-soils during major rainfall and scarp failure events, in contrast to positive pore-water pressures only at near-surface soils following heavy rainfall (Chapter Three). These data suggest that emergent soil moisture or groundwater seepage out of scarp faces are not dominant or required for scarp failure, in contrast to hypotheses of Brooks et al. (2009). Regardless of water source, dispersion and erosion of sub-surface silt and clay soils is important in scarp retreat and gully propagation.

6.4.2.a.3 Stabilization

Few gullies in the lower Mitchell appear to be in a stabilization or accretion phase. Rather expansion is the dominate phase with the sporadic initiation of gullies still occurring. For many study sites, decadal changes in gully area suggest that growth occurs at a fairly constant rate at the decadal scale once initiated due to the fairly regular monsoon climate and evolution toward stabilization. If the estimated timing of initiation is correct (~1900 AD) along with minimum projected dates until stabilization (~2300 AD), then the cycle of erosion from initiation to stabilization could be on the order of 400 years or greater.

There are several unknown factors of erosion and stabilization when the sediment supply is reduced once scarps incise to grade. Increased roughness from both tree and grass vegetation colonization (e.g., Chapter Five) could stabilize gullies, in addition to grade control provided by indurated alluvium at depth. However, additional intrinsic or extrinsic disturbances (climate, base-level change, land use) could reinitiate or perpetuate cycles of gully incision. A recovery phase of aggradation is unlikely in the future due to a lack of upslope sediment sources (i.e., hillslopes), unless river aggradation at the megafan scale occurs and reinitiates a cycle of major floodplain accretion.

This conceptual model for alluvial gully erosion in northern Australia differs in many ways from those used to describe colluvial gullies and valley-bottom cut- and fill-cycles in south-eastern Australian (e.g., Prosser et al. 1994; Prosser and Winchester 1996; Wasson et al. 1998). Most importantly is the strong exponential decay of gully erosion rates and sediment production over time observed in SE Australia, where the highest erosion rates occurred during the initiation phase immediately after disturbance (e.g., Rutherfurd et al. 1997; Olley and Wasson, 2003; Rustomji and Pietsch 2007; Whitford et al. 2010), similar to studies in the United States (Graf 1977; 1979). In these locations, gullies are often confined by bedrock in hillslope drainage hollows or narrow valley fills of higher order drainage lines, which ultimately restrict the volume of unconsolidated sediment available for erosion and the degree of incision. Floodplain alluvial gullies described here are generally unconfined both horizontally and vertically, with abundant stores of dispersible sediment. While exponential decay of erosion rates was observed for several study sites, the coefficient k values were typically much smaller than observed or modelled in other studies. Initial linear gully expansion in planform was observed at several sites (e.g., Figure 6-4a-d; Figure 6-14), but at a majority of sites lateral expansion was commensurate with elongation, sometimes to the extreme for continuous scarp-front gullies (Brooks et al. 2009; Chapter Two; Figure 2-10d). This expansion in all directions provides a relatively continuous supply of sediment until grade stabilization.

6.4.3 Geomorphic thresholds and gully initiation

From the erosion rate data and conceptual model of gully evolution, it is clear that the current phase of widespread, rapid gullying into the Mitchell alluvial floodplains is a post-European phenomenon. Several key questions remain, however. Why did widespread degradation occur within the last 130-years after a floodplain sediment storage period of tens of thousands of years? Was a geomorphic threshold crossed (*sensu* Schumm 1973)? What were the causative factors leading to landscape degradation via gully erosion?

A geomorphic thresholds is defined "*as a threshold of landform stability that is exceeded either by intrinsic change of the landform itself, or by a progressive change of an external variable*" (Schumm 1979). The geomorphic literature on gully erosion and channel incision is full of analyses of internal and external factors exceeding stability thresholds resulting in dramatic landscape change (e.g., Schumm and Hadley 1957; Cooke and Reeves 1976; Graf 1979; Prosser et al. 1994; Prosser and Slade 1994; Tucker et al. 2010). Intrinsic or independent factors over long time periods commonly include climate, relief, base level, geology, soil type, weathering, sediment storage volume, inherited terrain, and development of critical slope angles for erosion. Extrinsic or dependent factors over shorter time periods include fluctuations in rainfall and hydrology, changes in vegetation cover and resistance, and anthropogenic land use (Schumm and Lichty 1965). These will be discussed below in relation to alluvial gullying on the Mitchell fluvial megafan and are summarized in (Table 6-7).

Table 6-7 Intrinsic and extrinsic variables influencing alluvial gully erosion along the Mitchell fluvial megafan following Schumm and Lichty (1965).

Variables	Intrinsic or Extrinsic	Sub-Variables	Relevant References
Climate	Intrinsic	• Monsoon climate • Long-term sediment supply	• Kershaw 1978; Kershaw and Nanson 1993 • Nanson et al. 1992 vs. Parker et al. 2008
Relief Base level	Intrinsic	• Evolution of Mitchell fluvial megafan during Pleistocene • River incision into the upper megafan • Gull of Carpentaria relative sea level	• Grimes and Doutch 1978 • Brooks et al. 2009 • Chappell et al. 1982; Woodroffe and Chappell 1993
Geology Soil type Chemical weathering	Intrinsic	• Storage volume of alluvium (silt/clay floodplains) • Soil type (sodic, hard-setting, silty or loamy, duplex-soils) • Soil chemical weathering (ferricrete and calcrete pisoliths)	• Grimes and Doutch 1978; Brooks et al. 2009 • BRS 1991 • Pain and Ollier 1992
Inherited terrain	Intrinsic	• Uneroded floodplain terrain • Shallow drainage hollows, short/steep gullies on immediate river banks, and large creeks	• Brooks et al. 2009 • Gilbert 1845; Leichhardt 1847; Hann 1872; This chapter
Hydrology	Extrinsic	• Cyclone landing frequency • Decadal ENSO/IPO cycle of rainfall • Storm rainfall erosivity • Flood magnitude and frequency	• Nott et al. 2007 • Lough 1991; Heinrich et al. 2008; Risbey et al. 2009 • Yu 1998; Lu and Yu 2002 • Chapter Three
Vegetation Land use	Extrinsic	• Aboriginal and European fire regimes • European cattle introduction and herd growth • Reduced soil resistance due cattle vegetation consumption • Increased soil disturbance by cattle tracks (pads) and roads • Increased riparian weed invasion	• Crowley and Garnett 2000 • This chapter; Queensland State Archives • Schumm 1979; Graf 1979; Prosser and Slade 1994 • Condon 1986; This chapter; Brooks et al. 2009 • This chapter; Queensland State Archives
Land use and Hydrology Interactions	Extrinsic	• Interactions between cattle stocking rates and decadal rainfall	• McKeon et al. 2004; Henry et al. 2007; Stafford Smith et al. 2007

6.4.3.a.1 Relief and base level

The long-term evolution of the Mitchell megafan during the Pleistocene is an intrinsic or independent factor influencing the *recent* evolution of alluvial gullies. The incision of the Mitchell River into the Pleistocene alluvium of the upper megafan units has increased the local relative relief between the river high-floodplain and thalweg, and set up the potential energy needed for a secondary cycle of erosion (i.e., Grimes and Doutch 1978; Brooks et al. 2009; Chapter Two). While low sea levels during the Pleistocene potentially influenced this megafan head trenching, other factors such as reduced sediment supply from the Australian continent (Nanson et al. 1992) could have had an overriding influence. This is supported by a regional comparison to the Fly–Strickland River (PNG), which over the same time scale and identical base level changes has backfilled its entrenched floodplain channel network with sediment reducing local relative relief (Parker et al. 2008). More subtle declines in relative base level (~2m) over the last 6000 years in the Gulf of Carpentaria (Chappell et al. 1982; Chappell 1983; Woodroffe and Chappell 1993) have also influenced the relative relief in the Mitchell delta. However, the degree that this has influenced alluvial gullying in the Mitchell delta below Koolatah (Figure 6-1) remains unclear due to the active nature of this Holocene floodplain. Regardless of these dynamic factors influencing relief over cyclic geologic time, the strong relationships seen today between local relative relief and gully scarp height and density support the idea that relief is a primary factor influencing the potential for alluvial gully erosion (Brooks et al. 2009; Chapter Two).

6.4.3.a.2 Soil chemistry and weathering

The heterogeneity in volume, texture, and chemistry of alluvial deposits across the Mitchell megafan influences the long-term potential for alluvial gully development. A majority of the soils proximal to river channels where alluvial gullies are mapped in Figure 6-1 are described as sodic or alkaline, hard-setting, silty or loamy, duplex-soils (red- and yellow earths), deposited in the Pleistocene or Holocene (Grimes and Doutch 1978; BRS 1991; Brooks et al. 2009; Chapter Two; Chapter Three). This is in contrast to distal floodplain and wetland soils with higher clay contents, located 10's of kms away from main- and palaeo-channels. Soil chemistry data at gullied study sites documented that soil pH, conductivity, and exchangeable sodium percentage (ESP) all increase with depth (Chapter Three). ESP values > 6 at key gully sites indicated highly dispersive soil conditions with a natural predisposition to erosion (Naidu at al. 1995).

These soil conditions have developed over geologic time as a result of the inherited properties of the parent alluvial material, in addition to the intense tropical weathering and monsoonal wet/dry cycles in this region. This weathering is highlighted by patchy surface lags of nodules or pisoliths of ferricrete and calcrete within gullies (Pain and Ollier 1992). These pisoliths ubiquitously develop after gully exposure of sub-soils, when initial soil mottles (iron, manganese) permanently oxidize or when carbon liberated from dying vegetation after erosion oxidizes with available calcium (Goudie 1973).

6.4.3.a.3 Hydrology and climate

The monsoonal hydrology of the Mitchell catchment is important from both surface soil erosion and floodplain inundation perspectives. During the wet season (Dec-Mar), when >80% of the mean annual rainfall occurs, convective storm rainfall intensity and kinetic energy result in high rainfall erosivity indexes (R-factor) (Yu 1998; Lu and Yu 2002; Chapter Three). If soils are bare at the end of the long dry season from either grazing or burning, the effective kinetic energy for soil erosion can be enhanced. Major overbank flooding from monsoonal runoff usually occurs later in the wet season after considerable seasonal vegetation growth. However, the hydrological flood regime and longitudinal variability in relative relief strongly influence the hydrologic connectivity of the river with its inset- and high-floodplain units, which in turn can affect gully erosion processes on floodplain fringes (Chapter Three).

Compared to longer-term glacial-interglacial cycles, the monsoonal climate of the Cape York Peninsula has been relatively stable over the last 6000-years following the last glacial maximum (Kershaw 1978; Kershaw and Nanson 1993). Despite decadal fluctuations in climate in northeastern Queensland influenced by ENSO/IPO cycles (e.g., Figure 6-13c; Lough 1991; Heinrich et al. 2008; Risbey et al. 2009), there is no major evidence for rapid landscape unravelling via widespread gullying until after European settlement and cattle introduction. The rapid increase of cattle into the lower Mitchell after 1900 was coincident with several years of above average rainfall centered on 1911 (Figure 6-13c), which could have exacerbated the erosional impacts of major land-use changes along with subsequent droughts. However, these rainfall cycles are not unusual or unprecedented in the Mitchell catchment either in the subsequent instrument record (1971-1979; 1996-2001; 2006-2011; Figure 6-13c) or in proxy rainfall records measured by Nott et al. (2007) at the Chillagoe Caves in the central Mitchell catchment (100 km from WPGC2; Figure 6-1). This latter 800-year proxy record from $^{18}O/^{16}O$ ratios in limestone stalagmites demonstrated that cyclone landing frequency and magnitude were relatively low between AD 1800-2000, the same period which a majority of alluvial gullies initiated (Figure 6-5). In comparison, there were more frequent and larger cyclone events between AD 1400 and 1800, which did not trigger widespread gully erosion.

6.4.3.a.4 Inherited terrain and early phases of gully erosion

Erosion rate data from historic air photos, recent LiDAR data, early explorer observations, and conceptual models of gully evolution (this chapter; Brooks et al. 2009; Chapter Two) indicate that alluvial gullies can erode into both 1) flat, featureless, uneroded, floodplain terrain (e.g., Figure 6-2; Figure 6-4c-d; Brooks et al. 2009; Chapter Two) and 2) precursing features such as shallow drainage hollows, short and steep gullies on immediate river banks, and larger creeks (e.g., Figure 6-4a-b; Figure 6-14; Figure 6-15; Brooks et al. 2009; Chapter Two). The ubiquitous nature and frequent spacing of alluvial gullies along hundreds of kilometres of river and lagoon banks suggest that previous floodplain features are not needed for their development. Instead, only an initial bank disturbance is required. However, where previous features do or did exist, gully erosion can preferentially propagate up these features. These topographic irregularities can be preferential sources of surface- or soil-water draining off the floodplain from direct rainfall or overbank flooding. They are preferential grazing areas or migration routes for animals, and often have unique inherited soil conditions. These local inherent factors may influence whether or not a given area is an incipiently unstable component of a landscape and prone to degradation by gully incision (Schumm 1973; 1979).

6.4.3.a.5 Vegetation and land use

The influence of vegetation on the stability of valley floors and initiation of gullying depends on the balance between resisting and energy dissipating vegetative factors, and the critical shear stress of flowing water needed to entrain sediment. In the words of Schumm (1979) "…*for a given biomass there is a critical tractive forces at which incision of the valley floor will take place, and for a given tractive force there is a minimum value of biomass below which the valley floor becomes unstable and gullying begins*". Evans (1998) reviews the varying thresholds of vegetation cover needed to avoid severe erosion in rangelands. Both Graf (1979) and Prosser and Slade (1994) provided empirical evidence that reduced vegetative cover or biomass for a given hydrological regime can induce channel incision and gullying. Both natural factors such as drought and fire, and anthropogenic factors such as tree clearing, grazing, and fire regime changes can influence vegetative cover and thresholds of gully erosion. Grazing impacts have often been cited as a major contributing factor in reducing vegetative cover and initiating gully erosion (e.g., Eyles 1977; Condon 1986; Prosser and Slade 1994; Prosser and Winchester 1996; Pringle et al. 2006), in addition to the more direct soil disturbance of hard-hoofed animals (Greene et al. 1994; Dunne et al. 2011).

In the lower Mitchell, the growth trend in alluvial gully area (Figure 6-5) correlates to the upward trend in cattle numbers (Figure 6-13). However, this correlation does not necessarily support a *continued* cause and effect relationship between cattle grazing and gully area. More likely, the similarity in these trends suggests that the *timing* of the initiation of many of these gullies coincided with the *timing* of the introduction of European cattle in the late 1800’s, providing support for the concept of land-use change pushing the landscape across as threshold towards instability. However, ongoing land-use disturbance could exacerbate or accelerate gully erosion initiated decades before, which is supported by field observations of ubiquitous soil disturbance and surface and gully erosion from daily cattle migrations through riparian zones to and from large water bodies.

Across the Mitchell megafan, major change in land use from traditional Aboriginal management to widespread cattle grazing from the late 1800’s onward brought major changes to the native grass understory of riparian woodland communities. Large numbers of free-range cattle concentrated in riparian zones for water access, grass feed from fertile soils, and cattle drives along river stock routes to market (Queensland State Archives, Section 6.3.7). This pressure would have reduced native perennial grass cover and vigour, which were important for stabilizing dispersible soils especially in the late-dry and early-wet seasons. Accompanying this direct grazing was the invasion of noxious weeds, the introduction of exotic annual grasses, the alteration of fire regimes, and patchy woodland thickening. These types of vegetative changes are widespread across northern Australia, but vary by habitat type and management regime (Neldner et al. 1997; Fensham and Skull 1999; Crowley and Garnett 1998, 2000; Sharp and Whittaker 2003; Bowman et al. 2004; Sharp and Bowman 2004).

Vegetation changes were also accompanied by direct soil disturbances by cattle. Dense and deep cattle tracks (pads) leading over steep river banks down to late-season water holes have cut into the fragile soil surfaces, exacerbating the initial loss of vegetative grass cover and channelizing overland flow from rain and floodwater into gullies. Cattle tracks also typically follow the easiest path to the river or water, which in many cases is down hollows or existing bank gullies, resulting in heavy physical disturbance of these conditionally stable features. The degree that cattle have indirectly influenced gully erosion by increasing runoff efficiency and volume is unquantified for the Mitchell megafan, but is also a possibility due to changes in soil compaction, biological crusts, vegetation cover, infiltration, and evapotranspiration (Bridge et al. 1983; McIvor et al. 1995; Trimble and Mendel 1995; Evans 1998).

It is hypothesized that these land-use changes to intensive cattle grazing pushed the incipiently unstable components of the landscape across a threshold towards instability (*sensu* Schumm 1973), which lead to an increase in the initiation of alluvial gully erosion, both on steep river banks and within previously un-channelled hollows. The long-term evolution of the Mitchell megafan reviewed above created the template for gully erosion potential (relief, climate, soil chemistry, etc.), while shorter-term changes in vegetative cover and soil erosion resistance pushed the landscape across a stability threshold.

Notwithstanding the major changes brought about by the introduction of cattle, these changes likely worked synergistically with other natural factors already in operation such as climate variability. The history of land degradation in Australian rangelands emphasizes the importance of permanent or episodic destocking of sensitive areas during long dry seasons and drought years to retain natural resiliency of grassland communities and their soil protection properties (McKeon et al. 2004; Henry et al. 2007; Stafford Smith et al. 2007). The initial spike in cattle numbers in the lower Mitchell in the early 1900's coincided with an above average rainfall period that could have exacerbated initial cattle impacts to the landscape, as could have the maintenance of high cattle numbers into the beginning of the subsequent drought period (Figure 6-13).

The initiation of major alluvial gully erosion coincident with the introduction of cattle has been observed in other alluvial plains in the Northern Territory (Condon 1986; McCloskey 2010) and western and central Australia (Pickup 1991; Pringle et al. 2006). For example Condon (1986) summarized that "*[alluvial] gullies have been initiated from cattle pads over the high bank in earlier times when there would have been large concentrations of cattle watering on the rivers after the small waterholes in the backcountry had dried up towards the end of the dry season. Once channelized flow had reached the B horizon, the rate of down cutting and side cutting would be very rapid in these highly dispersible clay soils*." This land-use impact scenario is similar to the lower Mitchell River. However here we provide empirical evidence for 1) the rapid increase in alluvial gully erosion rates post-European settlement, and 2) the intrinsic and extrinsic factors leading toward landscape instability.

6.5 Conclusions

Overall, this study demonstrates the fragility of northern Australia's soils to land-use change post-European settlement and the potential to cross erosional thresholds that permanently destabilize floodplain and riparian landscapes. This is supported by the "multiple lines of evidence" approach in analysing changes in gully erosion over time. Once initiated by human land use and left to their own devices, these gullies will continue to erode vast areas of the riparian savanna landscape for hundreds if not thousands of years, unless direct management actions are trialled in an adaptive management program.

Chapter Seven: Rehabilitation of Alluvial Gullies on the Mitchell River Fluvial Megafan

7.1 Introduction

Alluvial gully erosion concentrated along the floodplains of major water bodies is widespread across northern, tropical Australia: including the catchments of the Mitchell River (Brooks et al. 2006; Brooks et al. 2008; 2009); the Gilbert, Leichardt, Nicholson, and Gregory Rivers in the Gulf of Carpentaria (Simpson and Doutch 1977; Brooks et al. 2006); the Victoria (Condon 1986; McCloskey 2010) and Daly (Sattar 2011) Rivers in the Northern Territory; the Fitzroy in Western Australia (Payne et al. 1979), and many Great Barrier Reef (GBR) catchments in Queensland such as the Normanby (Brooks and Spencer 2011) and Burdekin Rivers (Rebecca Bartley, personal communication). Recent research in the lower Mitchell catchment has demonstrated that widespread alluvial gully erosion initiated in the late-1800's as a result of dramatic land-use changes from traditional Aboriginal management to widespread cattle grazing post-European settlement (Shellberg et al. 2010; Chapter Five; Chapter Six). Locally, sediment production from alluvial gullies can be > 100 t/ha/yr, which is high compared to both Australian and World standards (Chapter Four). At the catchment scale in the Mitchell, alluvial gullying of floodplains is a dominant sediment source, producing > 3 million tonnes per year of sediment (Brooks et al. 2008; Chapter Six; Rustomji et al. 2010).

The erosion of floodplain soils via alluvial gully erosion presents a major threat to 1) the local pastoral industry through the loss of productive riparian land, 2) downstream aquatic ecosystems influenced by high suspended sediment concentrations and habitat changes from sedimentation (i.e., pool and lagoon infilling), and 3) cultural use of water bodies for subsistence, commercial, and ceremonial purposes (i.e., fisheries production), which are affected by the cumulative impacts of all land-use induced sediment pollution from upstream catchments. The post-European settlement landscape degradation from unsustainable grazing practices highlights the need for alternative and adaptive grazing management programs to be developed to slow or halt alluvial gully erosion and improve the integrity of savanna grasslands and woodlands. However, before widespread soil conservation practices are implemented to reduce alluvial gully erosion, a trial rehabilitation program is needed to determine the most cost-effective, practical and sustainable land management and bioengineering activities needed to reduce both local erosion and overall sediment yields at the catchment scale.

Interest in alluvial gully rehabilitation is growing among numerous indigenous and non-indigenous land owners, hoping to slow or halt widespread land degradation. To date, attempts at reducing alluvial gully initiation and propagation in northern Queensland have been ad hoc with mixed results. Efforts have focused heavily on hard engineering techniques that focus on symptoms rather than causes of erosion, which are neither sustainable nor process-based. There is a strong need to implement management actions that are guided by data from well researched demonstration projects that promote local and regional expertise. A trial rehabilitation program is needed that builds off the foundational work on the driving (geomorphic history, relief, climate, floodplain hydrology) and resisting (soil chemistry, vegetation cover) factors for alluvial gully erosion (Brooks et al 2009; Chapter Three) and the human land-use contributions to this erosion (Chapter Six). This will ensure that targeted remediation measures will actually address the causes of human accelerated soil erosion, rather than just the symptoms and immediate gully erosion of concern.

The objective of this chapter is to develop a detailed proposal for alluvial gully rehabilitation trials in the lower Mitchell catchment by:

- Reviewing scientific literature on the gully and sodic soil rehabilitation.
- Discussing lessons learned to date from ad-hoc gully stabilization efforts in the Mitchell catchment.
- Proposing controlled rehabilitation trials for experimental alluvial gully complexes in the Mitchell catchment, guided by local, national and international literatature and rehabilitation experiences.
- Outlining the development of Best Management Practice (BMP) guidelines for alluvial gully erosion reduction and rehabilitation.

The economic and social aspects of rehabilitating land degraded by alluvial gully erosion locally or across northern Australia are beyond the scope of this chapter. However, undoubtably before soil conservation practices are implemented, the economic and social benefits and costs of gully rehabilitation need to be investigated and taken into account at the local and regional scale. For example, Yitbarek et al. (2010) studied the financial costs and benefits of gully rehabilitation in Ethiopia by monetizing 1) loss of agricultural land area and productivity, 2) nutrient loss, retention and replacement costs, and 3) the overall rehabilitation expenditure. However future studies should additionally quantify on-site losses of riparian habitat integrity and carbon sequestration potential, as well as the off-site impacts of downstream sedimentation, aquatic habitat degradation, and cultural use of the landscape.

7.2 Gully Rehabilitation Literature Review

" . . . *Bibliography (review) is a necessary nuisance and a horrible drudgery that no mere drudge could perform. It takes a sort of inspired idiot to be a good bibliographer (reviewer) and his inspiration is as dangerous a gift as the appetite of the gambler or dipsomaniac - it grows with what it feeds upon and finally possesses its victim like any other invincible vice."*
Ornithologist, Elliott Coues, 1897, in The Osprey.

7.2.1 Introduction

Humans often intervene in natural or human accelerated processes such as gully erosion or river instability in attempts to engineer stability, promote human uses of the environment, or repair environmental damage caused by humans. Often these interventions focus on “technological fixes” and engineering that aim to fix or repair or improve natural processes degraded by human actions (Katz 2000). This anthropocentric world view often creates landscape “artifacts” for human needs, but often fall short truly restoring natural processes (Simon et al. 2007) and can be akin to “faking nature” (Elliot 1982).

The extent that natural processes can actually restored back to the pre-disturbance conditions often depends on the extent of initial degradation (Roni et al. 2005). For the least disturbed situations, a case can be made for preservation or limitation of further degradation. For more degraded conditions, a case can be made for restoration, rehabilitation, mitigation, or in extreme cases, dereliction (Boon 1992). For geomorphic degradation and recovery in fluvial situations such as degraded rivers or incising gully channels, Brierley and Fryirs (2005) highlight the many different recovery pathways or restoration trajectories that can occur due to natural recovery or human management intervention. If the degradation pathway is not too severe, then restoration actions can bring the geomorphic conditions and processes back toward, but not completely to, the intact pre-disturbance condition. However if geomorphic turning points are passed along the degradation pathway, then intervention actions will not result in restoration, but rather in the creation of a new condition that falls between the fully restored and fully degraded scenarios. This is most often the case in river rehabilitation.

Systematically there is inadequate monitoring to assess the degree of success of rehabilitation or restoration efforts (Bernhardt et al. 2005). Often the existing condition, degradation pathway, recovery potential, and restored condition goal are poorly defined. More recent riverine and landscape restoration paradigms have focused on learning from history (Wohl et al. 2005; Wohl and Merritts 2007; Kondolf et al. 2006; Mika et al. 2010) and working with and promoting natural recovery processes to the greatest extent possible at both the local and landscape scales

(Brookes and Shields 1996; Ebersole et al. 1997; Thexton 1999; Callahan 2001; Simon et al. 2007)

Despite these important philosophic and practical issues, humans continue to implement projects to reduce soil erosion using a variety of programs and techniques to meet societary goals. For gully erosion, a wide range of physical, biological, and chemical techniques are used to modify both gully form and processes to meet varying objectives of natural resource management. To date, there have been relatively few attempts to synthesize the full range of scientific research and on-ground techniques used to reduce or rehabilitate gully erosion around the world. This is in contrast to the more detailed progress of stream and river restoration science and application (e.g., Brookes and Shields 1996; Rutherfurd et al. 2000) and the broader research field of incising channels (e.g., Wang et al. 1997; Darby and Simon 1999). However in sum there is a large body of literature directly and indirectly applicable to gully rehabilitation that draws from the fields of hydrology, geomorphology, soil science, agricultural, rangeland science, ecology, geotechnical engineering, bioengineering, and watershed management. Reviews of gully rehabilitation science have been few, but with a several exceptions (e.g., Heede 1978; Boucher 1990; Lal 1992; Grissinger 1996). Conferences on the process-based science surrounding gully erosion are now common (Poesen and Valentin 2003; Valentin et al. 2005; plus more recent 2007 and 2010), but the focus on gully rehabilitation is typically a small component. In contrast there is a large body of grey-literature that has been produced by governmental agencies and field-practitioners that covers in various forms the evolving state-of-the-art of gully rehabilitation practice (Heede 1976; Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; NRCS 2007b; Jenkins and McCaffrey 2008).

The goal of this literature review is to synthesize the wide range of physical, biological, and chemical techniques and supporting science used to reduce or rehabilitate gully erosion. An emphasis will be place on the rehabilitation of gully systems in tropical northern Australia eroding into sodic soils.

7.2.2 Vegetative protection and soil erosion resistance

7.2.2.a.1 Vegetation before the onset of gully erosion

Vegetative cover in the form of grass, shrubs and trees and organic detritus (mulch) plays a protecting and stabilizing role for soil, predominantly reducing soil erosion. Roots increase the cohesion of soil and resistance to erosion; near-surface vegetation and mulch protect the soil from rain drop impact and increase the resistance to overland flow velocities; deeper roots of over-story vegetation reduce the potential for mass movement (Thornes 1990; Gray and Sotir 1996; NRCS 1992). Vegetation also plays a mediating role in the hydrological cycle by intercepting precipitation, increasing actual evaporation, transpiring soil water and possible groundwater, increasing infiltration through root networks and soil amended with organic material, decreasing water runoff, and increasing depression storage due to surface roughness (Penman 1963; Eamus et al. 2006).

For grassland and woodland savanna biomes, the vegetative ground cover on the soil surface and associated root biomass plays the most important role in soil protection and erosion resistance. The kinetic energy of rain drops is moderated by ground cover such as the leaf and stem structure of grass and/or the residue organic matter (mulch) remaining after senescence. This ground cover reduces the effective energy available at the soil surface to detach soil particles (Wischmeier and Smith 1978; Thornes 1990; Marston and Dolan 1999) by either direct drop splash or raindrop-induced flow transport (Ghadiri 2002; Kinnell 2005). Without ground cover, the high erosivity of rainfall in the Australian tropics (Yu 1998; Chapter Three) and beyond can directly impact the soil surface at full energy, which subsequently 1) breaks down soil aggregates, 2) dislodges soil particles by direct splash transport and/or indirect onward transport by sheet or concentrated flow, and 3) creates soil surface seals and crusts from dislodged clay particles. The later can provide transient protection from further rain drop impact (Kinnell 2005; Walker et al. 2007). However on exposed soils, the loss of aggregate stability from both raindrop impact and soil dispersion, especially in sodic soils (Sumner 1995), can create surface seals, crusts and scalds, reduce infiltration rates, and promote sheet and concentrated flow that accelerates soil surface and subsurface erosion.

Grazing animals in rangelands can reduce the grass ground cover, vigour, and diversity directly by consuming, trampling and shearing vegetation, and/or indirectly via soil compaction, loss of soil organic carbon, reduced infiltration and soil water availability, and indirect changes in species presence/absence or dominance (Trimble and Mendel 1995; Evans 1998). In rangelands, the loss of ground cover from grazing has been correlated to a decrease in water infiltration, increase in water runoff, and increase in surface soil erosion and sediment yield (Tunstall and Webb 1981; Bridge et al. 1983; Greene et al. 1994; McIvor et al. 1995; Dunne et al. 2011). Often but not always, thresholds of vegetation cover exist below which significant soil erosion can occur (McIvor et al. 1995; Evans 1998).

Conversely, the proactive management of grazing impacts on vegetation in Australian savanna rangelands has been shown to increase vegetation cover and reduced soil erosion and sediment yield from hillslope areas (McIvor et al. 1995; McKeon et al. 2004; Stafford Smith et al. 2007; Bartley et al. 2010a; 2010b). However for gullies on or below hillslopes, the relationship between up-slope water production influenced by vegetative cover and down-slope gully erosion from runoff remains less clear in Australian rangelands (Bartley et al. 2010a; 2010b). In rangelands of India, the destocking or careful rotational management of cattle has also been shown to result in the dramatic recovery of savanna vegetation within several seasons (Hudson 1987), including directly within gullies or ravines where stock have been excluded (Haigh 1984; Raizada et al. 2005). These benefits are in addition to the benefits of direct revegetation or afforestation of gullies and ravines mentioned below.

Once concentrated surface runoff occurs, vegetative cover such as perennial grass on down-slope areas can enhance the resistance of the soil to erosion through root cohesion (Gyssels et al. 2007; De Baets et al. 2006; 2007) and surface roughness (Prosser and Slade 1994; Knapen et al. 2009), which decrease soil erodibility and increase the critical shear stress needed for erosion, respectively (Knapen et al. 2007; Knapen and Poesen 2010). For the initiation of rills and gullies from concentrated overland flow, there are intrinsic thresholds of vegetative cover and root biomass beyond which a given shear stress from flowing water will erode a channel. Both Graf (1979) and Prosser and Slade (1994) provided empirical evidence that reduced vegetative cover or biomass for a given hydrological regime can induce gully erosion. Both natural factors such as drought and fire, and anthropogenic factors such as grazing, tree clearing, and fire regime changes can influence vegetative cover and thresholds of gully erosion. In Australia, grazing impacts from sheep and cattle have often been cited as a major contributing factor in reducing vegetative cover, increasing runoff, and initiating gully erosion (e.g., Condon 1969; Eyles 1977; Prosser and Slade 1994; Prosser and Winchester 1996; McKeon et al. 2004; Pringle et al. 2006).

7.2.2.a.2 Revegetation after the onset of gully erosion

Once gully erosion has initiated, vegetation can still play an important mitigating role in reducing erosion and trapping transported sediment. Vegetation is an integral part of most channel evolution processes and models (Simon and Hupp 1992; Hupp 1992), including gully evolution (Gellis et al. 1995; 2001). Increasing vegetation with gully channels and networks can occur through removing chronic disturbances inhibiting recovery (e.g., grazing or clearing) and thus promoting natural recovery, or by direct planting of vegetation within or around gully networks. Recent studies have documented the dominant role of recolonizing or planted vegetation (grass, shrubs, trees) in stabilizing gully floors and channels, increasing sediment deposition and promoting channel aggradation, reducing downstream sediment yields, and driving positive feedback loops that promote landscape recovery (Vanacker et al. 2007; Molina et al. 2009; Reubens et al. 2008; Reubens et al. 2009; Sandercock and Hooke 2011). Colonizing plants with specific anchoring traits on badland slopes can also be effective at increasing soil cohesion and resistance to erosion, which is important for more proactive rehabilitation efforts (Burylo et al. 2009).

For alluvial gullies in the Mitchell River, Chapter Five has documented both grass and Eucalyptus tree colonization onto gully inset-floodplains of following gully scarp retreat, indicating the natural recovery potential. However, the influence of this vegetation on sediment storage and positive feedbacks toward gully stabilization remain unquantified, as are the influences of ongoing grazing on the full recovery potential of the vegetation.

Vegetation is often directly planted into eroding gully channels to promote recovery, often in association with other mitigating features such as grade control structures, terracing and slope re-grading, and organic and chemical soil amendments (see below). Caution should be used for when and at what stage of channel evolution vegetation replanting (or other intervention) should occur. The success of plant establishment is linked to geomorphic stability and micro-site conditions (Simon and Hupp 1992; Hupp 1992; Reubens et al. 2008; Reubens et al. 2009), and major geomorphic change associated with early stages of channel evolution can destroy premature rehabilitation efforts.

Bioengineering intervention has often been used in gully stabilization to potentially overcome some of the geomorphic evolution and plant establishment concerns (NRCS 1992; NRCS 2007c). Completely new habitat and geomorphic conditions are often created mechanically for direct planting, in the hopes that future vegetation establishment will stabilize the soils and offset any additional tendency for geomorphic change (NRCS 1992). Many techniques and materials can be utilized such as mechanical re-grading associated with live staking, live fascines, or live branch packing of woody shrubs in addition to direct planting of grasses (NRCS 1992). For example, the perennial-grass vetiver (*Vetiveria zizanioides*) from Asia is deep-rooted, non-invasive (sterile), and versatile, leading to its use around the world to stabilize soils and slopes (Gray and Sotir 1996; Mickovski and van Beek 2009). It is most often used in combination with other bioengineering methods such as slope re-grading. In an effective design at gully slope stabilization, Ndona and Truong (2005) document the complete re-grading of a gully complex using slope terracing and the planting of vetiver hedge rows along contours to maintain long-term stability.

In Australia, the use of vegetation planting for rehabilitation of gullies and tunnel erosion has aimed at re-establishing perennial grass and savannas woodlands to maintain a hydrological balance, prevent excess surface and subsurface water runoff, and reduce soil erosion (Boucher 1990; 1995). Revegetation has often been conducted in concert with chemical amelioration or more invasive structural manipulation (see below), making the isolation of the vegetative effects difficult.

In northern Australian tropical savannas, large scale revegetation and soil stabilization efforts in the Ord and Fitzroy Rivers since the 1960's have had mixed results in reducing soil erosion from rangelands degraded by overgrazing and gullying. In the Ord River in Western Australia, destocking cattle, eradicating feral animals, contour ploughing of hardened soils, and seeding exotic shrub and grass species on denuded interfluves and shallow hillslopes was successful at increasing ground cover and infiltration and reducing runoff (Hudson 1987; Tongway and Ludwig 2002; Payne et al. 2004). Dramatic changes in vegetation cover occurred such as increases in native grasses, but altered species diversity and proliferation of exotic species remains problematic (Payne et al. 2004). However, efforts at stabilizing gully floors and head scarps using vegetation and structure were more sporadic with generally poor results (Tongway and Ludwig 2002; Payne et al. 2004). This is unfortunate as gully erosion was and continues to be the dominant source of sediment in this catchment (Wasson et al. 2002). In the nearby Fitzroy River in Western Australia, generally similar rehabilitation efforts of severely degraded perennial grass cover on alluvial river frontage (Payne et al. 1979) also had mixed results both environmentally (Western Australian Department of Agriculture 1981) and economically (Wilcox and Thomas 1990).

In the south-eastern United States, soil and gully erosion were dramatically accelerated following forest clearance, agricultural development, and cotton farming in the 1800's (Trimble 1974; Galang et al. 2007) with landscape recovery and reforestation occurring after farm abandonment after the 1920's. In the Sumter National Forest of South Carolina, Law and Hansen (2004) describe a long-term (80+ yr) governmental program of landscape rehabilitation following severe land degradation and gully erosion from early agricultural settlement. Rehabilitation focused on afforestation, revegetation of eroded gullies and slopes with native species, use of fertilizers to promote vegetation establishment, and where applicable, mechanical or structural measures within gullies used to aid vegetation establishment and landscape recovery. Development of multi-stakeholder funded native plant nurseries and revegetation programs was a key to dramatic landscape recovery.

On steep badlands in France eroding into marls (lime-rich mudstones), revegetation and afforestation of highly eroded catchments can reduce sediment yields by an order of magnitude, which is a result of both water yield reductions and slope stabilization (Lukey et al. 2000 Mathys et al. 2003). More recent experimentation has focused on vegetation barriers (strips or buffers) used for trapping sediment eroding off badland slopes. Rey (2004) documented that low shrub and herbaceous vegetation barriers placed on bottom of eroding slopes could trap most all of the detached sediment. The minimum vegetation barrier area was 20% of the upslope eroding area for effective sediment trapping. Scaled to larger eroding gully catchments, targeted vegetation barriers could be effective at reducing sediment yields and promoting gully rehabilitation (Rey 2004).

On the North Island of New Zealand, large-scale afforestation efforts with exotic conifer trees (*Pinus radiata; Pseudotsuga menziesii; Pinus nigra*) have been implemented to reduce chronic gully erosion on steep terrain following native forest clearance post-European settlement. Numerous research studies have documented the processes and rates of this massive gully erosion, as well as the success of rehabilitation and afforestation techniques over the last 50-years in reducing gully area, soil erosion, and sediment yield (DeRose 1998; Gomez et al. 2003; Marden et al. 2005; Parkner et al. 2006; Herzig et al. 2011; Marden et al. 2011). In the Waipaoa catchment, DeRose (1998) estimated that sediment production was reduced by 38% between 1939 and 1992 in a 4 km^2 area due to afforestion. In the overlapping Te Weraroa sub-catchment, Gomez et al. (2003) estimated from sediment budgeting that sediment production from gullies was reduced by 62% due to afforestation over a similar period, along with reduction of water yield by up to 30%. Using a modelling framework calibrated to historical air photo estimates of erosion rates, Herzig et al. (2011) estimated that historic afforestation efforts have reduced sediment yield by ~ 33% in the Waipaoa catchment and ~ 16% in the Waiapu catchment. In contrast to historic afforestation efforts that targeted hillslopes, model results from Herzig et al. (2011) suggested that future afforestation efforts should target ALL present and newly initiating gullies at a variety of scales to maximum sediment yield reduction. Betts et al. (2003) concluded that afforestation should target gullies and surrounding hillslopes during the early stages of development before mass-wasting commences, to reduce excess pore-water pressures. Otherwise, large mass-wasting processes once initiated can overwhelm any riparian tree planting within a gully network. However, Marden et al. (2005) suggested that initial afforestation efforts should focus on any available plantable surface on hillslopes, with follow-up planting targeting internal gully surfaces, channels, and riparian zones after hillslope canopy closure (~10 yrs) and sediment supply reduction.

In China, large catchment-scale efforts at reducing soil and gully erosion in the Loess Plateau Region and elsewhere have utilized widespread revegetation and afforestion programs across space and time to stabilize gullies and hillslopes and reduce downstream sedimentation (Chen et al. 2007). Most revegetation efforts (tree and grass planting) were also implemented and monitored in concert with other stabilization techniques, such as the installation of check dams, sedimentation reservoirs, contour berms, surface water diversion ditches, and terracing, in addition to changes in land use (Huang et al. 2003; Zhang et al. 2008). Revegetation efforts have focused on hillslopes and to a lesser extent on revegetating gully bottoms and sidewalls (Chen and Cai 2006), despite these areas being the dominant sources of sediment (Li et al. 2003). After decades of implementation and monitoring, numerous studies have documented reductions in both water and sediment yield at the catchment scale from cumulative efforts (Huang et al. 2003; Chen and Cai 2006; Zhang et al. 2008; Rustomji et al. 2008). Once decoupled from climatic variations, reductions in *water yield* can largely be attributed to reservoir storage (Zhang et al. 2008) and afforestation (Huang et al. 2003a; 2003b). Causes of *sediment yield* reductions are more complex due to the interactions of multiple measures. Thus, the exact influence of the revegetation measures on gully stabilization and sediment yield remains uncertain, with the structural trapping of sediment by dams likely dominating observed sediment reductions to date (Zhang et al. 2008; Rustomji et al. 2008).

Furthermore in China, the success in establishing trees and plantations during afforestation efforts to control erosion have also been mixed, with many area experiencing a die back of planted trees due to low rainfall and soil moisture availability (Xu et al. 2004; Trac et al. 2007; Cao et al. 2010). Planting species that are better adapted to local environments (in China’s case shrubs and steppe species) is likely key to long-term sustainable rehabilitation (Cao et al. 2010; Chen 2010).

In India, agricultural production for subsistence farming is vital for community wellbeing along the riparian zones of major rivers ravaged by “*ravine*” erosion (*sensu* Haigh 1984; Yadav and Bhushan 2002). This form of gully erosion into alluvium is akin in form and process to alluvial gully erosion in Australia (*sensu* Brooks et al. 2009). These alluvial ravines next to major rivers have been well documented in terms of causal factors such as climate, dispersive alluvial soils, tectonics, and land use (overgrazing, deforestation, agriculture) (Sharma 1982; Singh and Singh 1982; Sharma 1987; Singh and Agnihotri 1987; Singh and Dubey 2000). Soil conservation measures and gully (ravine) rehabilitation efforts have been extensive since the 1950’s in India (Haigh 1984; 1998), with efforts mainly focused on afforestation, agroforestry, and managing intensive agricultural systems (Yadav and Bhushan 2002; Yadav et al. 2003). The establishment and management of vegetation systems in gullied lands has the duel goals of 1) maintaining productive agricultural/agroforestry output for human needs via crop diversification, and 2) improving water retention and management during rainfall, infiltration, runoff, and channel flow processes (Bhushan et al. 1992; Narayan et al. 1999; Yadav and Bhushan 2002; Yadav et al. 2003). The complete destocking of cattle from ravines and gullies has also been shown to result in the dramatic recovery of grasslands (Haigh 1984; Raizada et al. 2005). Similar to China, often these agroforestry management systems in India have included additional physical measures to retain, infiltrate, and dissipate water through contour berms, terracing, mechanical slope re-grading, and channel grade-control structures (described below).

7.2.2.a.3 Surface mulch amendments

In agricultural settings, soil surface cover from crop residue and mulch following no-tillage agriculture can significantly increase soil water retention and reduce soil erosion compared to conventional tillage (Thomas et al. 2007; Triplett and Dick 2008). No-tillage soils with cover from crop residue have significantly lower soil erodibility coefficients (Kc) than conventionally-tilled or reduced-tilled soils (Knapen et al. 2007). Much of the reduction in soil erosion can be explained from reduced physical soil disturbance and increased surface cover protecting unvegetated soils from rainfall kinetic energy, aggregate breakdown, and seal formation. Secondary benefits come from increased infiltration and deep drainage, increased surface roughness, decreased runoff velocity and volume, and increased soil organic carbon (see below) (Thomas et al. 2007).

In non-agricultural settings, surface cover from plant residues, mulch, and compost is similarly important in reducing soil erosion and increasing soil water retention. Management actions can either promote the retention of plant organic matter on the soil surface (see above), or actively (re)introduce organic mulches to soil surfaces to reduce future erosion. The later is one of the most common soil erosion reduction techniques for exposed or denuded soils, while the former is the most sustainable. Direct mulch application is now common place at construction sites (Gray and Sotir 1996; Faucette et al. 2005; McLaughlin and Brown 2006; NRCS 1992), in areas burned by fire (Robichaud et al. 2010), and at river bank revegetation projects (Rutherfurd et al. 2000; NRCS 2007c). Often mulches are used in combination with grass seeding or tree planting to improve germination conditions such as retaining moisture, protecting seeds from down slope wash, and inhibiting weed growth and competition.

Dry loose mulches include local mulches of natural grass or forest debris (leaves, stems, woodchips), introduced agricultural straw (wheat, barley, rice, etc.), introduced wood mulch (chips, shreds, strands), and various types of compost. They can be applied by hand or mechanically using blowers or dropped from helicopters (Robichaud et al. 2010). They are often spread in combination with plant seeding. Caution should be used to obtain “weed-free” mulches, as weeds associated with some straw mulches can have unintended consequences once established at rehabilitation sites (Beyers 2004; Kruse et al. 2004). Depending on application rate and depth, they can also have unintended consequences of inhibiting the emergence of seedlings through the mulch (Robichaud et al. 2010).

Geotextile fabrics of various types (straw, coconut, jute, etc.) and erosion control blankets (organic material interwoven into a mesh) have been extensively used at construction sites and streambank stabilization projects over the last few decades (Gray and Sotir 1996; NRCS 2007c). These blankets and fabrics can be rolled out onto soil surfaces and tacked in place to retain cover in place compared to other loose dry mulches. Their performance at erosion control varies (Faucette et al. 2009a), but they are most often used with other techniques such as grass seeding or tree planting.

Compost erosion control blankets have been increasingly used for erosion control in the last decade. These “blankets” are actually just surface covers of certified quality compost applied to standard depths. Compost can be applied via manure spreaders or pneumatic blowers that deliver it to the soil surface. Seed or other soil amendments like PAM or gypsum can also be delivered to the soil surfaces with the compost when using pneumatic blowers. Compost erosion control blankets, and mixtures of compost with other soil amendments, have been shown to be highly effective at erosion control, typically exceeding the performance of other standard techniques in isolation or combination (Faucette et al. 2005; 2007; 2009a).

Wet mulches (a.k.a. hydromulch) include mixtures of water and mulch that can be sprayed onto soil surfaces. They often include mixtures of grass or other seeds (a.k.a. hydroseed), and soil binding agents (tackifiers) of either organic (polysaccharides from plants) or synthetic (polymers such as PAM, see below) form. They can be mixed on site in large truck mounted tanks using local and imported dry ingredients (seed, PAM, mulch, etc.). Since hydromulches stick to soil surfaces, they generally stay in place and are wind resistant. Compared to dry mulches and compost, they do not roughen the soil surface and thus are less effective at resisting overland flow. Their mulch components also break down quicker than dry mulches and compost, resulting in less soil protection over time. However, the establishment of grass as a result of hydroseeding can progressively take over the role of soil protection and binding.

In landscapes naturally prone to fire such as tropical savannas, the generation and protection of natural surface mulches of organic detritus is intricately linked to the proactive management of the fire regime. Fire breaks, season of fire use, intensity of fire, and annual frequency of fire could all be important factors in creating or retaining surface mulches and organic carbon. The retention of applied surface mulches such as straw for rehabilitation will also be affected by fire potential, and thus should be managed cautiously.

7.2.2.a.4 Soil organic matter amendments

Soil organic carbon (SOC) (living and dead) within a soil profile is important in maintaining soil structure and reducing soil erodibility. SOC can help cement soil particles into stable aggregates, increase biological activity, and increase the porosity and permeability of soils (Tisdall and Oades 1982; Carter and Stewart 1995). Biological activity associated with SOC can transform organic material into polysaccharides and other natural polymers that bind soil particles into aggregates important for stability in sodic soils, similar to synthetic polymers (see below) (Sumner 1995).

For sodic soils that have a tendency to slake as well as disperse, increasing SOC can significantly decrease soil slaking (Chan and Mullins 1994), likely due to both increased aggregate strength and reduced wetting rates. Slaking is the process of soil aggregates fragmentation under rapid wetting when matrix suction is at its maximum. However, Rengasamy and Olsson (1991) state that while SOC can help reduce slaking, it will not help with reducing dispersion until Na^{+} is first replaced with Ca^{+2} to stabilize aggregates.

The amendment of agricultural soils with organic matter or compost is common for soil fertilization and structural improvement. Modern applications of organic matter to a variety of soil types and uses have moved beyond just livestock wastes to include biosolids (sewage sludge), paper industry wastes (pulp), cheese whey, and other industry and agricultural waste products (Graber et al. 2006). Many of these organic soil amendments have been found to be beneficial to aggregate stability and soil structure in agricultural settings (Graber et al. 2006). Compost erosion blankets for surface soil protection and organic matter amendment also have become increasing popular and effective (Faucette et al. 2005; 2007; 2009a). However, the application of compost and soil organic matter to protect, stabilize, and fertilize soils in other settings such as rangelands degraded by gullies has been limited.

Overall, the importance of SOC to the stability of soils highlights the importance of the progressive management of surface vegetation communities in maintaining pools of carbon available for incorporation into the soil profile. This could be especially true in semi-arid savanna rangelands where SOC can dominate total carbon stocks (Chen et al. 2003) and below-ground SOC is influenced by the above-ground dynamics of grasslands, over-story woodlands, and land use such as grazing and fire management (Chen et al. 2005). However, since SOC typically decreases with depth in highly inorganic soils, the influence of SOC is likely most important for soil surface processes influencing erosion such as infiltration, surface sealing, scaling, runoff depth, and surface soil erosion resistance.

7.2.3 Chemical soil amendments

Sodic soils with high levels of exchangeable sodium suffer from physical degradation of the soil structure due to enhanced swelling and aggregate dispersion upon wetting. Sodic soils are prone to erosion from sheet wash, rilling, and gullying due to lack of structural and aggregate stability. They can also suffer from low fertility. The soil types, chemistry, physical degradation associated with sodic soils are extremely complex and both spatially and temporally diverse across Australia and the world (Naidu et al. 1995). Despite this diversity, there are several common chemical methods for ameliorating sodic soils in both agricultural and rangeland settings.

7.2.3.a.1 Gypsum

Gypsum ($CaSO_4$) is the most common soil amendment for rehabilitating sodic and hardsetting soils in agricultural soils (Sumner 1995; Keren 1996; Mullins 1998; Graber et al. 2006) and dryland pasture soils subject to gully erosion or scalding (Jones 1969; Muirhead 1974; Floyd 1974; Boucher 1990; Boucher 1995). Reduced clay swelling and dispersion is accomplished by replacing exchangeable sodium (Na^+) with calcium (Ca^{+2}) on clay particle exchange sites (cation-exchange effect) and increasing the concentration of cations in surface water when high quality rainwater predominates (electrolyte effect). Typically the use of by-product gypsum (phosphogypsum from phosphoric acid creation) is preferred over mined- gypsum, due to its finer particle size and more rapid solubility (Levy 1996; Graber et al. 2006). Lime ($CaCO_3$) and calcium chloride ($CaCl_2$) can also be used, but lime is less soluble than gypsum and calcium chloride more expensive.

Gypsum can have long- or short-term beneficial effects to the structure and chemistry of sodic soils, depending on the rate of application, surface or subsurface application, soil type, and the soil properties such as the exchangeable sodium percentage (ESP) and concentration of electrolytes in the surface soil. When gypsum is mechanically broadcast onto soil surfaces with low electrolyte concentrations under natural rainfall conditions, both the cation-exchange effect but especially the electrolyte effect are important in reducing swelling, dispersion, crust formation and soil surface sealing, which increase soil permeability, (not porosity), hydraulic conductivity and field infiltration rates of surface rainwater (Keren 1996; Graber et al. 2006). Surface application also partially protects the soil (mulch-effect) from direct rainfall impacts and mechanically inhibits seal formation. Overall these surface effects of gypsum decreases surface soil erosion by 1) increasing infiltration and decreasing runoff depths, 2) increasing aggregate stability and decreasing soil detachment, 3) increasing surface roughness, decreasing velocity, and 4) increase suspended clay flocculation and deposition (Levy 1996; Graber et al. 2006). However the electrolyte effect on reduced soil dispersion and erosion can be short lived if high-quality rainwater continuously flushes electrolytes from the soil surface deeper into the soil profile or down slope on a soil surface.

The cation-exchange effect is more important for prolonged changes in soil chemistry and structural stability (Keren 1983; Sumner 1995; Keren 1996), especially if high ESP values are found throughout the profile. This might be especially important if the stability and dispersibility of sub-soils is influencing the propagation of gully head scarps. If soils are highly sodic at depth and leading to enhanced gully erosion, sub-surface application may be important through deep ripping (ploughing) of the soil and gypsum application throughout the tilled layer (Jayawardone and Chan 1995). However, if sub-surface soils are dramatically more sodic than surface soils, deep ripping may not be desirable to avoid bring these sodic soils to the surface.

The gypsum application rate depends on the area and volume of soil to be treated, the existing soil ESP values, and the future target ESP values that will promote soil stability. Typical surface application rates are between 3 to 6 t ha^{-1}, up to 15 t ha^{-1} (Jayawardone and Chan 1995; Boucher 1995; Sumner 1995). Minimum surface application rates of ~ 2 t ha^{-1} are needed to assist re-establishment of vegetative grass cover (Boucher 1995). Rates higher than 10 to 15 t ha^{-1} will be needed to reduce subsoil sodicity (Floyd 1974; Jayawardone and Chan 1995; Boucher 1995). Several methods are available to calculate the gypsum requirements of soils depending on chemical and physical characteristics (Keren 1996; Suarez 2001).

7.2.3.a.2 Synthetic polymers

Synthetic organic polymers can be used in sodic soil as conditioners to improve aggregate stability, reduce surface seal formation, increase infiltration rates, and reduce runoff and erosion (Levy 1996; Graber et al. 2006; Ben-Hur 2006; Sojka et al. 2007). Polyacrylamide (PAM) and polysaccharide (PSD) are the two most commonly used and researched synthetic polymers for soil conditioning, although many formulations of these exist. They are typically applied in solution form just to the soil surface where they are absorbed onto clay particles or the surface of aggregates, reducing repulsive forces and dispersion. However they also can be applied in granular form due to solubility issues, however with mixed results (Graber et al. 2006). Polymer application can also be supplemented with gypsum with additive effects, especially under high kinetic-energy rainfall events that break down surface aggregates and promote seal formation (Levy 1996; Ben-Hur 2006).

Soil stabilizing polymers have been most often used in irrigated agriculture for promoting infiltration and reducing erosion. However polymers (especially PAM) are increasingly being used for erosion control in non-agricultural and dryland settings. For example, polymers are being used to reduce erosion and soil loss from construction sites (Hayes et al. 2005), mine waste areas (Vacher et al. 2003), roads and road embankments (McLaughlin and Brown 2006; McLaughlin et al. 2009), landfills (Flanagan et al. 2002), and following rangeland or forest fires (Robichaud et al. 2010). Often PAM is used in combination with other soil stabilization treatments, such as gypsum, mulches, grass seeding, and grade-control structures. PAM can be combined into hydromulch or hydroseed mixtures and spayed onto soil surfaces by truck-mounted sprayers or even helicopters (e.g., Robichaud et al. 2010). However the use of a mixture of stabilizers makes it hard to isolate the cause and effect of individual components. Some erosion studies have found that PAM was partially ineffectual in isolation (Hayes et al. 2005), while others clearly showed reduced soil loss from isolated PAM application (Flanagan et al. 2002). Most frequently there are added benefits to including PAM into erosion control treatments (Zhang et al. 1998; McLaughlin and Brown 2006; Faucette et al. 2007; McLaughlin et al. 2009). When included in hydroseed mixtures, the short-term benefits of PAM in increasing infiltration and reducing runoff can increase grass establishment and growth (Flanagan et al. 2002), which in turn promotes longer-term soil stabilization.

The application of synthetic polymers such as PAM to preventing or reducing deep gully erosion has not been thoroughly researched. Since polymers are most often used on soil surfaces to reduce sheet-flow and shallow-rill erosion, their application to gully control would be under situations where the reduction of the initiation of gullying was desirable, or where existing gully systems were re-graded via ripping and sculpting and the new bare surfaces needed stabilization.

7.2.3.a.3 Fertilizers

Most subsurface soils that gullies erode into are low in fertility and nutrients, such as sodic soils or C horizons of saprolite. Several gully rehabilitation trials have incorporated inorganic fertilizers into treatments as tool to boost soil fertility and enhance the establishment of native vegetation. In south-eastern Australian, Boucher (1995) recommended a mixture of superphosphate and lime to aid revegetation of gully (tunnel) erosion following deep ripping or land re-grading. Alternatively a mixture of superphosphate and phosphogypsum could be used, both created during similar industrial processes.

In the south-eastern United States, Law and Hansen (2004) describe the successful use of fertilizer application to increase the regeneration success of native plants in and around eroding gullies. They applied 0.4 tonnes/ha of slow release fertilizer (35-17-0) at US$250 per ha during the growing season to eroded gullies recently planted with native vegetation. In heavily degraded area they recommended multiple treatments as dictated by active monitoring on soil conditions. In another gully erosion control study in Nepal, Higaki et al. (2005) found that the application of a compost fertilizer to crusted, nutrient poor, lateritic soil on an alluvial terrace aided in the stabilization of gullied surfaces and germination of grasses.

7.2.4 Physical control

7.2.4.a.1 Tillage of gullies

Tillage is the mechanical digging and overturning of the soil surface using human hand, animal, or machine power. For small, shallow, "ephemeral" gullies often in agricultural settings, it is conventional practice for farmers to machine plough or till through gully channels with machinery and continue cropping that land area (Poesen et al. 2003). However, often ephemeral gullies reform in the same general topographic location during subsequent runoff events creating chronic soil loss (Poesen et al. 2003). This is especially true where conventional tillage leads to exposed soils prone to erosion, compared to no-tillage agriculture that retains crop residue and mulch, increases soil water retention, and reduces soil erosion (Thomas et al. 2007; Triplett and Dick 2008). The more progressive use of permanent vegetation buffer strips or grass waterways along these preferential gully pathways has been proven to be effective at reducing sediment loss (Stannard 1977; Poesen et al. 2003).

In Australian tropical rangelands, tillage using chisel and disk ploughs and rippers has been used along with direct grass seeding to rehabilitate bare eroded plains and the shallow upper extents of gully systems (Hudson 1987; Tongway and Ludwig 2002; Payne et al. 2004). While successful at improving both exotic and native cover on the eroded plains, the influence of these measures on revegetating and reducing gully erosion were unclear but likely minimal (Wasson et al. 2002).

In south-eastern Australia where tunnel erosion (subsurface gullying) is a common response to land-use disturbance, deep tillage and ripping has been used to break up tunnels (Floyd 1974; Boucher 1990; Boucher 1995). However the physical benefits of reducing tunnel connectivity and increasing vertical water infiltration are often short lived. Successful long-term rehabilitation depends on the establishment of vigorous vegetative cover (grass and trees) and control of grazing and feral animals following initial tillage. Chemical amendments have also been helpful (Floyd 1974; Boucher 1990; Boucher 1995).

For Australian sodic and hardsetting soils in both agricultural and rangeland contexts, tillage has been used as a physical mechanism to loosen the soil, reduce bulk density, increase macro-porosity, improve soil hydraulic conductivity, and reduce runoff (Jones 1969; Muirhead 1974; Cunningham 1974; Jayawardone and Chan 1995). These structural improvements are usually short lived in sodic soils depending on future management, unless soil amendments are used such as gypsum, vegetation is used to protect the soil surface from structural decay, and/or organic matter is used to improve aggregate stability. For improvement of sodic soils to greater depths, deep ripping and ploughing to >0.5m has been used along with chemical amelioration with gypsum (Jayawardone and Chan 1995).

7.2.4.a.2 Re-grading gully slopes

For deeper gullies too large to plough, deep ripping, earth moving and landform re-grading and re-sculpting using bulldozers or other machinery has often been used in engineering intervention in gullies. Often the goal is to reduce the average land slope by battering back the over-steepened sections of a slope (Gray and Sotir 1996). Slope reduction can decrease stream power in rills and gullies, but if the slope-length is increased providing greater water volume concentration, then changes to stream power can be marginal or worse. Alternatively if average slopes can not be reduced, bench or step terracing has been used for agricultural protection and slope stabilization on steep hillslopes for thousands of years (Hudson 1987). This is conducted by effectively reducing local slopes and slope-lengths but maintaining average slopes

Conventional re-grading techniques using modern machinery have been extended to gully slope stabilization. Due to the operating expense of heavy machinery, these techniques are most often used when vital infrastructure is being threatened (e.g., roads, houses, dams) or when land reclamation is desirable from an agricultural or economic standpoint. For example, economic farming subsidies for wheat in the European Union have indirectly promoted the remoulding of silty-clay gully or badland slopes to increase agricultural land availability (Clarke and Rendell 2000). These engineering techniques can create dramatic changes to the landscape, however there success at actually reducing soil erosion is questionable. On many new slopes, rill, gully, and landslide erosion re-initiated soon after engineering works. By remoulding both erosional badland slopes and depositional fans into more uniform slopes with only seasonal vegetation cover, the projects effectively increased the slope-length and the connectivity of the hillslopes with downstream channels. Former depositional slopes at the base of badlands no longer buffered downstream reaches from sediment inputs, with resulting increases in overall sediment yield (Clarke and Rendell 2000).

In less developed countries with greater human capital and demand for productive agricultural land, gully rehabilitation has been taken to a more intensive management level. For example in India along eroded alluvial soils in riverine riparian zones, the re-grading and terracing of ravine or gully slopes is common to reclaim land for both agriculture and agroforestry (Prajapati et al. 1974; Haigh 1984; Yadav and Bhushan 1989; Bhusman et al. 1992; Narayan et al. 1999; Singh and Dubey 2000; Yadav et al. 2003). Most of the proactive reclamation for intensive agriculture is concentrated near the heads of gullies where existing fields are under threat from gully advancement. Yadav et al. (2003) documented the optimal size of small terrace plots on reclaimed land that could maximize rainfall infiltration and reduce water runoff, thereby reducing downslope plot soil erosion and downslope gully erosion. The reclamation of the more degraded and dissected ravine terrain closer to the river is more problematic, but even in this zone remnant knolls and hill tops are re-graded using terracing and bunds for agriculture and agroforestry. Even gully beds are occasionally used for agriculture with the aid of check dams (Yadav and Bhushan 2002). Similarly in the Congo, Ndona and Truong (2005) also describe the complete re-grading of a gully complex using slope terracing. Much of this extensive work was done with hand tools, with the goal of stabilizing slopes to protect infrastructure and improving the livelihoods of urban inhabitants.

In Australia, the complete re-grading of gully networks has long been used as an engineering intervention (Stannard 1977; Boucher 1990; 1995; Bartlett 1991; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Often, re-grading has been conducted in concert with vegetation planting, chemical soil amendments, and improved stock control, such as during the creation of grassed waterways from incised gully networks (Stannard 1977). However in other cases, re-grading is done as a one-off treatment by farmers or road maintenance crews with little insight from technical experts. When re-grading or soil ripping has occurred on dispersive soils without chemical amendments, adequate vegetative improvements, and stock control, gully channels and tunnel erosion have often reformed during the next wet season (Boucher 1990). The monitoring of gully slope re-grading in Australia, and control for other influencing variables, has been insufficient to determine the long-term effectiveness of engineering attempts to create geomorphic stability, let alone a new geomorphic system in dynamic equilibrium.

As an example, in 2006 as part of a soil conservation and coal development mitigation project, Anglo Coal, the Soil Conservation Services of NSW, and the Hunter River CMA (funded by NHT) conducted a large gully rehabilitation project that completely re-graded and re-shaped a 500m long x 8m deep gully below an old farm dam. Gypsum was added, pasture grass and trees were planted, and the dam at the head of the gully was enlarged for water diversion. After poor initial plant survival during drought, green-waste compost was imported to the site and reseeding with grass, which after renewed rain provided great ground cover to the site. Monitoring of hydrologic and geomorphic parameters has been minimal to date. No quantitative data on pre- and post project sediment yield from the gully system exist to confirm the hypothesis that engineering works actually reduced soil erosion along with water reduction from the dam, or support an alternative hypothesis that the engineering works potentially increased sediment yield at least temporarily until vegetation established. Additional examples of gully re-grading and engineering can be found in the grey-literature (Bartlett 1991; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008).

7.2.4.a.3 Water retention and diversion structures on hillslopes above gully heads

For controlling both water and sediment runoff and the initiation of gully erosion, numerous structural methods have been developed to retain water and sediment in situ on hillslopes (retention structures) and/or divert water to areas where it can infiltrate without erosion (diversion structures). The goal of retention structures is to capture water and sediment locally as they move down slope, reduce slope-lengths, reduce overland flow velocities and depths, promote infiltration, and increase evaporation and/or vegetative water use. Most often structures are built or installed on contour in a continuous or staggered fashion perpendicular to the fall line. Large retention structures such as ponds and dams constructed along channels and drainage lines will be discussed further below. The goal of diversion structures is to both capture water and sediment down slope in addition to diversion of water to appropriate discharge locations, such as away from gully heads and drainage lines.

At the local scale, small check dam structures are used for soil/water retention and erosion control, especially for construction projects, road slopes and drainage ditches. These include silt-fences made of mesh fabric, straw bales, coir bundles and wattles, compost berms, and compost filter socks (Gray and Sotir 1996; NRCS 2007c; Faucette et al. 2009b). For more intensive biogeotechnical engineering of hillslopes, larger retaining structures are used in association with vegetation planting, using structures such as concrete walls, rock gabions, rock riprap, timber and concrete cribs, and other innovative structures (Gray and Sotir 1996; NRCS 1992; NRCS 2007c). Bioengineering treatments that incorporate both physical structure and vegetation include live staking, live fascines, live crib walls, terraced brush-layers and hedge rows and berms on contour (Gray and Sotir 1996; NRCS 1992).

Once the scale of structural erosion control reaches entire or multiple hillslopes, the options change for practical or cost-effective structural control. Retention structures such as straw bales and silt fences can still be used, but labour costs increase. In forested settings, contour-felled log erosion-barriers can be used for sediment trapping (Robichaud et al. 2010). As with all retention structures, they can rapidly fill up with sediment and become ineffective at erosion control over time. This highlights the need for consistent maintenance programs or a combination of treatments to reduce water and sediment runoff from hillslopes.

In large-scale agricultural and rangeland settings, water and sediment retention structures on hillslopes or plains are constructed on contour and made out of local soil material and formed into contour furrows, contour banks or berms, and terraces (Gifford 1978; Hudson 1987; Thomas et al. 2007). Contour banks are can also be planted with grass, crops, or hedgerows to increase sediment retention (Hudson 1987; Gray and Sotir 1996). In Australian rangelands, contour banks are advocated by government and ubiquitously used to control shallow hillslope runoff, promote infiltration, spread water, and retain soil in situ in association with or without the use of grass, shrub or crop cover (Quilty 1972b; Bartlett 1991; Tongway and Ludwig 2002; Payne et al. 2004). Small, frequent, and cumulative waterponding banks are also used to reclaim scalded duplex soils in arid rangelands by retaining and infiltrating water and leaching salts (Jones 1969; Cunningham 1974; Thompson R., 2008).

Banks of various types can be constructed using either road graders or disk ploughers or bulldozers, with graders being the most economical. Contour banks can be stagged across and down slopes to retain and diffuse concentrated water flow, and can either be continuous structures or structures with periodic gaps. Gap absorption and gap spreader banks can provide the duel functions of energy dissipation and water spreading to maximize use (Quilty 1972b). Ditches either above or below the banks spread water laterally, while banks below gaps in upslope banks dissipate energy and further spread water laterally. The spacing and storage volume of contour banks are a function of slope and expected rainfall-runoff volumes of a given magnitude-frequency. Maintenance of contour banks is commonly needed over time (~decade) to repair breaches in the banks from water or stock or traffic and maintain the water and sediment trapping capacity.

For gully stabilization or the reduction in gully initiation, water diversion structures such as contour banks or ditches are often used immediately upslope or along gully channels to intercept water before it converges into an existing or potential gully area (Quilty 1972a; 1972c; NRCS 2007b). In Australia, they are typically constructed at a subtle but appropriate grade to divert water but prevent scour in the ditch (Quilty 1972c; Bartlett 1991; Jenkins and McCaffrey 2008). However, extreme caution is warranted in selecting exactly where diverted water is released for dissipation, as discharge areas can become zone of concentrated water flow and initiate or accelerate gully erosion in unintended locations (Haigh 1984; Quilty 1986). Engineered waterways (grass or rock) are occasionally constructed for receiving diverted water and dissipating energy (Stannard 1977; Bartlett 1991; NRCS 2007b; Jenkins and McCaffrey 2008). Unfortunately regarding structural runoff control treatments, the statement by Gifford (1978) that "*many of these efforts suffer from lack of data regarding actual influences of treatments on resources*" still remains true today.

In Spain, small earthen banks (~30cm high) are often built by farmers to divert water away from gully head scarps eroding into alluvial terraces (bank or alluvial gullies) (Oostwoud Wijdenes et al. 2000). Research demonstrates that these banks can significantly reduce head scarp retreat, but Oostwoud Wijdenes et al. (2000) concludes that improper discharge of diverted water can promote gully side wall erosion, or perhaps lead to piping in dispersible soils by increasing the hydraulic head of water ponded behind banks. In India, where reclamation of gullied landscapes is essential for agricultural protection, contour banks and terraces have been effective at local water retention, spreading water for plant use between structural banks, and controlling water runoff that fuels down slope gully erosion (Haigh 1984; Yadav and Bhusman 1989; Singh 1992; Yadav et al. 2003).

7.2.4.a.4 Farm dams and reservoirs at or above gully heads

In south-eastern Australia, small earthen dams and reservoirs are commonly built above gully heads within shallow hillslope depressions or existing ephemeral channels (Quilty 1973a; Young 1973; Starr 1977). They have the goals of trapping hillslope sediment, impounding water runoff and reducing downstream peak discharge rates, diverting water away from downstream gully heads and channels, and/or using the water locally for stock and farm uses. They are commonly advocated and partially funded by government groups for both erosion control and farm development (Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Typically these earthen dams are constructed out of compacted local clay material, dressed with stockpiles of topsoil, and provided with earthen spillways lined with clay and grass, or armoured with rock or concrete to dissipate energy (Quilty 1973a; Young 1973; Starr 1977). They are also typically associated with armouring downstream gully head scarps (see below) to reduced head cutting into the dam foundation, or the complete reshaping of downstream gully channels (see above). Retention volumes and sediment trap efficiencies depend on design, particle size fraction (sand vs. silt/clay), and dam location (tributary vs. mainstem). Armstrong and Mackenzie (2002) estimated that farms dams used for gully control trapped >70% of the sediment yield and significantly reduced downstream sediment supplies, similar to other studies (Verstraeten and Prosser 2008).

In the southeast United States, earthen dams or "drop pipe structures" are commonly built at the head of gullies (>3m deep) eroding up into agricultural fields. These structures consist of corrugated-steel drop-pipes through earthen embankments 4 to 6 m high (Shields et al. 2002;

Wilson et al. 2008). They are essentially a farm dam placed immediately at a head cut. The effectiveness of these structures at reducing long-term sediment yields is unknown, especially due to their relatively short life-spans and common failure (Wilson et al. 2008). However, they can be modified for ecological benefits (Shields et al. 2002; 2007).

Small farm dams are ubiquitous across Australia. The design standards and life expectance of small dams is typically less than for large reservoirs (Pisaniello 2010), especially those constructed out of local material and targeting gully stabilization and sediment retention (Quilty 1973a; Young 1973; Starr 1977). The questionable long-term functionality and stability of using farm dams to mitigate water/sediment runoff and gully erosion needs to be balanced against more sustainable methods to control water runoff and gully erosion, such as complete hillslope and channel revegetation and/or altered land-use practices. In the United States, there are >2,000,000 small dams (<2m high) many over 50 years old (Graf 1999). Removal of these and larger dams has accelerated over that last two decades due to safety concerns over ageing infrastructure, loss of dam or reservoir functionality due to sedimentation, high costs of maintenance, and/or increasing concerns about the environmental impact of dams or dam failures (Pohl 2002). The number, age and condition of small farm dams in Australia are unquantified. Dam failure is a major concern worldwide (Graham 1999) including small farm dams in Australia (Pisaniello 2010). When small dams are constructed on top and out of local material such as dispersible sodic soils, tunnelling and pipe erosion can lead to their failure (Floyd 1974; Starr 1977; Boucher 1990). Failure is also common during extreme flood events following long drought periods and minimal maintenance, typical for the Australian continent. For example, several earthen dams located at study sites of Armstrong and Mackenzie (2002) have deep rilling and tunnel erosion on their dam face that could threaten the future integrity of the dams (Shellberg personal observations).

7.2.4.a.5 Armouring gully head scarps

Structural control of gully head scarps (head cuts) is often the most instinctual reactions to severe gully erosion. If it is eroding right there, lets do something right there. Similar to many other physical treatments to gully erosion, *head scarp armouring treats symptoms rather than addressing the cause of erosion.* Instincts can be wrong. However, if designed and engineered correctly for the right soil type and hydrogeomorphic environment, armouring can provide short-term gains in soil erosion reduction, at a monetary and potentially environmental/geomorphic cost.

One of the first instincts of famers and land managers is to place obstructions at the head cut in attempts to protect the soil surface, dissipate energy, or slow retreat via armouring. At first, anything and everything is tried. Old tyres, old cars, old rubble, old fencing wire and scarp metal, and occasionally dead stock add to the mix from falling over the escarpment. Most often these structures do not work due to their ad hoc, patchy application and their failure to address the mechanism for head cut retreat. In dispersible sodic soils where scarps are driven by both direct rainfall-runoff and subsurface water seepage out if the scarp face, the structural failure of the soil at the soil aggregate level will promote erosion right around or through these temporary obstructions. In the worse case scenario these rubbish items can redirect water and hasten the erosion, or in the case of old tyres, their slow chemical breakdown can lead to chemical leaching and the pollution of the environment (Fitzpatrick et al. 2005).

As the next step up, civil engineering designs are often used to armour gully head scarps. Rock rip-rap and gabion is a ubiquitous tool used for slope stabilization (Gray and Sotir 1996). However, in silt/clay soils with high levels of exchangeable sodium driving dispersion, large angular rock is ineffective at holding soil in place due to soil dispersion and sediment suspensions moving around or through the rock pores. For hillslope gullies in semi-confined valleys, excavation down to bedrock or more stable soil and backfilling with rock can effective. These structures effectively become grade control structures at the former location of the head scarp or cut. The more classic style of sequentially-stepped grade control structures used over long channel lengths in semi-confined channels will address further below.

In Australia, engineered structures have been used for the stabilization of gully head cuts (via grade control) in semi-confined hillslope-gully channels (Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Several structural derivatives exist including weirs, chutes, flumes, and drop structures. They are only applicable where surface overland flow dominates erosion and hillslope topography concentrates water into un-channelled depressions or ephemeral channels. They are not applicable to unconfined gullies where soil dispersion dominates and leads to subsurface tunnel or seepage erosion. Typically they are constructed out of rock, gabion and/or concrete. Armoured chutes carry water over an inclined slope and dissipate the water in a stilling basin at the gully floor level. Drop structures let water flow off a concrete or rock step onto other steps or a stilling basin. Most structures are designed with cut-off walls at the inlet, both at depth into the soil and laterally, in order to prevent water tunnelling around the structure in unconsolidated soil. Incorporation of vegetation into these structures for bioengineering is less common, but a possibility. Overall, no research studies on the long-term effectiveness, stability, and geomorphic impacts of these structures have been conducted in Australia.

7.2.4.a.6 Grade control structures within gully channels

Grade control structures are natural or engineered structures used to control channel-bed incision (degradation) and grade (slope) of unstable gully, creek, and river channels. They have been engineered by humans for thousands of years to trap water and sediment in small headwater channels for agricultural purposes (e.g., Norton et al. 2002), and most recently in human history to completely engineer channels destabilized by human disturbance (Neilson et al. 1991; Watson et al. 1999). For gully erosion, grade control structures such as check dams have been extensively used around the world to engineer bed stability and trap mobilized sediment (Lal 1992; Grissinger 1996; see references below). Gully check dams are most often utilized in semi-confined or confined gullies eroding into hillslopes, and less often in unconfined alluvial settings.

Grade control structures can be constructed out of a variety of material such as rock riprap, gabions, compacted earth fill, concrete, cement, steel sheet piling, steel mesh and posts, treated lumber, natural large woody debris (LWD), woven brush or brush debris, live vegetation such as willow fences or other species, sand bags, soilcrete bags, or other locally available material. They function by providing hard-points and artificial-steps on the bed of channels that resist erosion, reduce upstream slope and stream power, and dissipate energy. They function best where they can be tied or keyed into adjacent banks or slopes so that water does not erode around and outflank the structure. They can be designed into a variety of three-dimension forms (check dams, weirs, drop structures, flumes) that influence both channel geometry and hydraulics (Watson et al. 1999). Their successive spacing depends on initial and desires slopes. For steep channels, structures are typically spaced so that the upstream structure does not influence the water and sediment storage capacity of the downstream structure. When spaced closer, they can form a series of step-pool sequences; whereas with wide spacing in low gradient rivers they function more as low broad riffles. Thus grade control structures can be adapted to meet the site specific rehabilitation needs and geomorphic conditions.

In North America, for thousands of years the Zuni Native Americans have utilized brush structures arranged cumulatively along longitudinal profiles of incising gullies and arroyos to control incision and trap water and sediment for agriculture (Norton et al. 2002). The interwoven or intertangled brush structures act as semi-permeable barriers to flow and water that retain runoff, reduce velocities and erosive forces, trap sediment, and increase soil moisture. Depending on structure spacing, they can be cost effective and just as functional as more engineered structures (Gellis et al. 1995). Further south in Mexico, check dams made of layered earth and shrubs have also been traditionally used to control gully erosion and trap sediment

(Bocco 1991). However, these types of vegetative structures can suffer from decay over time without maintenance (Peterson and Branson 1962; Law and Hansen 2004).

More modern engineering structures for gully grade-control have come into vogue over the last century. The use of loose rock, gabion and wire-fence check dams for gully control has been extensive in the United States, with numerous design specifications (Heede 1974; 1978; Gellis et al. 1995; Law and Hansen 2004; NRCS 2007b). In larger incised gullies and stream channels, more elaborate grade control structures have been used, such as corrugated-steel drop-pipes through earthen embankments across gullies (Shields et al. 2002; Law and Hansen 2004; Wilson et al. 2008), and larger rock, concrete, and steel drop structures and weirs (Neilson et al. 1991; Mendrop and Little 1997; Watson et al. 1999; NRCS 2007a). Interestingly due to the large environmental impacts of heavily engineered structures, the use of natural materials such as large wood and brush has increased for stream stabilization in attempts to mimic natural forms and processes (Slaney and Zaldokas 1997; Abbe et al. 2003; Shields et al. 2004).

In Australia, a variety of techniques and materials have similarly been used for installing check dams in gully systems. One common and cost effective design for sequentially-stepped grade-control in confined channels has been to use steel-wire mesh and posts anchored across gully cross-sections to trap sediment and debris behind the weirs (Crouch 1984; Armstrong and Mackenzie 2002; Jenkins and McCaffrey 2008). However outflanking these structures in dispersible soil can be problematic once filled with sediment. Grade control weirs have additionally been constructed out of sequentially-stepped loose or interlocking rock or rock-filled gabions. Small earthen dams placed sequentially along gully drainage lines are also common as larger grade control structures, which can also be equipped with diversion banks and ditches that spread floodwater outward from the dam and away from the gully and disperse it across pastoral fields (Quilty 1973a; 1973b). Over time, designs for gully control and stabilization have become more elaborate and expensive, including larger rock and concrete drop structures (Bartlett 1991; Carey 2006; Jenkins and McCaffrey 2008). Most recently, engineered large woody debris structures have been utilized for grade control in small channels and large rivers (Brooks et al. 2004; 2006s; 2006b).

Gully check dams in other countries around the world have also developed similar or innovative techniques and materials. In Africa, Nyssen et al. (2004) describe soil conservation measures in the mountainous terrain of Ethiopia that have installed >70,000 loose-rock check-dams in gullies and ephemeral channels. They are constructed by hand using typically local volunteer labour, utilizing local rock fashioned into compound rock steps and weirs. In finer-grained soils in Nigeria, Okagbue and Uma (1987) describe the use check-dams made out of wood wicker fences (timber, planks and pile) that are used in tandem, interwoven with wire and rope, and backfilled with compared earth. In India, sand bags fashioned into compound weirs have are cost effective and relatively easy to install with local labour. More elaborate drop-structures are also heavily utilized to control the grade of agricultural fields above reclaimed gully channels and networks (Yadav and Bhushan 1994; 2002; Yadav et al. 2003). In Nepal, check dams made of rock gabion and pre-cast concrete blocks were effective in trapping sediment and reducing headcut retreat into alluvium on a large terrace (Higaki et al. 2005). In mountainous terrain in Spain, large check-dams (2-15m high) have been used to retain sediment in confined ephemeral and gully channel segments, with dams engineered out of local rock, cobble, and cement mortar (White et al. 1997; Alcoverro et al. 1999; Boix-Fayos et al. 2007; 2008; Castillo et al. 2007).

In the Chinese Loess Plateau region, hundreds of thousands of check dams of various sizes and designs have been constructed to store sediment for grade control, sediment and water storage, local agricultural production in the impoundment area, and reduction in downstream sediment loads (Xu et al. 2004). Often these check-dams are not in gullies per se, but in large creeks and river channels in confined valleys draining from extensively gullied catchments. Many are large, low-head, earthen or concrete dams up to 100m wide with spillways and foundations designed for peak flood events. Collectively these check-dams store over a half-billion m^3 of sediment and create over 3000 km^2 of new farmland (Xu et al. 2004).

7.2.4.a.7 Effectiveness of grade control structures within gully channels

Despite the common usage of grade control structures around the world for gully control, sediment retention and/or yield reduction, only a handful of studies in a piecemeal fashion have critically assessed their short- or long-term effectiveness. This is especially true in Australia, where literature advocating grade-control structures is common but literature on their long-term functionality is sparse. Due to the dynamic nature of fluvial channels, monitoring and maintenance of all-sized grade control structures are key to their long-term successes and functionality. Rarely are monitoring and maintenance programs adequately funded to ensure the long-term success of these rehabilitation structures.

In the American Southwest, Gellis et al. (1995) assessed the stability and functionality of 47 mostly earth and some rock check-dams (1-10m high) in large gullies (ephemeral arroyo channels). He found that 60% had been breached or outflanked and 65% were more than 50% filled with sediment. Interestingly, of 23 rock and brush structures (i.e., Norton et al. 2002), only 36% had been breached or were prone to breaching, with relative success attributed to their frequent spacing. Failure of structures occurred due to soil piping, flood scour on the structure, downstream head cutting, active channel change associated with channel evolution, and a general lack of maintenance (Gellis et al. 1995). In an earlier appraisal of hundreds of erosion-control structures and types in arid Arizona and New Mexico, Peterson and Branson (1962) found that over half the structures had failed within a few years. Rock and brush grade-control structures in gullies had the highest failures rates compared to earthen dams and water spreaders, which was attributed to poor construction standards on top of unconsolidated material prone to piping, outflanking and erosion.

In Wyoming, Marston and Dolan (1999) discussed the failure of two-dozen large check-dams built to retain sediment from Eocene claystone and sandstone badlands. The dams failed from a lack of maintenance and large intense convective storms, re-releasing millions of m^3 of sediment back into the system. Despite the short lived nature of many of the check dams that also failed to target the regional erosion hotspots, land management efforts still resulted in a 25% reduction in sediment load over decades, attributed to other rehabilitation measures such as destocking fragile desert rangelands.

In Tennessee, Barnhardt (1989) revisited a gully stabilization project area 50 years after the constructions of hundreds of log check dams to control gully erosion and the conversion of farmland to forestland. Most of the structures had failed due to high rainfall events, improper spacing and construction, lack of maintenance of structures, excess surface water inflow from roads, and most importantly from the ongoing geomorphic adjustment and evolution initiated by land-use disturbance decades before. Barnhardt (1989) concluded that "*reclamation techniques must address the underlying geomorphologic processes involved with the development and modification of stream channels and hillslopes*".

In Ethiopia, Nyssen et al. (2004) documented the frequent collapse of loose rock check-dams (39% of 400 dams after 2 years) and need for frequent maintenance. Their failure was related to channel slope and catchment area used as a proxy for stream power. Bypassing of dams due to soil piping and outflanking in cracking Vertisols was also noted. Dam spacing frequency, height, and design with a spillway and apron were also important factors for stability. In Nigeria, Okagbue and Uma (1987) documented the failure of many timber-fence check-dams due to undercutting and soil piping through or around the dams. In India, Yadav and Bhushan (1994) also noted the problem of soil piping undermining in situ constructed drop structures used for gully grade-control. Florido (1985; cited in Lal 1992) in the Philippines found that rock check dams were more effective at sediment retention than log, brush or hogwire check dams. For large rock and mortar check-dams in Spain, Boix-Fayos et al. (2007) reported that 72% of 58 structures were completely filled with sediment and 81% showed signs of erosion and bed coarsening downstream of the dam due to turbulent scour and sediment starvation. Similar results in a nearby catchment by Castillo et al. (2007) showed that 81% of 36 structures had filled in with sediment and 2 structures had failed. Most dams also experienced erosion downstream, but the net affect of storage upstream to erosion downstream was overall storage of sediment.

In New Zealand, chronic high sediment supply from large fluvio-mass movement gully complexes initiated following native forest clearance has largely overwhelmed and buried early attempts at gully stabilization using large-scale check dams, vegetation fascines, and even levees to protect agricultural fields (Marden et al. 2005). However, similar grade control structures in smaller catchments < 1 ha have been more successful (Marden et al. 2005). Overall however, large scale reforestation was much more effective at reducing sediment yields at the catchment scale (DeRose 1998; Gomez et al. 2003; Herzig et al. 2011).

The complete failure of check-dams and grade control structures, similar to larger dams, can have catastrophic impacts on downstream channel habitat, accelerated sediment supply, and human safety and infrastructure. For example, a flash flood in the Spanish Pyrenees resulted in the failure of ~ 40 rock and mortar check-dams (2-15m high) that released 50,000 m^3 of stored sediment that contributed to the death of 87 people (White et al. 1997; Alcoverro et al. 1999). In China, the failure of more than 80% of the check-dams in the Shanbei region in 1977/1978 during major rainfall-runoff events highlighted the need for proper design of check-dams (Xu et al. 2004). As a result fewer check-dams are being built due to additional costs to engineer stability for design floods. Li et al. (2003) also noted the periodic failure of check dams (used for farming) during mountain flood torrents.

While many studies document the trapping and storage of sediment behind check-dams as a mitigation measure of upslope sediment supply, fewer document the success of actually stopping gully incision or the head-ward growth of gully head-cuts. Several authors emphasis the importance of the exact timing and location of structural intervention relative to the stage of gully channel evolution *sensu* Simon and Hupp (1992)(Okagbue and Uma 1987; Gellis et al. 1995; Simon and Darby 2002). For example, Simon and Darby (2002) document the relative ineffectiveness of large grade-control structures at reducing channel erosion rates in Mississippi because intervention occurred too late in the evolutionary cycle. They recommend that to be effective, grade-control structures would need to be placed just upstream of active headcuts during the early stages (I or II) of channel evolution when active incision and erosion is at its greatest. For this purpose, hundreds of corrugated-steel drop-pipes through earthen embankments (a.k.a. drop pipe structures) have been built at or above gully heads in the region (Shields et al. 2002; Wilson et al. 2008). However the effectiveness of these structures at reducing long-term sediment yields is unknown, especially due to their relatively short life-spans and common failure (Wilson et al. 2008). Their relative contribution to sediment reduction is also unknown, due to multiple catchment-scale soil-conservation measures (tree planting, riparian buffer strips, grass strips, agricultural land retirement, and grade control) and inherent channel recovery through geomorphic evolution (Kuhnle et al. 2008). Increasingly it is becoming apparent that structural intervention is not the panacea for gully and channel stabilization, with a renewed emphasis on working with mechanistic processes of natural channel evolution that primarily responds to driving and resisting forces and the inputs of energy and material (Barnhardt 1989; Callahan 2001; Simon et al. 2007).

7.2.4.a.8 Effectiveness of grade controls structures and sediment retention dams at the catchment scale

It could be argued that damming gully systems with small or large grade-control structures and/or sediment retention dams could have the greatest effect on short-term sediment yields for large scale sediment retention compared to other rehabilitation efforts conducted in concert (Xu et al. 2007). However over the long-term as reservoirs fill up with sediment (Gellis et al. 1995; James 2005; Castillo et al. 2007; Boix-Fayos et al. 2007), eventually fail (White et al. 1997; Graham 1999; Alcoverro et al. 1999; Pisaniello 2010), or need to be removed (Graf 1999; Pohl 2002; James 2005), these engineering measures are less sustainable compared to other methods like intensive vegetation management, afforestation, or land-use modification in upslope catchments. *Building sediment retention dams is a classic example of treating the symptoms rather than addressing the cause.* Nonetheless sediment detention reservoirs have been and continue to be built around the world in a variety of environments to mitigate upstream land-use impact, reduce downstream sediment supply, and provide additional water resource functions (Armstrong and Mackenzie 2002; Huang et al. 2003; Xu et al. 2004; James 2005; Rustomji et al. 2008; Zhang et al. 2008).

In catchments with severe gully erosion, sediment detention dams can dominate the reduction of sediment yield over time (Armstrong and Mackenzie 2002; Xu et al. 2004; Rustomji et al. 2008) and mask the assessment of the effectiveness of other soil stabilization efforts such as catchment revegetation or improved best management practices during land use. In an attempt to quantify the relative influence of gully erosion rehabilitation measures such as check-dams and land-use change toward reforestation, Boix-Fayos et al. (2008) used an erosion model calibrated to field data collected in Spanish headwater catchment (Boix-Fayos et al. 2007). They estimated that land use alone reduced sediment yield by 54% over 40 years, while large check-dams alone reduced yield by 77%. While both measures were effective, the check-dams had a short-term effect with no long-term benefits and several side effects such as scour downstream of dams and failure potential. In contrast, land-use changes resulted in permanent reductions in erosion at the sources. In an Australian study using a similar erosion model, Verstraeten and Prosser (2008) modelled the cumulative sediment yield effect of thousands of farm dams, typically located above incised gully networks but below hillslopes. They estimated that the farm dams in sum reduced hillslope sediment yields by 120% of pre-European yields, but that post-European gully and bank erosion downstream kept sediment loads elevated at 250% above background. However a much larger mainstem reservoir downstream has almost fully mitigated sediment yields further downstream back to pre-European disturbance values. Due to overall low sediment yields to the reservoir, long-term concerns over reservoir infilling are minimal regardless of upstream land use.

7.3 Existing Rehabilitation Efforts in the Mitchell River

7.3.1 Re-grading alluvial gully slopes along the Burke Development Road

Along the unpaved road networks of the lower Mitchell River megafan, road maintenance crews have been battling with the duel challenge of maintaining road integrity and reducing erosion created by road use and maintenance activities since European settlement. The impermeable nature of compacted road surfaces generates excess volumes of surface water runoff, which can generate or accelerate alluvial gully erosion adjacent to the road prism if water is not drained frequently enough or its energy fully dissipated. Road cuts near river/creek crossings are especially problematic for initiating alluvial gully erosion, as the river high-floodplain soils directly adjacent to river channels are sodic, dispersible, and thus highly erodible. Due to the incision of river channels into the surrounding megafan floodplains over geologic time, these near river locations are the highest points of local relative relief on the landscape, creating the potential energy for alluvial gully erosion (Brooks et al. 2009).

Numerous attempts at improving road stability and reducing erosion over time at different river crossings along the Burke Development Road offer examples of the high erodibility of these alluvial soils and the difficulty in engineering stability. For examples, as an attempt to reduce chronic erosion at the cut slope approach to the Walsh River road crossing, road crews have repeatedly battered back the cut slopes that constantly erode via sheet, rill, and gully erosion. Several roadside “mitre-drains” or “V-drains” have been constructed, but their frequency is often insufficient and hampered by a lack of suitable and stable locations to drain excess water. After initial cut slope re-grading, rill erosion on the slope and gully erosion in the road ditch re-initiated following rainfall (Figure 7-1). After one wet season, rills and gullies enlarged enough to threaten the road prism again (Figure 7-2). Subsequently, large rip-rap rock was brought in to armour the roadside ditches. It is uncertain to what degree this rock will stabilize gully erosion over the long run, due to the high dispersibility of the matrix alluvial soil and the ability of water and dispersed sediment to flow around or under obstructions such as rock (Figure 7-3). Buttressing the toe of the cut slope will at least temporarily reduce knickpoint migration of rills and gullies into the slope. However, cut slopes remained relatively unvegetated with grass due to poor growing conditions and unrestricted grazing, allowing deep rilling to continue unmitigated.

Figure 7-1 Road cut slope after initial re-grading in 2007 and one initial rainfall event.

Figure 7-2 Road cut slope after one wet season in 2008. Note rilling and gullying.

Figure 7-3 Road slope bank after two wet seasons in 2009. The gully in the road ditch was armoured with rip-rap, and rilling on the largely unvegetated cut bank continues.

In situations where large alluvial gully scarps have migrated over time into road prisms, road crews have developed the practice of completely re-grading gully head scarps with bulldozers, in the hope of stalling their advancement into roads. To date, these re-grading efforts have not been conducted in association with any revegetation efforts, mulch or fertilizer application, chemical amelioration, or cattle exclusion. In most cases, newly shaped surfaces begin re-eroding via sheet flow and rilling almost immediately during the first wet season rains. After two wet seasons, deep rills often cut through the slope and new dendritic gully channels reform into the slope (Figure 7-4). In the example in Figure 7-4, the location of the break in slope (scarp) did not changed locally, as the actual scarp retreat rate of this entire gully front (1980m) was measured to be only ~ 0.10m/yr. However, the benefits to slope stabilization and sediment yield reduction remain highly unclear without other rehabilitation measures.

a) b)

Figure 7-4 Changes in gully head scarp morphology a) in 2007 following bulldozer re-grading, and b) in 2009 after two wet seasons. Note the original head scarp in the background (before condition), the deep rills reforming gully channels in the foreground in 2009, and little vegetation cover on the slope surface.

7.3.2 Stabilizing gully slopes at Mount Mulgrave Station

The Mount Mulgrave Station homestead is located on the banks of the Mitchell River near the point on the river profile where local relative relief is a maximum (Brooks et al. 2009). The station house, quarters, sheds, corrals, and air strip are literally surrounded by alluvial gullying due to the high potential energy, soil dispersibility, and land-use related disturbances post-European settlement (Chapter Six). Erosion threats to the infrastructure have prompted various actions to stabilize gully scarps.

Where gully scarp retreat threatened the integrity of the air strip and hanger (Figure 7-5a), a section of gully scarp was re-graded with a bulldozer, backfilled with some sand and gravel, and revegetated with grass. A small berm was constructed above the surround soil surface along the scarp front so as to reduce overland flow from pouring off the old scarp face. Since the scarp was located inside the air strip fence line, the re-established grass thrived due to reduce grazing pressure from periodic rotation and spelling (Figure 7-5ab). This combination of measures was successful at reducing scarp retreat over the last decade. Similar success in gully front stabilization has been achieved along the river frontage just downstream of the station house (extreme top left corner of Figure 7-5a). In comparison, the remaining untreated scarp front on the outside of air strip fence line (Figure 7-5a bottom) continued to erode at an average rate of 0.13 m/yr over 50 years, with maximum rates up to 1.4 m/yr. Furthermore, the placement of old tyres in the gully bottom and at the head scarp in isolation of the other measures above was not effective at reducing scarp retreat (Figure 7-6).

A more recent attempt at stabilizing a gully scarp at Mount Mulgrave has involved the use of many tonnes of sand and small gravel dumped on top of a scarp face (Figure 7-7). The material originated from the local river causeway that annually needs to be unburied from wet season deposition. Preliminary observations after one wet season indicated that most of the sand is still in place, but that several areas of sub-surface water sapping and slumping of the sand face exist at the new graded scarp face. Several drawbacks of using river sand and gravel for stabilization include the spread of riverine weeds onto the high-floodplain savanna (e.g., noogoora burr and others), and the poor vegetation colonization potential of well drained and nutrient poor sand. Similar to earlier efforts, it could be beneficial to mix sand into the native silt soils to produce a sandy loam that could be proactively revegetated with native grass and trees.

a) b)

Figure 7-5 a) Oblique aerial view of a gully head scarp at Mount Mulgrave next to the air strip fence line (in black). Note the dark green vegetated patch within the air strip (middle right) which represents a section of the gully front that was re-graded, backfilled with some gravel, re-vegetated with grass, and only lightly grazed in rotation. b) Ground view in October 2008 of the re-graded section of gully scarp.

Figure 7-6 Old tyres are not an effective measure to reduce gully erosion and can add toxic material to soils and waterways from the photo-chemical breakdown of the tires over time.

Figure 7-7 Oblique aerial view of a gully head scarp at Mount Mulgrave that has been backfilled with local river sand in an attempt to slow erosion into the road in the background. Note the original scarp front remains intact in the right side of the photo.

Despite these qualitative observations of the apparent successes and failures at reducing alluvial gully scarp migration and erosion, to date there are no rigorous field data that quantify the effects of these stabilization measures in isolation or in combination. Initial stabilization attempts have been ad hoc and focused heavily on hard engineering techniques that are unsustainable and not process-based. Actions have not been based on lessons learned from gully reduction and stabilization techniques world-wide or in south-eastern Australia (see literature review above), nor were these lessons adapted to the extremely unique situation of alluvial gully erosion in the Mitchell River (Brooks et al. 2009). Therefore, there is a strong need for scientific quantification of alluvial gully rehabilitation measures and the associated geomorphic processes that are influenced by human intervention. An adaptive management and experimentation program is needed that utilizes field trials with treatments and controls to guide future efforts, ensure that actions are successful, treat causes rather than symptoms, and not waste of money. A preliminary proposal will be outlined below.

7.4 Proposed Rehabilitation Trials in the Lower Mitchell

7.4.1 Goals

There are several goals for the proposed gully rehabilitation trials in the lower Mitchell, which include:

1. Trial different alluvial gully stabilization techniques that integrate and address biological, chemical, and physical factors driving and resisting erosion.

2. Work with local landowners to implement sustainable grazing practices around alluvial gullies and riparian zones near water bodies.

3. Educate and train local landowners and the wider pastoral community about specific rehabilitation techniques and the benefits of soil conservation, through the development of regional best management practices (BMP's).

7.4.2 Locations and landowners

Field trials into alluvial gully management and rehabilitation should be located at multiple regional sites each containing numerous experimental gully catchments of different treatments and controls. Sites should span a range of hydrogeomorphic and edaphic conditions, similar to existing intensive study sites (Brooks et al. 2009; Chapter Three; Chapter Six). Ideally, multiple sites in regional catchments across northern Australia would be researched for alluvial gully rehabilitation (e.g., Mitchell, Normanby, Burdekin, Victoria, etc.). Initially for the lower Mitchell catchment, sites should build off existing datasets at past study sites (Shellberg et al. 2010; Chapter Three; Chapter Four; Chapter Five; Chapter Six).

Sites should also be of interest to local landowners from both stabilization and educational learning standpoints. To date, several landowners in the lower Mitchell have expressed interest in conducting gully stabilization experiments on their properties, specifically Mount Mulgrave Station, Highbury Station and the Kowanyama Aboriginal Council (Aboriginal Trust Lands). In addition, managers at both Wrotham Park/Gamboola Stations and Bellevue Station have expressed interest in more progressive riparian fencing programs to reduce erosion along waterways, with future discussions needed for the potential for expansion into stabilization trials. These properties in total span the full continuum of the longitudinal profile of the Mitchell River through the Mitchell fluvial megafan (Brooks et al. 2009). They possess a diverse suite of alluvial gully complexes that have varying drivers and resistors to alluvial gully erosion.

Building off the combination of past research sites (code in parentheses) and landowner interest, it is proposed that following sites be included in gully stabilization trails:

- Mount Mulgrave (MMG1 to MMGC7)
- Wrotham Park (WPGC2 and WPGC3)
- Highbury (HBGC1 and HBGC2)
- Kowanyama Aboriginal Lands (KWGC2 and KWGC1).

Within each site listed above, hierarchically nested experimental gully catchments would need to be delineated according to discrete drainage networks and partitioned via fencing for trialling different rehabilitation techniques (see BACI study design below). To date, these experimental catchments have only been identified for Kowanyama and Highbury. The experimental catchment design for Highbury will be used as an example below.

In addition to these non-road influenced gully sites listed above, future collaboration with the Main Roads Departments of Carpentaria, Kowanyama, Tableland Regional, and Cook Councils could lead toward the establishment of additional experimental sites for alluvial gully stabilization along major roads such as the Burke Development Road. Gully erosion is ubiquitous along unpaved roads due to excess water runoff, traffic disturbances, and annual maintenance such as grading, but can be reduced through implementation of road Best Management Practices (BMPs). However, road BMP's for alluvial gully stabilization or reduced initiation are not well founded by experimental trials and research data collection. Existing BMP's for management of alluvial gullies along the Burke Development Road have been largely ad-hoc based on trial and error, with little documentation of the long-term success or failure of different techniques (see above). Therefore, well documented experimentation and reporting of findings is warranted.

7.4.3 Study design

A before-after control-impact (BACI) study design (Green 1979; Smith 2002) is essential for documenting the statistical significance of different treatments, and overall, the success or failure of the project. Ideally, multiple control sites should be used (MBACI) due to inherent variability between sites and the difficulty in selecting one representative control (Kibler et al. 2010). Multiple controls improve the understanding of natural variability compared to treatment effects (Underwood 1994a; Underwood 1994b). In addition, multiple years of before and after treatment data should be collected to document both the natural and post-treatment variability in monitoring parameters. For this reason many site above have been selected that have at least some existing data from recent surveys and historical air photographs [Shellberg et al. 2011 (Shellberg et al. 2010; Chapter Three; Chapter Four; Chapter Five; Chapter Six).

An example BACI study design for a Highbury site (HBGC2) is included below. A series of 15 discrete alluvial gully catchments surrounding and upstream of Twenty-Mile Lagoon have been selected as either control or impact (treatment) for experimental manipulation (Figure 7-8). A range of treatment strategies will be trialled as outlined further below. Control sites will be located along the same drainage line at an upstream lagoon. The Twenty-Mile Lagoon area has multiple advantages as a general site for gully manipulation. First, all the gully catchments drain to a similar local base level and are located within similar soils along a shallow alluvial ridgeline. Second, significant existing fencing infrastructure exists near this lagoon, from which proposed fencing can be expanded from. Third, several gullies around this lagoon have been sites of past and ongoing research on gully erosion rates using GPS (2007 to 2009). Fourth, LiDAR topographic data exist at the site from a 2006 survey, in addition to a detailed air photograph series covering 60 years (1949, 1955, 1969, 1982, 2006, 2008). These data can be used to better define pre-project (before) erosion rates and volumes (Figure 7-9; Figure 7-10).

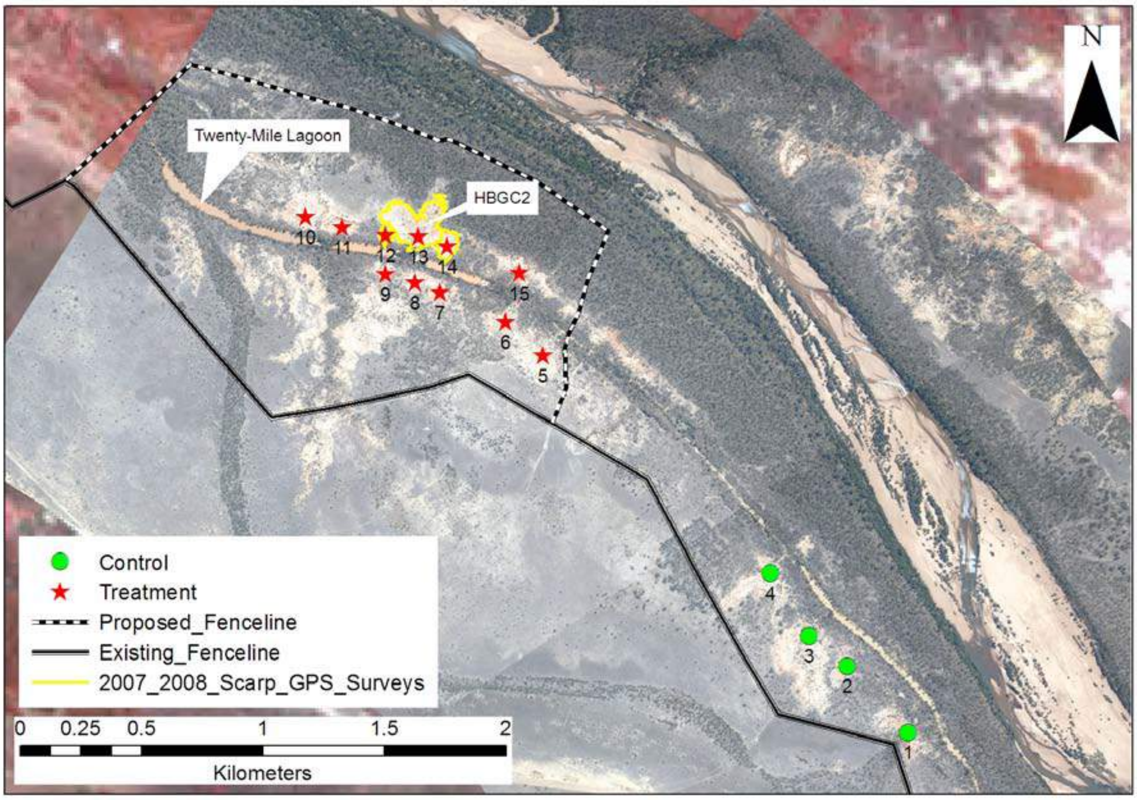
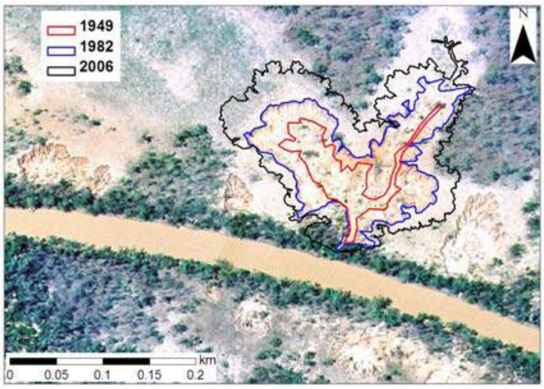
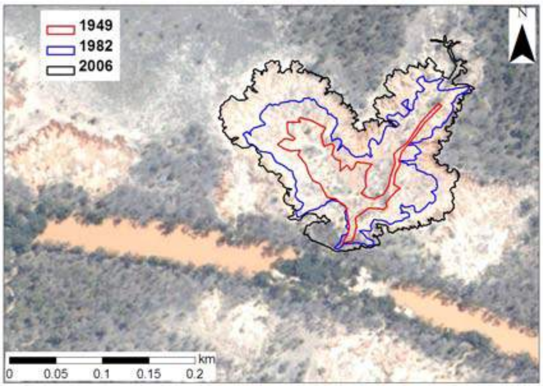


Figure 7-8 Experimental gully catchments at Highbury (HBGC2) surrounding Twenty-Mile Lagoon.





A) HBGC2 1982 Photo B) 2006 Photo

Figure 7-9 Changes in gully scarp location from 1949 to A) 1982 and B) 2006 at HBGC2.

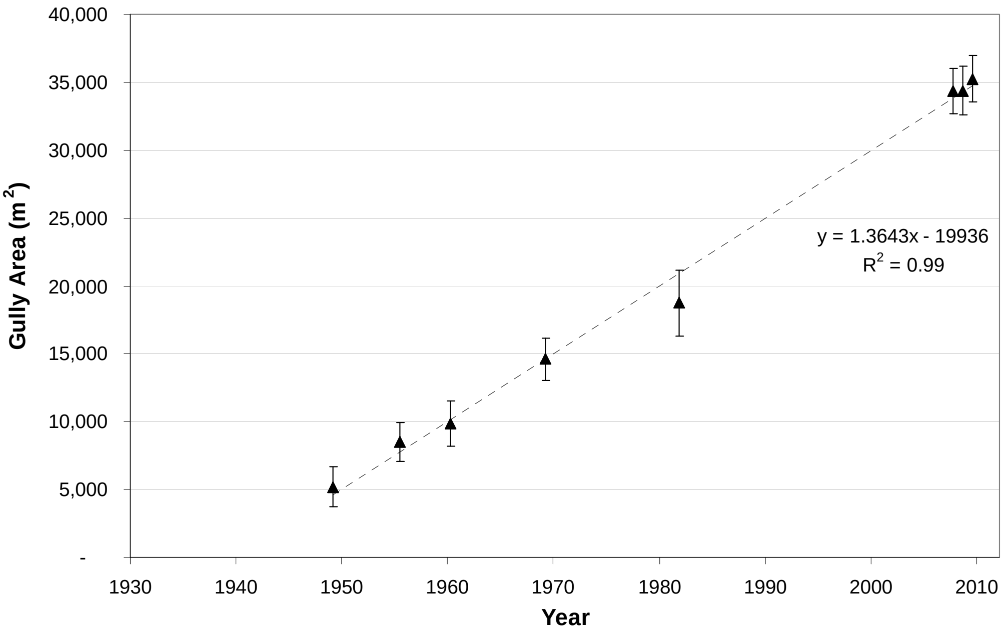


Figure 7-10 Changes in gully planform area over time at HBGC2

7.4.4 Treatments

Based on local observations, empirical data, and the gully stabilization literature review above, a suite of different techniques will be utilized that integrate and address biological, chemical, and physical factors driving and resisting erosion. These treatments will be used in isolation or in combination (Table 7-1).

7.4.4.a.1 Biological

- **Cattle Fencing** will be used to exclude cattle from the treatment area, but not the control area (Figure 7-8). Alternatively, some treatment areas could remain open to cattle while still using other treatment options. Additionally if funding is available, fencing that can exclude exotic pigs could also be erected, or additionally fences that are barriers to native marsupials. Fencing exclusion of cattle and possibly other animals will reduce vegetative (biological) and soil (physical) disturbances with gully complexes and around surrounding shallow hillslopes, and increase soil protection through root cohesion and rain drop interception.

- **Native Perennial Grass Seeding and Planting** will be used to re-establish grass surface cover, root density and depth, and surface roughness. Seeding and planting will focus on three erosion process zones: 1) the uneroded floodplain soils upslope of gully head scarps, 2) the scarp zone immediately surrounding gully heads, and 3) along the floor or bottom of the gully. Grass seeding and planting should be conducted near the start of the wet season once consistent rains are predicable.
  - For combination trials in association with physical soil ripping and grading and chemical amelioration (see below), grass seeding should follow grading once growing conditions are suitable.
  - Mechanical broadcasting could be used for seed dispersal, or alternatively hydroseeding (slurry of seed, water, mulch, and possibly fertilizer).
- **Native Tree Planting** will be used to increase the density of trees growing along the floor or bottom of the gully and at the bottom of the head scarp, mimicking accelerated colonization. They could also be planted around denuded areas above gully scarps, such as scalds. Planting should be focused near the start of the wet season once consistent rains are predicable and soils are amenable to planting with a shovel.
- **Fire Management** will be conducted to *exclude* fire from both control and treatment sites for initial simplicity. The presence or absence of fire is a major complicating factor in the experimental treatment of gully erosion or their long-term stabilization. However, since fire is such a ubiquitous part of the Australian savanna landscape (Russell-Smith et al. 2003: 2006), fire could be included as a variable in more complex experimental designs into the future.

7.4.4.a.2 Chemical

- **Gypsum ($CaSO_4$)** is the most common soil amendment for ameliorating sodic soils to reduce soil aggregate dispersion and increase infiltration. Phosphogypsum (industrial by-product) is preferred over mined gypsum due to finer particle size and higher dissolution rate. Application can either be 1) onto the soil surface through mechanical broadcasting or 2) mixed into the soil profile during deep ripping and tilling. Both types of treatments will be trialled. The application rate depends on the area and volume of soil to be treated, the existing soil ESP values, and the future target ESP values that will promote soil stability. Typical application rates are between 3 to 6 t ha^{-1} for surface application up to greater than 10 t ha^{-1} for subsurface application.
- **Fertilizer** will be used to address the low nutrient status of some sodic soils subject to alluvial gully erosion, by applying nitrogen and phosphorous fertiliser to soils. This could be done concurrently with gypsum application, or incorporated into a hydroseed mixture. However, fertiliser should be used with caution, as it may promote the establishment and growth of undesirable weed species in the area (e.g. Arnold 1997).
- **Organic Mulch** will be used to provide protection of the soil from direct rainfall impact, increase the organic matter of sodic soils, improve water retention, and increase the survival of germinating grass seeds. Different types of much will be trialled, including straw and compost.

7.4.4.a.3 Physical

- **Engineering Gully Head Scarps** will be used to reduce the slope of the active gully head-cut through slope battering and contour shaping with heavy machinery. Due to the failure of this method in isolation to permanently reduce gully erosion (see review above), this techniques will be used in combination with other treatments such as revegetation and chemical amelioration.

- **Soil Ripping** will be used to break up the scalded soils upslope from gully head scarps, with simultaneous gypsum application. This will be followed by native perennial vegetation seeding and planting, and perhaps fertilizer application depending on soil conditions.
- **Bioengineering Grade Control Structures** will be used to provide grade control within the floor and main drainage channels of the gully using both brush structures (Gellis et al. 1995; Norton et al. 2002) and engineered log jams of large wood debris (Brooks et al. 2006), scaled to the size of gully outlet channels. Structures will be concentrated toward the steeper portions of the longitudinal profile – near the base of the active gully head scarp – in order to retain eroded scarp sediment and maintain the channel slope at a steeper angle (Chapter Six). Structures widths will greatly exceed individual channel widths as to prevent lateral outflanking in dispersible soils.

Table 7-1 Gully treatment/control sites, methods, and purposes at Highbury (HBGC2).

Gully Site #	Control / Treatment	Process	Method	Purpose
1	Control	Control	Status Quo	Control
2	Control	Control	Status Quo	Control
3	Control	Control	Status Quo	Control
4	Control	Control	Status Quo	Control
12	Treatment	Physical Biological	Fencing Only	Improve surface cover and plant vigour
13	Treatment	Physical Biological	Fencing Only	
14	Treatment	Physical Biological	Fencing Only	Reduce soil disturbance
7	Treatment	Biological	Grass/Herb Hydroseeding (w/ Fencing)	
8	Treatment	Biological	Tree Planting (w/ Fencing)	Increase Surface Cover, Plant Vigour, Root Depth
9	Treatment	Biological	Grass/Herb Hydroseeding Tree Planting (w/ Fencing)	
11	Treatment	Physical	Bioengineering Structures (w/ Fencing)	Stabilize Gully Profile
15	Treatment	Physical	Slope Engineering Grass/Herb Hydroseeding (w/ Fencing)	Stabilize Gully Head Scarp
5	Treatment	Chemical	Chemical Treatment with Surface Gypsum (w/ Fencing)	
6	Treatment	Chemical	Chemical Treatment with Subsurface Gypsum Through Tilling and Slope Battering (w/ Fencing)	Improve soil structure and reduce soil dispersibility (replace Na^{+} with Ca^{+2})
10	Treatment	Biological Physical Chemical	All Treatments	All of the Above

7.4.5 Monitoring

The before-after control-impact (BACI) study design of gully rehabilitation treatment effects will utilize existing pre-project (before) erosion data where available. Additional new pre-project data also will be collected as part of the study design. Monitoring post-project (after) conditions will occur for a minimum 3-years following initial implementation (i.e., typical budget timeframe). However, ideally post-project monitoring will be incorporated into a longer-term monitoring program (+10-years) to better quantify long-term variability and project success.

Monitoring metrics will include a suite of variables measured over space and time that measure physical, chemical, and biological characteristics.

7.4.5.a.1 Physical

Physical monitoring of gully rehabilitation efforts will focus on geomorphic changes and net sediment erosion.

- **Scarp Retreat Rates (Linear)**
  - *Historic Air Photo Data* will be used to define historic pre-project scarp retreat rates, building off existing data in the Mitchell catchment collected in Chapter Six (e.g., Figure 7-9; Figure 7-10).
  - *GPS Data* at the sub-meter scale across entire gully scarps will be used to define recent pre-project scarp retreat rates and future post-project changes, building off existing data in the Mitchell catchment collected in Chapter Six (e.g., Figure 7-9; Figure 7-10).
  - *Total Station Surveys* at index sections of gully scarps will be used to more accurately measure the location changes of gully scarps pre- and post project implementation.
  - *Time-lapse Cameras* at index sections of gully scarps will be used to both measure subtle daily changes in scarp retreat (i.e., Shellberg et al. 2011 (Chapter 3, Hydrogeomorphology) and provide for improved project education.
- **Gully Erosion (Volumetric Net Erosion)**
  - *Airborne LiDAR data* has been collected pre-project at the scale of entire gully networks at numerous sites in the Mitchell and Normanby catchments in 2006 and 2008. Post-project repeat airborne LiDAR surveys will allow for volumetric differencing to calculate net erosion rates between survey dates.
  - *Terrestrial LiDAR data* will be collected at index sections of gully scarps pre- and post project implementation to measure local net erosion of soil at both the gully scarp and internal gully scarp face.
  - *Longitudinal profiles and cross sections* of gully outlet channels and scarps will be surveyed annually with a total station at targeted locations pre- and post implementation as a supplement and ground-validation of terrestrial and airborne LiDAR surveys.
- **Hydrologic**
  - *Rainfall* will be measured using continuous tipping buckets at each project area

- *Stage-Discharge* rating curves will be measured at several key control and treatment gauge sites to measure water runoff volumes pre- and post project implementation (i.e., Chapter Four).
- *Suspended Sediment Concentrations* will be measured at key gauge sites with single-stage and depth-integrated samplers to estimate suspended sediment load pre- and post project implementation (i.e., Chapter Four).

7.4.5.a.2 Chemical

Soil chemistry will be measured pre-project at treatment and control sites to define baseline soil conditions and determine the degree that chemical amelioration is needed for soil stability and productivity. Soil chemistry will be measured periodically post-project to determine how soil chemical conditions change through time and respond to rehabilitation measures. In addition to these chemical metrics, changes in soil physical conditions will be assessed as a response to chemical amelioration.

- **Chemical Soil Metrics**
  - *pH and electrical conductivity*
  - *Exchangeable Sodium Percentage* (ESP)
  - *Sodium Adsorption Ratio* (SAR)
  - *Soil Fertility* (nitrogen, phosphorus, potassium)
  - *Soil Organic Carbon*
- **Physical Soil Metrics** relating to soil chemistry
  - *Bulk density*
  - *Particle size analysis* of soil and aggregates in a flocculated and fully dispersed state.
  - *Soil dispersion ratio* (measure of water stable aggregates)
  - *Hardsetting and scalding* seasonal variability and extent (penetrometer)

7.4.5.a.3 Biological

Biological monitoring efforts will focus on vegetative changes of native and introduced grass and trees species pre- and post gully rehabilitation. Additional biological attributes such as termite mound density and size, and other soil fauna diversity and density, could also be assessed. Vegetative conditions will be assessed seasonally (quarterly) at either 1) permanent quadrates laid out in a gridded fashion across gully complexes or 2) at points along transects following the point-centered quarter method (Penfound 1963; Mitchell 2007).

- **Vegetative metrics**
  - *Grass species composition and diversity* (native and exotic)
  - *Grass cover, root density, plant vigour*
  - *Extent of grass utilization by herbivores*
  - *Dry matter available at peak yield* (end of wet season, dry weight rank method)
  - *Extent of scalded un-vegetated area*
  - *Density of cattle trails and other herbivore paths*
  - *Tree and shrub cover, density, and diversity* (native and exotic)

7.5 Best Management Practice (BMP) Guideline Development

Currently there is a lack of awareness among land owners and managers in northern Australia as to the relationship between land-use practices and alluvial gully erosion, let alone knowledge about how to minimize and manage alluvial gully erosion via Best Management Practices (BMP's). A prerequisite for farmers and graziers changing their land management practices to achieve sustainability is the awareness of the issues leading to land degradation, and the knowledge of the pathways and tools of how to reduce erosion via altered practices. From previous experience, the best way to change a farmer/grazier/operator's practices is to involve or show them a realistic field trial of how sustainable practices and rehabilitation can be achieved.

Best Management Practices (BMP's) need to be developed from the outcomes of the gully rehabilitation trials and monitoring data outlined above and conducted at multiple sites across northern Australian. To date, generalized BMP guidelines for colluvial or hillslope gully rehabilitation in southeast Australia (e.g., Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008) are not directly applicable to alluvial gullies in northern Australia, which involve different forms and processes. Furthermore, existing generalized Best Management Practices (BMP's) for grazing land in northern Australia are not specific enough to address the complexities of managing alluvial gully erosion initiation or reduction (e.g., Coughlin et al. 2007; 2008).

The following steps will be taken to develop regional BMP's for alluvial gully erosion and disseminate the knowledge across northern Australia.

- Trial different alluvial gully stabilization techniques that integrate and address biological, chemical, and physical factors driving and resisting erosion.
  - Work with local grazing land owners and managers to implement sustainable grazing practices around alluvial gullies and riparian zones near water bodies.
  - Work collaboratively with Council and Main Roads work crews to trial innovative road maintenance BMP's surrounded alluvial gullies.
  - During rehabilitation trials, involve land managers, stock hands, machine operators, Aboriginal rangers, Traditional Owners (TOs), and other interested stakeholders to maximize the learning, training, and implementation of soil erosion reduction principles and gully rehabilitation techniques.
- Develop a regional BMP Guideline Manual for alluvial gully reduction and rehabilitation
  - Synthesize rehabilitation trial outcomes and scientific data into a BMP manual.
  - Involve landowners and stakeholders in the development of the BMP manual.
  - Develop a communication strategy aimed at tailoring communication outputs to target audiences (landholders, managers, stakeholders).

- Produce printed and multimedia educational products for dissemination to stakeholders across northern Australia.
- Distribute BMP guidelines and education products to stakeholders through a broad range of existing networks and media.
- Undertake follow-up surveys via phone, email, or in person regarding the uptake of information about alluvial gully erosion, rehabilitation, and BMP's in northern Australia.
- Develop additional targeted educational outreach programs to stakeholders such as seminars, workshops, and regional land-use conferences.
- Continue future collaboration and monitoring where fruitful and reasonable.

Chapter Eight: Conclusions and Future Research

8.1 Conclusions

Overall, this research has quantified many previously unknown fluvial geomorphic forms, processes, and rates unique to alluvial gully erosion in the Mitchell River catchment and perhaps northern Australia.

- Alluvial gullies are widely distributed across the Mitchell fluvial megafan but are concentrated along major water waterways according to large-scale landscape evolution and the presence of highly dispersible sodic soils. Alluvial gullies are unique in form and process compared to hillslope colluvial gullies and perhaps one end member of a continuum of erosion processes. They evolve into a variety of forms initiated by river bank disturbances and their evolution is predicable using a location-for-time substitution.

- The hydrogeomorphic factors influencing alluvial gully erosion are controlled by the monsoonal climate and the mixing of different water sources across the floodplain perirheic zone. River incision into the megafan and the resulting floodplain connectivity control the degree that river backwater and overbank floodwater influence gully scarp retreat. In their absence, direct rainfall and local runoff drive scarp retreat at the daily scale. The hydrogeomorphic triggers of alluvial gully initiation are less certain.

- Empirical data within one alluvial gully complex demonstrates that suspended sediment is highly concentrated in available water discharge and that sediment yields are high for both Australian and World data. Sediment concentrations and yields can be modelled using transport-limited equations due to the abundant supply of sediment from gully scarps and internal gully areas.

- The growth of alluvial gully complexes via scarp retreat is commensurate with the development of small inset-floodplains on the floors of gullies, which are progressively colonized by Eucalyptus trees and other vegetation. Trees can be dated by carbon and radium radionuclide analysis and used to determine the minimum age of gully initiation and maximum rates of gully expansion.

- Historical air photographs can be used to delineate changes in gully area over the last half-century. Extrapolating these area changes backward in time at numerous sites in the Mitchell catchment suggests that widespread gully initiation was triggered during or after the period of European cattle introduction to the landscape. These data are supported by young OSL dates of gully inset-floodplains and LiDAR data that suggest the current style and magnitude of gullying was unprecedented. Land-use change and chronic cattle disturbance along river banks pushed the landscape across a threshold towards instability, which it was intrinsically close to as a result of the evolution of the fluvial megafan and floodplain soils over the Quaternary.

- A paradigm shift is needed in terms of land management and cattle grazing practices to reduce chronic soil erosion in the savannahs of northern Australia. Cattle should be managed more cautiously in or excluded from the riparian zones and steep banks of rivers, streams, and other water bodies, which will aid in passive or proactive rehabilitation efforts. A trial rehabilitation program is needed to determine the most cost-effective, practical, and sustainable land management and bioengineering activities needed to reduce existing alluvial gully erosion, and prevent future gully initiation, by targeting the process-based causes of gully erosion rather than the symptoms.

8.2 Future Research

The findings presented here are just a small beginning to a potentially more detailed research path leading toward a deeper understanding of alluvial gully erosion. Future research on alluvial gully erosion will undoubtably be interdisciplinary, similar to the present study. It will incorporate the scientific fields of hydrology, geomorphology, spatial geography and remote sensing, soil science, geochemistry, geotechnical engineering, bioengineering, restoration-ecology and -geomorphology, agricultural and rangeland science, environmental and agricultural economics, all of which directly feed into the broader disciples of sustainable and adaptive land-use management at the catchment scale. A partial, non-exhaustive list of potential future research tasks, ideas and questions will be outlined below, most of which either were not addressed in this study or could be improved upon beyond the preliminary results presented here.

8.2.1 Alluvial vs. colluvial gullies

The conceptual and quantitative differences between unconfined alluvial (floodplain) and confined colluvial (hillslope) gully erosion need to be elaborated on further in a quantified comparative study. Beyond these two end members of gully types, there is a full continuum range of gully types that likely incorporate materials and processes from both end members, which should be investigated in more detail. The inherited geology and terrain and degree of valley confinement are likely important first order controls on geomorphic process domains and the evolution of incisional gullies into various types of regolith.

8.2.2 Improved spatial mapping of alluvial and colluvial gullies

The accuracy of the spatial mapping of both alluvial and colluvial gully distribution in the Mitchell catchment and across northern Australia should be improved upon as technology, scientific efforts, and land management advance. The ASTER based delineation of alluvial gullies used in Chapter Two was subject to inaccuracies, despite ground truthing and air photo based corrections, which were due to ASTER scene-to-scene variability in emission spectra, the inability to map gullies under tree canopies, and the lack of spectral contrast between dissected alluvial gullies and nearby un-incised scalded areas. Undoubtably, Light Detection and Ranging (LiDAR) topographic mapping will become more cost effective and widespread into the future, and it should be used at the landscape scale to map alluvial and colluvial gully incision, quantify erosional change from repeat surveys, and improve upon catchment sediment budgets. Additional mapping of large alluvial gully complexes could be trialled using airborne radiometric surveys that measure variations in potassium, thorium, and uranium radionuclides in the top 30 cm of soil. The unique geochemistry of ferricrete and calcrete deposits in denuded alluvial gully complexes could emit unique radiometric signals. New surveys at a variety of scales from the Geological Survey of Queensland are available for the Cape York region. In the meantime, improving upon satellite based remote sensing techniques, spectral analysis, and field and air photo verification could also be fruitful.

8.2.3 Detailed floodplain soil physical and geochemical data and mapping

Available soil classification data for the Mitchell fluvial megafan are relatively coarse with only sporadic points with quantified field data of soil physical, chemical, and biological properties. This is especially true for the floodplain soil transition areas through river riparian zones, where there is a high degree of spatial heterogeneity in soils between river inset-floodplains in the macro-channel, the high-floodplain, and distal floodplains. These soil transition zones are the initiation and propagation areas for alluvial gullies, and their soil properties have a strong influence on gully development. Soils data from this study only provided a cursory addition to these near-river soil conditions and highlighted the need for future detailed soil analysis.

Additional horizontal and vertical soils data (physical, chemical, and biological) should be collected from a variety of soils and alluvial gully types on the Mitchell megafan, concentrated along major river and creek channel zones mentioned above. Analyses should focus on soil properties that assess soil erodibility and dispersibility, such as aggregate stability and exchangeable sodium percentage (ESP) metrics. Information should also be collected on hydraulic conductivity and permeability, the susceptibility of soils to compaction, scalding and hardsetting, soil fertility and the availability of nitrogen and phosphorus nutrients, soil organic matter and biotic health, and additional basic metrics like pH and conductivity. The unique development of ferricrete and calcrete nodule formation from nodules and root casts respectively should also be investigated (see below).

Improved soils field data should be incorporated into higher-resolution mapping and classification of soil types along the waterways of the Mitchell megafan. This detailed mapping could be developed with the aid of improved technology, such as high-resolution satellite imagery, LIDAR surveys of topography and landforms, and radiometric surveys of potassium, thorium, and uranium radionuclides. An improved soil classification system could serve as the baseline for developing specific land management units for the long-term sustainability of soil resources and regional economies.

8.2.4 Ferricrete and calcrete nodule development in alluvial gullies

The tropical landscape of northern Australia holds a vast quantity of quantitative information on erosion rates and processes, which are held as data within the trees, sand grains, and ferricrete and calcrete nodules that are ubiquitous across the landscape. For example, following the exposure and oxidation of massive alluvial soils after gully erosion, nodules or pisoliths of ferricrete (Fe/Mn oxides) and calcrete (Ca/Mg oxides) readily form on the surface of exposed gullies, creating lag deposits and duricrusts. This process is a result of the relative and/or absolute accumulation of precipitated elements moving through the soil profile and accumulating in soil mottles or other concretions, which then harden or indurate once permanently oxidized following gully erosion exposure. The time of the formation of these pisoliths into a closed system is potentially datable via uranium-thorium-radium-lead decay series. It was originally hypothesized that the formation/induration of these pisoliths was directly linked to the gully retreat and oxidation process, and that dating pisoliths distributed across a gully floor could provide a detailed chronology of gully position and erosion rates over time.

Initial gamma spectrometry analysis of the U/Th/Ra/Pb activities in bulk samples containing hundreds of ferricrete (Fe/Mn oxides) nodules has been inconclusive. The radionuclides in the U-238 and Th-232 decay series appear to be in secular equilibrium when the ferricrete nodules are bulked in mass. This indicates that the elements in the nodules or original soil mottles have been in situ and in equilibrium for long time periods. It remains unknown at what point the elemental composition of soil mottles transitions from fully open, to partially-open, to fully closed systems. Fully closed systems are need for at least some disequilibrium to occur and for accurate dating of the time since system closure. Attempts at dating the timing of induration or system closure of nodules should not be abandoned, nor should their geomorphic application. Higher resolution analysis of the closed systems of individual nodular cores could be attempted using techniques such as Laser Ablated Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS). Additional analysis and comparison of the radionuclide composition of both un-indurated soil mottles and indurated pisoliths could help quantify the timing of radionuclide movements and system closure. Due to the known young age of alluvial gullies in the Mitchell (<150 years) and the subsequent recent induration of soil mottles into pisoliths, analysis should focus on shorter-lived radionuclides such as Ra-228 and Th-228 of the Th-232 decay series. Furthermore, the geochemical development and dating of calcrete nodules and root casts following gully retreat should also be investigated, as their secular equilibrium is still in unmeasured.

On a related geomorphic research front, the geochemical transformation of mobile solutes of Fe, Mn, Ca, and other metals into soil mottles and eventually pisoliths upon permanent oxidation is important from both soil erosion and sediment transport perspectives. The fine-grained floodplain soils of the Mitchell fluvial megafan naturally do not contain many coarse particle sizes greater in diameter than sand. When these soils re-erode via secondary erosion cycles associated with alluvial gullying, they predominantly produce fine silt and clay particles. However, the development of pisoliths and duricrusts from solute precipitation increases the overall particle size distributions of eroded sediment, which can lead to the concentration of these coarser particles on the soil surface as lag deposits and cemented duricrusts. These coarser particles can subsequently partially protect the underlying finer grained soils for further raindrop impact and erosion. However when these nodular pisoliths are entrained by overland flow into gully channel networks, they can become an important part of the bedload flux as well as the suspended load flux as the particles are abraded. Indurate pisoliths particles, presumably from nearby alluvial gullies, have been observed to be a part of the bed material load of the Mitchell River along its lower 350km course. Thus the geochemical transformation of mobile solutes into precipitates and indurated bedload particles could represent an important part of overall sediment budgets in tropical landscapes. This process should be investigated further, and perhaps these sediments could be used as geochemical tracers of both the bedload and suspended load originating from alluvial gullies.

8.2.5 Pore-water pressure and geotechnical stability

Measuring subsurface soil pore-water pressure at gully head scarps using continuous tensiometers was generally problematic. This was largely due to the use of tensiometers in remote locations where the wetting and drying of subsurface soils during wet seasons was extreme and tensiometer desiccation was common. Future efforts should focus on using study sites that are more accessible by personnel during the dry season, such as near cattle stations, in order to ensure that tensiometers are full of water and in place for measurement during episodic rainfall events. Alternatively or additionally, other technology for in situ soil moisture measurement (via capacitance, time domain reflectometry, or neutron probes) could be utilized and calibrated to local soil moisture conditions. However, tensiometers have the unique advantage of providing important pore water pressure data useful in geotechnical engineering equations to calculate applied stresses at which soil structure or blocks fail, and to model these changes through time and space. This is essential in determining the internal mechanisms of scarp retreat, quantifying the relative importance of direct rainfall and runoff vs. seepage of soil moisture and groundwater vs. river backwater and floodwater in causing scarp failure and retreat. It is also important in identifying potentially effective rehabilitation measures to stabilizing gully head scarps. Ideally, the number of tensiometers also should be increased (dozens) to better define the horizontal and vertical variability in pore water pressure and seepage gradients (Dr. Andrew Simon, personal communication).

8.2.6 Empirical erosion rates from field studies

The style of empirical field research on alluvial gullies initiated here in the lower Mitchell catchment should be expanded to other floodplain field sites across northern Australia in order to quantify the full range of variability in alluvial gully erosion rates and processes. Specifically, other sites in the greater Gulf of Carpentaria catchment should be investigated since this is likely the epicentre of alluvial gully erosion in Australia. Empirically-based field research should be emphasized in order to build up a foundation of basic rate and process observations, from which a later modelling effort can be incorporated and driven by fundamental datasets. Specifically, additional field water and sediment gauging efforts in alluvial gullies will be needed to better define the event, seasonal and annual variability in sediment yield to compare to more accurate measurements of scarp retreat, internal erosion processes and the evolution of gully morphology. More accurate scarp retreat measurements at various temporal scales should utilize improved technologies such as repeat airborne or terrestrial LiDAR and/or robust photogrammetric cameras and methods for DEM creation from oblique or vertical angles.

8.2.7 Modelling alluvial gully evolution

Additional modelling of the rates and evolution of alluvial gully erosion should be conducted in the future. This modelling will need to be based on and driven by improved data collected from field studies mentioned above. Specifically, combining better sediment yield data from gully catchments with more accurate scarp retreat data will help quantify the importance of internal erosion and sediment storage processes, and determine what addition variables will need to be measured and parameterized for model development. Subsequently, numerical drainage-basin-evolution models could be developed that utilize 1) local topographic data from LiDAR as initial pre-erosion landscape templates in both fully unconfined and partially confined alluvial settings, 2) stochastic rainfall and river backwater information as driving variables for erosion, 3) theoretical equations of sediment transport at the transport-limit, and 4) variations in resistance parameters such as soil texture and chemistry, stratigraphic changes in induration and erosion resistance, seasonal and decadal changes in vegetation species and cover, and land-use variables such as grazing pressure and fire regime. The numerical model evolution of alluvial gully form could be then validated against observed gully forms quantified from LiDAR data, such as LiDAR derived longitudinal profiles that define equilibrium (or disequilibrium) slopes, incision resistance from local induration, and the ultimate potential extents of gully expansion.

8.2.8 Improved tree age dating in alluvial gullies

The dating of *Eucalyptus* species and other trees growing in or around alluvial gullies could be improved upon by utilizing less subjective methods of tree ring boundary identification. Specifically, future studies should use new technologies for automated non-destructive measurements of wood density (x-ray radiography and densitometry) and trace element chemistry (X-ray fluorescence or synchrotron radiation induced X-ray emission). This would increase the spatial accuracy of ring sampling locations for carbon or radium radionuclide analysis, and allow for the cumulative mass integration from multiple tree slices to increase ring sample mass. Additionally, the ring widths from more precisely identified ring boundaries could be used for more classic dendrochronology purposes, such as cross-correlation of tree age overlaps with younger or older trees for master chronology development and/or correlation with rainfall or other environmental variables for proxy record development.

8.2.9 Additional stratigraphic dating within alluvial gullies and river floodplain deposits

The depositional history and stratigraphy of alluvial deposits within eroded gullies and the surrounding riverine floodplain landscape should be investigated in more detail in both the Mitchell catchment and others across northern Australia. Optically stimulated luminescence (OSL) dating of sand grain burial age provides an absolute method of developing the chronostratigraphy of alluvial deposits. Preliminary OSL dating from two gully complexes in study suggested that erosion, gully incision, and subsequent re-aggradation of gully inset-floodplains were associated with European settlement and the introduction of cattle grazing in the late-1880's. However, the spatial and temporal response to disturbances could have varied across the landscape. Additional OSL dating and stratigraphic interpretation of alluvial gully deposits at more distributed sites across the region could quantify the homogeneity or heterogeneity of landscape response to human disturbance and/or natural forcing.

Furthermore, the precise and absolute ages of Pliocene, Pleistocene, and Holocene alluvial landforms and stratigraphy of the region have been poorly quantified. Additional OSL dating of older alluvial deposits across the Mitchell megafan and beyond would improve our understanding of fluvial geomorphic evolution of during the Quaternary. Understanding the temporal development of these antecedent conditions would aid in the interpretation of why and when the landscape was primed for the contemporary phase of alluvial gully erosion. From initial OSL dating in alluvial gullies, it appears that large age gaps or unconformities exist between post-European gully deposits and the original Pleistocene river floodplain deposits that gullies have eroded into, which suggest an unprecedented phase of gullying. However additional spatial and temporal OSL dating from various gully, creek, and river sites across the megafan could uncover the more subtle and detailed transitions between original river floodplain development, slow drainage basin evolution into these floodplain deposits over time, and their rapid incision post-European settlement. This stratigraphic history during the Holocene would also be preserved in the Mitchell fan-delta, where OSL dating of pre-European sedimentation rates over the last 6000-yrs following the last sea-level high-stand could be compared to post-European sedimentation rates following catchment disturbance and widespread gully initiation.

8.2.10 Quantification of recent land-use impacts on gully initiation and propagation

This research demonstrates that *historic* land-use changes from traditional Aboriginal management to widespread cattle grazing from the late 1800's onward triggered widespread alluvial gully erosion in the lower Mitchell floodplains by pushing the landscape across its natural threshold of stability. The correlation between the growth trends in alluvial gully area and cattle numbers does not necessarily support a continued cause and effect relationship between cattle grazing and gully area, but rather a land-use trigger mechanism at or after the onset of land-use change. However, *ongoing and current* land-use disturbance could still exacerbate or accelerate gully erosion initiated decades before, and/or initiate new erosion or gullies, which need to be researched in more detail.

The variability in the timing of gully initiation post-cattle introduction suggests that individual components of the landscapes had different thresholds of stability and perhaps different degrees of land-use impact by cattle. Undoubtably, the most erosion prone components of the floodplain landscape have already been destabilized into large alluvial gullies. More stable features of the landscape have either eroded to a lesser degree or have remained quasi-stable. Nonetheless, field observations of current impacts from cattle grazing suggest that the initiation and acceleration of surface erosion and proto-gully incision is occurring, widespread, and caused by continued cattle migrations through riparian zones to and from large water bodies, in addition to road, track, and fence line associated gullying. However this erosion is less dramatic and interspersed amongst the historically triggered gullies. Since this current erosion from recent land use was *not* quantified in this study, the cumulative magnitude and relative importance of this more contemporary erosion outside major historic alluvial gully areas remains unknown. Thus, future studies should focus on quantifying the impacts of contemporary cattle grazing on floodplain soil erosion not triggered initially during historic land-use changes. This will support management decisions and actions needed to reduce further gully initiation or soil erosion, and passively or proactively rehabilitate pasture and riparian habitat.

8.2.11 Quantification of savannah grass influences on erosion resistance and water production

The importance of both direct rainfall and infiltration-excess runoff on alluvial gully scarp retreat has implications for grazing land management influences on soil-surface and grassland-vegetation conditions. However, local water balance studies in savanna floodplain regions in northern Australia are needed to quantify the influence of different grassland communities and conditions on the pathways of water on or through the alluvial soil, the overall production of water runoff, the resistance of alluvial soils to erosion, and the initiation and propagation of gullies. Local studies would add to the existing literature on these topics, at the same time as allow for these locally quantified processes to be incorporated into adaptive management plans.

For example, numerous studies around Australia and the world have demonstrated the importance of perennial grass cover in increasing rain splash protection, root cohesion, aggregate stability from organic matter, soil permeability, and water infiltration. Alteration of this perennial cover and associated properties via grazing, along with direct soil compaction and destruction of biological crusts by cattle, have also been shown to increase water runoff volumes and soil erosion. Furthermore once runoff occurs, perennial grass cover can increase the resistance of the soil to erosion through root cohesion and surface roughness, which increases the critical shear stress needed for sheet erosion, rilling, and gullying.

However, these types of studies have not focused on water yields and soil erosion from floodplain alluvial soils that are sodic, hardsetting, prone to structural breakdown through dispersion, episodically sealed from pore clogging and swelling, and heavy grazed and trampled along river frontages. They especially have not addressed the hydrologic issues of periodic backwater and full floodplain inundation and drawdown, which add additional elements of water production drivers. The importance of soil and vegetative resistance to erosion under these varying circumstances could be paramount to the stability of the landscape, as suggested in this thesis. However in floodplain environments in northern Australia, we do not know the exact thresholds of ground cover and root density resistance and water retention that are needed to avoid triggering alluvial gully erosion. Knowledge to this end could be generated from detailed and controlled experimental trials of alluvial gully rehabilitation, covered in Chapter Seven and summarized below.

8.2.12 Rehabilitation of alluvial gullies via experimentation and adaptive management

A detailed proposal for experimental trials of alluvial gully rehabilitation was outlined in Chapter Seven to determine the most cost-effective, practical, and sustainable land management and bioengineering activities needed to halt or reduce alluvial gully erosion once it has started, as well as reducing their future initiation, by targeting the process-based causes of gully erosion rather than the symptoms. Experimental trials with both control and treatment sub-catchments should be monitored by detailed water balance, sediment budget, and other chemical and biological procedures to isolate and identify specific causes and effects of land management actions. Treatments could include: 1) cattle exclusion and perennial grass enhancement to reduce water runoff and increase the soil resistance to erosion; 2) the use of contour banks to divert concentrated or diffuse overland flow away from gully scarps; 3) the use of soil amendments such as gypsum to increase aggregate stability, reduced surface sealing, and promote infiltration; 4) gully-scarp slope battering and intensive perennial grass establishment to bind and protect exposed soils; and 5) a combination of these treatments plus isolated controls. If implemented, the outcomes could be synthesized into regional best management practices (BMP) guidelines for alluvial gullies that would benefit the education and training of local landowners and the wider pastoral community about specific rehabilitation techniques and soil conservation actions.

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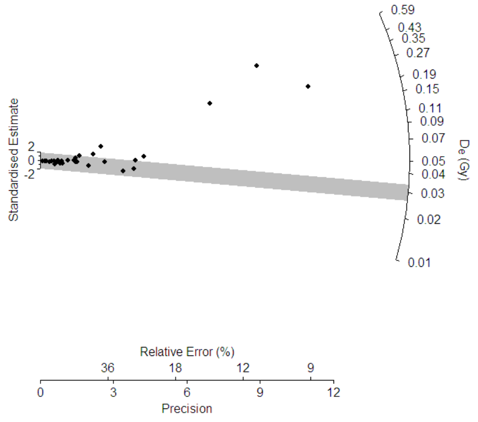
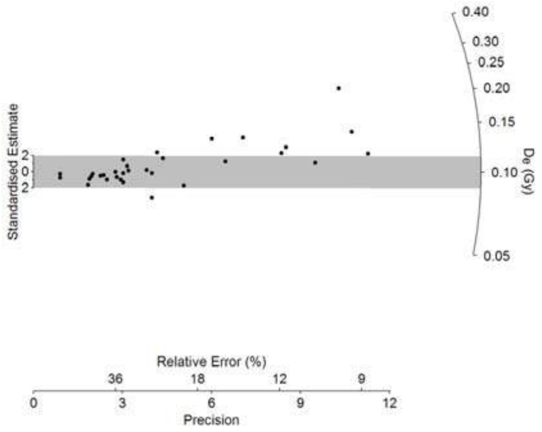
Appendix (OSL Radial Plots)

This appendix contains radial plots of optically stimulated luminescence (OSL) data presented from results in Chapter Six, Section 6.3.5, with methods in Section 6.2.7. The radial plots display the equivalent dose (D_e, Grays) for individual quartz grains on the y-axis and their standard errors (σ) as a relative error or precision on the x-axis, which were determined from a modified single-aliquot regenerative-dose (SAR) protocol (Olley et al. 2004). The gray band highlights the region encompassing 2 standard errors (2σ) of the final estimate of the equivalent dose (Table 6-2). This final equivalent dose estimate was determined by methods in Pietsch (2009) by fitting a "single Gaussian curve to the peak of a multi-Gaussian summed probability distribution", which is generally similar to leading edge or minimum age of the D_e distribution. Equivalent dose (D_e) was converted to age by dividing by the measured dose rate (D_r, Grays/year) received from radiation in the surrounding environment (Table 6-2).



HB-01



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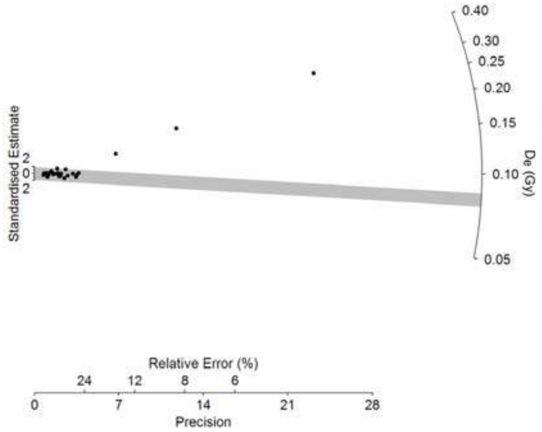

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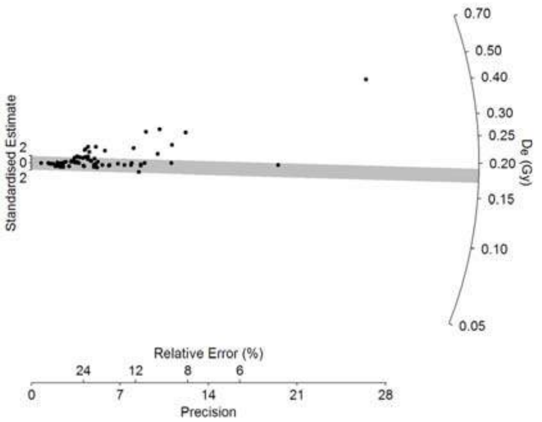

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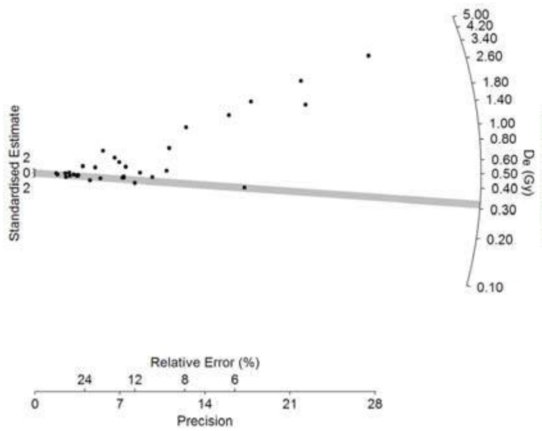

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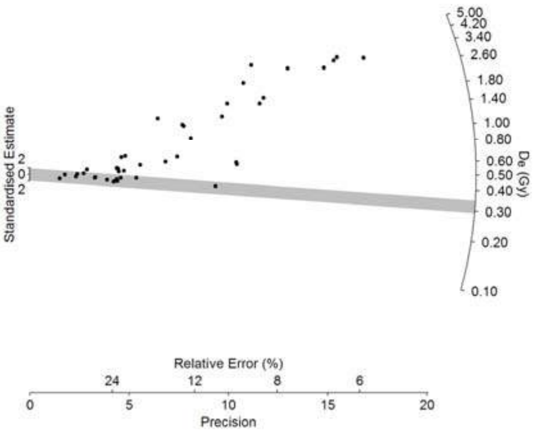

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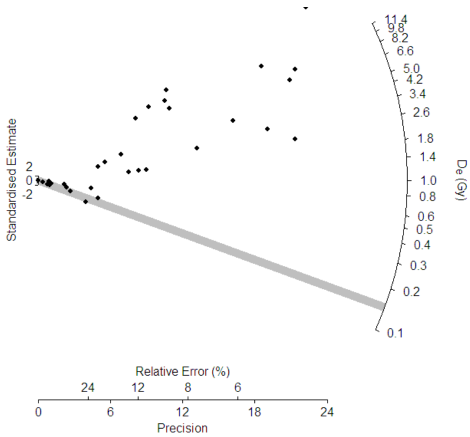
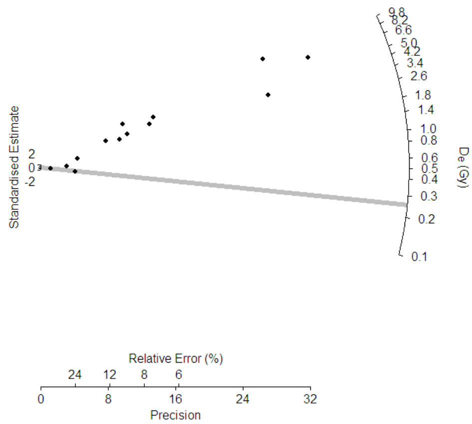
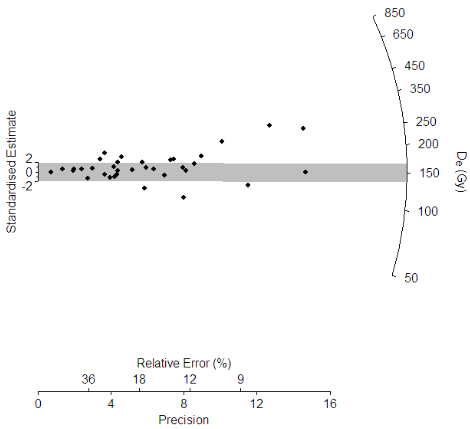


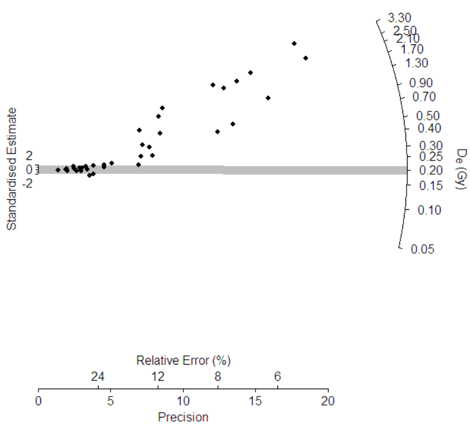
WP-05



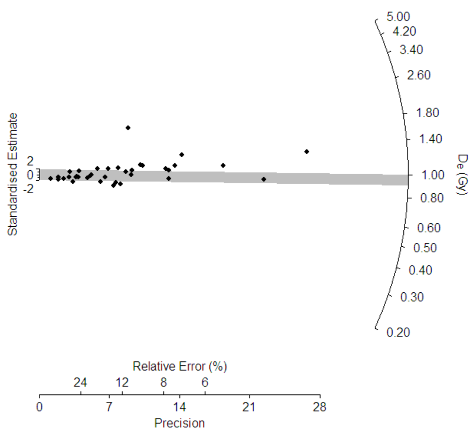
WP-06



WP-07



WP-10



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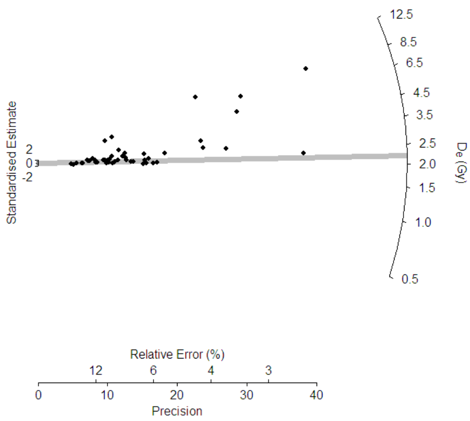

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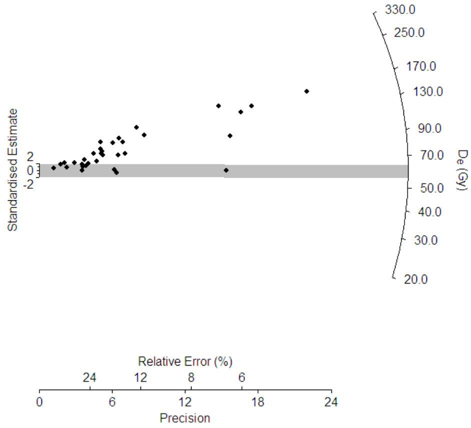

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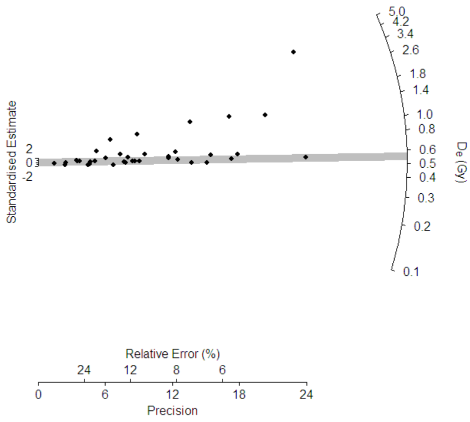
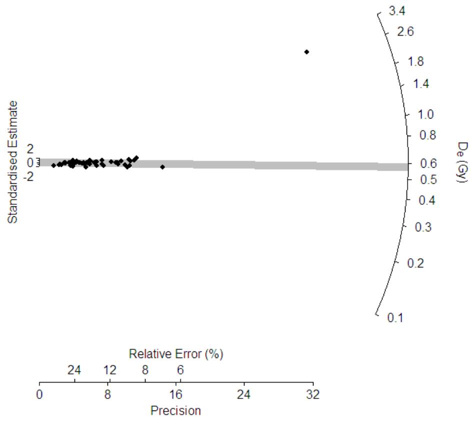


WP-19



WP-20