Alluvial Gully Erosion: A Dominant Erosion Process Across Tropical Northern Australia

J. Shellberg[1], A. Brooks[1]

November, 2012

[1] Griffith University, Australian Rivers Institute

Acknowledgement:

This project was funded by the Northern Gulf NRM Group, Land & Water Australia, Griffith University (Australian Rivers Institute), the Australian Government (Caring for Our Country Program and Reef Rescue Program), and TRaCK's funders as listed below.

Disclaimer

TRaCK has published the information contained in this publication to assist public knowledge and discussion and to help improve the sustainable management of Australia's tropical rivers and coasts. Where technical information has been prepared by or contributed by authors external to TRaCK, readers should contact the author(s), and conduct their own enquiries, before making use of that information. No person should act on the contents of this publication whether as to matters of fact or opinion or other content, without first obtaining specific independent professional advice which confirms the information contained within this publication.

While all reasonable efforts have been made to ensure that the information in this publication is correct, matters covered by the publication are subject to change. Charles Darwin University does not assume and hereby disclaims any express or implied liability whatsoever to any party for any loss or damage caused by errors or omissions, whether these errors or omissions result from negligence, accident or any other cause.

Copyright

This publication is copyright. Apart from any fair dealing for the purpose of private study, research, criticism or review as permitted under the Copyright Act, no part may be reproduced, by any process, without written permission from the publisher. Enquiries should be made to the publisher, Charles Darwin University, c/- TRaCK, Casuarina Campus, Building Red 1 Level 3, Darwin NT 0909.

TRaCK brings together leading tropical river researchers and managers from Charles Darwin University, Griffith University, the University of Western Australia, CSIRO, James Cook University, the Australian National University, Geoscience Australia, the Environmental Research Institute of the Supervising Scientist, the Australian Institute of Marine Science, the North Australia Indigenous Land and Sea Management Alliance, and the governments of Queensland, the Northern Territory and Western Australia.

TRaCK received major funding for its first phase of research through the Australian Government's Commonwealth Environment Research Facilities initiative; the Australian Government's Raising National Water Standards Program; Land and Water Australia; the Fisheries Research and Development Corporation and the Queensland Government's Smart State Innovation Fund.

In 2011 TRaCK received funding from the National Water Commission to undertake targeted projects as part of a 'synthesis and adoption' year to ensure research findings are relevant and more widely available.

Front cover – Photo by Andrew Brooks

For further information about this publication:
Jeff Shellberg and Andrew Brooks, Australian Rivers Institute, Griffith University, TRaCK
Email: j.shellberg@griffith.edu.au; andrew.brooks@griffith.edu.au

Or to find out more about TRaCK

Visit:	http://www.track.org.au/
Email:	track@cdu.edu.au
Phone:	08 8946 7444

ISBN: 978-1-921576-79-9
Published by: Charles Darwin University

Introduction

Gully erosion is the process by which running water cuts new unstable channels into erodible soil and weathered rock. It causes severe land degradation, and is a major source of sediment and associated nutrients to river systems and ultimately to coastal waters or inland basins. In northern Australia there is widespread gully erosion into unconfined alluvial deposits on active floodplains and terraces (relict floodplains) – here defined as *alluvial gully erosion*[4]. Alluvial gully erosion scarps are locally known as "breakaways" by pastoralists (Figure 1). Until this recent TRaCK research, alluvial gully erosion in northern Australia was poorly documented scientifically and is substantially different from colluvial or hillslope gullying in south-eastern or northern Australia.

Figure 1 An oblique photo of an alluvial gully "breakaway" migrating away from a river corridor and consuming the floodplain savanna landscape.

Alluvial and colluvial gullies – what is the difference and why does it matter?

Most research about gully erosion processes and rehabilitation management in Australia is based on *hillslope or colluvial gullies* typically found on the tablelands and mid-slopes of coastal south-eastern Australia[8] and northern Australia[11]. Hillslope gullies typically erode into colluvium (i.e., accumulated rock and soil at the base of hillslopes from long term gravitational processes and overland flow), but this colluvium can also be mixed with some minor alluvium (i.e., sediment transported, abraded, and sorted by flowing water in channels). Hillslope or colluvial gullies tend to be fairly linear erosional features, where their lateral and vertical erosion is confined by bedrock and their upslope migration tends to be self limiting as a function of the catchment area, slope, and the availability of colluvium to erode (Figure 2a). Hillslope gullies are not always directly connected to the downstream channel network, with the eroded sediment deposited in a "floodout" or small fan deposit[9].

Under these circumstances their contribution to the river sediment loads is significantly less than if they were fully connected to the drainage network.

Alluvial gullies on the other hand originate at steep stream banks and erode into adjacent, relatively flat, alluvial floodplains and terraces (Figure 2b). They have been inconsistently described in the international literature as bank gullies, ravines, valley-bottom gullies, and alluvial breakaways from locations around the world including Europe, India, Africa, USA, and Australia[4,20,21]. Due to a lack of bedrock confinement, alluvial gullies are often as wide as they are long and expand longitudinally and laterally until they develop new equilibrium channel slopes and consume massive volumes of floodplain alluvium. This alluvial material tends to be much finer sediment than most colluvial deposits, thereby contributing a higher proportion of fine sediment to river suspended sediment loads. They are also highly connected to the stream network, delivering their sediment load directly to the main channel.

The difference between alluvial and colluvial gully types is important because the factors controlling their initiation, progression and ultimate stabilisation differ substantially. While there is a long history of attempting to manage and control colluvial gullies in south-eastern Australia, often unsuccessfully, scientists and managers are only just beginning to address managing these far more extreme alluvial gullies that are found across northern Australia. It is clear that directly importing management approaches from hillslope gullies in southern Australia is unlikely to provide a solution to managing alluvial gullies in northern Australia, although there is much that can be learnt from past successful and unsuccessful experiences.

The erosion of floodplain soils via alluvial gully erosion presents major local and cumulative threats to:

1) The local pastoral industry through the loss of productive riparian land.
2) Existing human infrastructure (e.g., roads, fences, dams, buildings, water points).
3) Future potential agricultural development.
4) Downstream aquatic ecosystems influenced by high suspended sediment concentrations, associated nutrients, and habitat changes from sedimentation (i.e., pool and lagoon infilling).
5) Indigenous cultural use of water bodies for subsistence, commercial, and ceremonial purposes (i.e., fisheries production).
6) The long-term sustainability of the landscape and provision of ecosystem services.

a) *b)*

Figure 2 Examples of a) a tropical hillslope/colluvial gully that is elongate and eroding into relatively coarse colluvial material in the lower part of a hillslope, and b) a tropical alluvial gully eroding into deep alluvial deposits that is expanding laterally as well as longitudinally.

Distribution across northern Australia

Alluvial gullies are widely distributed across floodplain environments of northern Australia (Figure 3). However, they are not restricted to the tropics and exist in other locations across the continent and world[4,20,21]. In Queensland, recent satellite and air photo remote sensing have documented and mapped extensive areas of floodplains degraded by active alluvial gully erosion in many catchments (Table 1). These estimates are based on the mapping of bare, de-vegetated surfaces eroded by alluvial gullies[1,2,3,4,5,12]. They are a minimum due to vegetation masking of gullies under tree canopy; for example, in the Normanby catchment the true alluvial gully area is 7.6 times the bare area estimated from air photos[5]. However these conservative mapped estimates (Table 1) still can cover up 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 (NT, 811)[7,13] and Fitzroy (WA, 802)[15] catchments (Table 1). Alluvial gullies also have been studied in the Daly (NT, 814)[18],Ord (WA, 809)[14] and Fitzroy (QLD, 130)[23] catchments, and observed in the Flinders (QLD, 915), Norman (QLD, 916), Staaten (QLD, 918), Coleman (QLD, 920), Stewart (QLD, 104), and Burdekin (QLD, 120) catchments. They likely exist along additional floodplain rivers in the Australian tropics.

Table 1 Estimated minimum area of alluvial gullies in different catchments.

Catchment	Basin Number (Code) Figure 3	Bare Ground Minimum Area of Alluvial Gullies (ha)	% Catchment Area
Normanby (QLD)[5]	105	2,031	0.08%
Mitchell (QLD) [1,2,3,4,12]	919	16,700	0.23%
Gilbert (QLD) [1]	917	10,100	0.22%
Leichhardt (QLD) [1]	913	29,100	0.87%
Gregory/Nicholson (QLD) [1]	912	12,300	0.24%
Victoria (NT)[7]	811	10,400	0.22%
Fitzroy (WA)[15]	802	36,300	0.39%

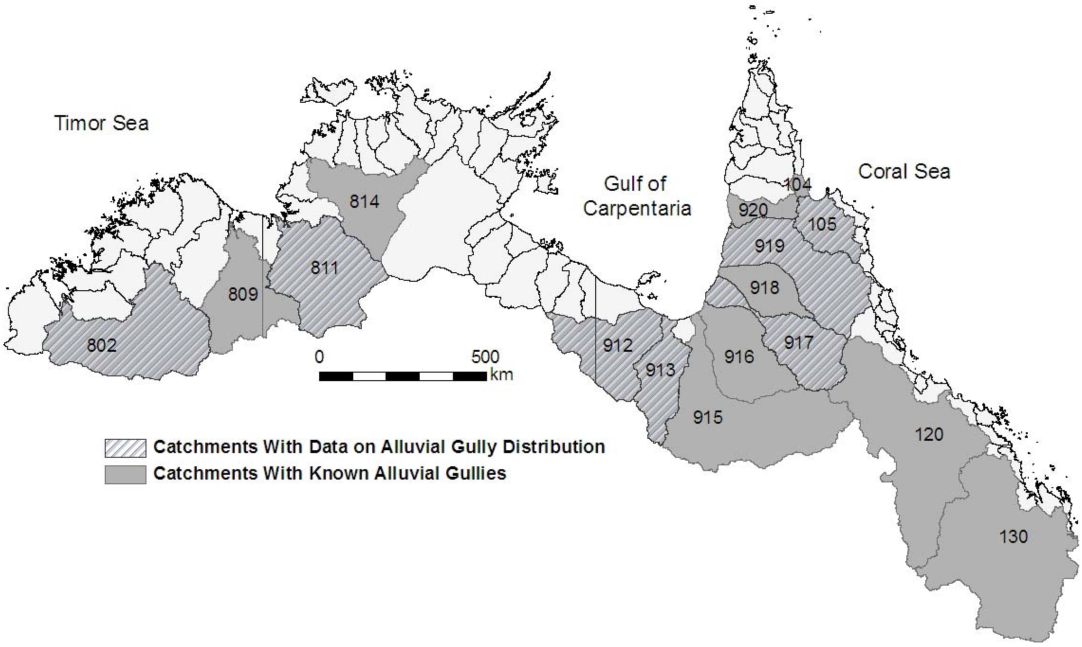


Figure 3 Map of catchments in northern Australia that either a) have data on alluvial gully distribution (stipple) or b) have known alluvial gullies that have not been quantified or mapped circa 2012 (dark gray). Catchment basin-numbers are included on the map, the text, and in Table 1.

Types and forms of alluvial gully erosion

From field research and remote sensing mapping across northern Australia, it is clear that alluvial gullies eroding into floodplain systems come in a variety of forms depending on local processes[1,2,4,5,7,13,20,21]. Most alluvial gullies drain directly into main channels (*proximal* gullies), while some gullies draining away from the main channel towards distally draining creeks or lagoons (*distal* gullies). Often both *distal* and *proximal* gullies will be found at a single location, consuming the floodplain from both directions (Figure 4). In planform (Figure 5), *linear* alluvial gullies are often young incipient gullies, commonly associated with land-use disturbances such as stock tracks, roads, and fences that tend to concentrate overland flow. *Dendritic* gullies are associated with well defined drainage networks, separated by distinct interfluves with often less distinct or continuous head scarps. *Amphitheatre* gullies are often as wide as or wider than they are long due to the lack of structural control, and have well developed head scarps that drain into relatively narrow outlet channels. *Continuous scarp front* gullies are mature in phase, located parallel with main channels, and develop from the coalescence of numerous laterally expanding amphitheatre gullies and/or from river bank erosion on meander bends.

Figure 4 A road located on the apex of an floodplain alluvial ridge that has been consumed by the merging of proximal and distal draining gullies. Note that in this situation, just direct rainfall and local runoff are needed for headward retreat that progresses until none of the original floodplain surface remains.

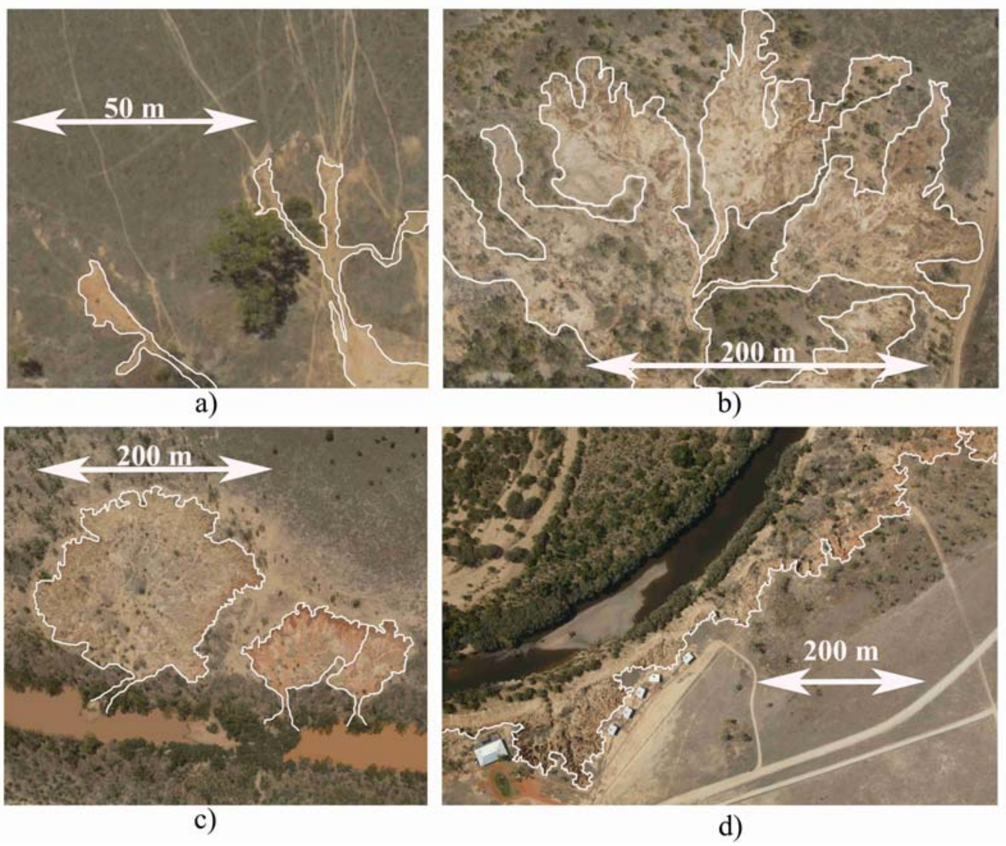


Figure 5 Examples of different planform morphologies of alluvial gullies: a) linear; b) dendritic; c) amphitheatre; d) continuous scarp front.

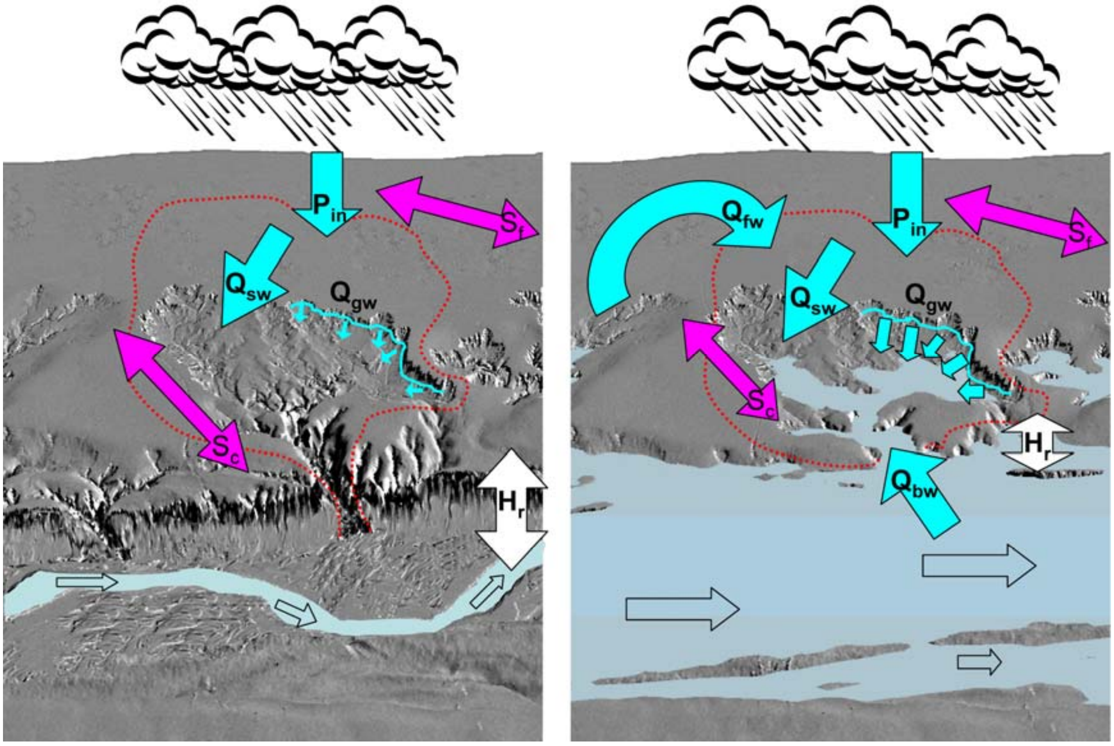
Natural factors influencing alluvial gully erosion

Alluvial gullies are typically concentrated at or near (< 3 km) the banks of main floodplain channels, where there is a break in slope on steep banks[4]. The elevational relief or vertical height between the river bed and high floodplain or terrace provide the potential energy for erosion. This height can be enhanced by river incision or entrenchment into the surrounding floodplain over geologic time[4,21]. The heights of gully head scarps are often correlated to this local relief and degree of river entrenchment[4].

The kinetic energy for alluvial gully erosion can come from multiple water sources such as direct rainfall, overland runoff, groundwater, river backwater, or overbank floodwater into subtle gully catchments that are difficult to delineate on the ground (Figure 6) [4,21]. This is in contrast to hillslope or colluvial gullies that have standard rainfall-runoff responses and easily definable catchment areas. Since alluvial gullies are often situated on floodplains or terraces near rivers and water bodies, river backwater or overbank flood water can contribute significantly to gully erosion[21]. The importance of these erosional drivers depends on the connectivity of the river with its floodplain or terrace, which is spatially controlled by the degree of river incision or entrenchment[4]. It is also temporally controlled by the frequency and magnitude of flood runoff from the river catchment[21], as influenced by climate and human development. However for a majority of the time, erosion from intense tropical rainfall on exposed soils and overland runoff from surrounding subtle catchment areas still can dominate alluvial gully erosion and scarp retreat[21].

The erodibility of floodplain soils plays a major role in the initiation, propagation, and distribution of alluvial gullies. Older, elevated, near-river, floodplain soils in the tropics are often highly weathered silty loams, compared to clay soils in distance floodplains and sandy soils in river[10]. Depending on the catchment parent geology, these floodplain soils can have elevated levels of sodium and magnesium, relative to preferred levels of calcium and potassium[10,21]. These “sodic” and silty soils have a predisposition to dispersion and erosion, especially if disturbed by natural or human factors[20].

Vegetation on banks and adjacent floodplains play the key mitigating role in resisting alluvial gully erosion into elevated and dispersible sodic soils. Native deep-rooted perennial grass performs best at protecting and binding *surface* soils to prevent erosion initiation, compared to tree, shrub or exotic weed species. Both natural factors such as drought and fire, and anthropogenic factors such as grazing, fire regime changes, weed invasion, fencing, roads, tree clearing, and agriculture can influence vegetative cover and erosion resistance[20]. Runoff volumes from alluvial gully catchments can be increased by low levels of ground cover[21], enhancing erosion susceptibility or rates. Animal tracks (pads) and roads that concentrate water can also overwhelm the effectiveness of grass cover in resistance soil and gully erosion.



a) b)

Figure 6 Conceptual model of erosional-drivers of alluvial gully erosion with approximate catchment area in red: 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).

Rates of gully expansion

Rates of linear and aerial gully expansion can vary widely depending on the location and erosion process. Recent (2005-2010) GPS surveys at 18 sites in the Mitchell catchment measured average linear rates of scarp retreat between <0.1 and 0.8 m/yr, with a median rate of 0.23 m/yr. However, maximum local rates at active lobes ranged between 2 and 15 m/yr (Figure 7)[4,20]. At gullies influenced by roads, scarp retreat rates up to 75m/yr have recently been observed.

Using historical air photos between the 1940s and 2000s (e.g., *Figure 12*), similar average linear rates of scarp retreat have been documented in the Mitchell[19,20] (median 0.37 m/yr; range <0.1 to 1.2), Normanby[5] (median 0.46 m/yr; range 0.1 to 0.7) and Victoria NT[13] (average 0.86 m/yr; range 0.3 to 1.6) catchments. In the Mitchell catchment, historic gully areas have increased between 1.25 to 10 times their initial 1949 area (Figure 8). Extrapolation of gully area growth trends backward in time suggests that the current phase of extensive gullying was initiated between 1880 and 1950 in the Mitchell[19,20]. Spatial and temporal projections of gully area growth into the future until channel profile equilibriums are reached suggest that alluvial gullies 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.

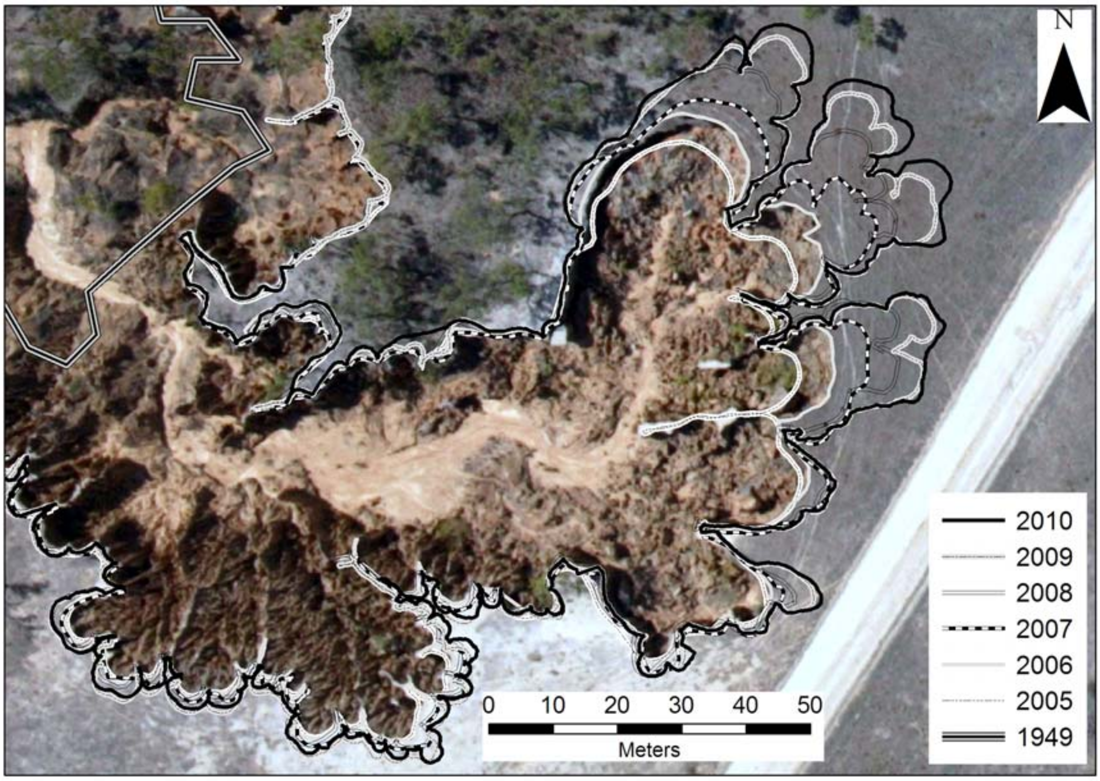


Figure 7 *Annual alluvial gully scarp expansion measured with GPS.*

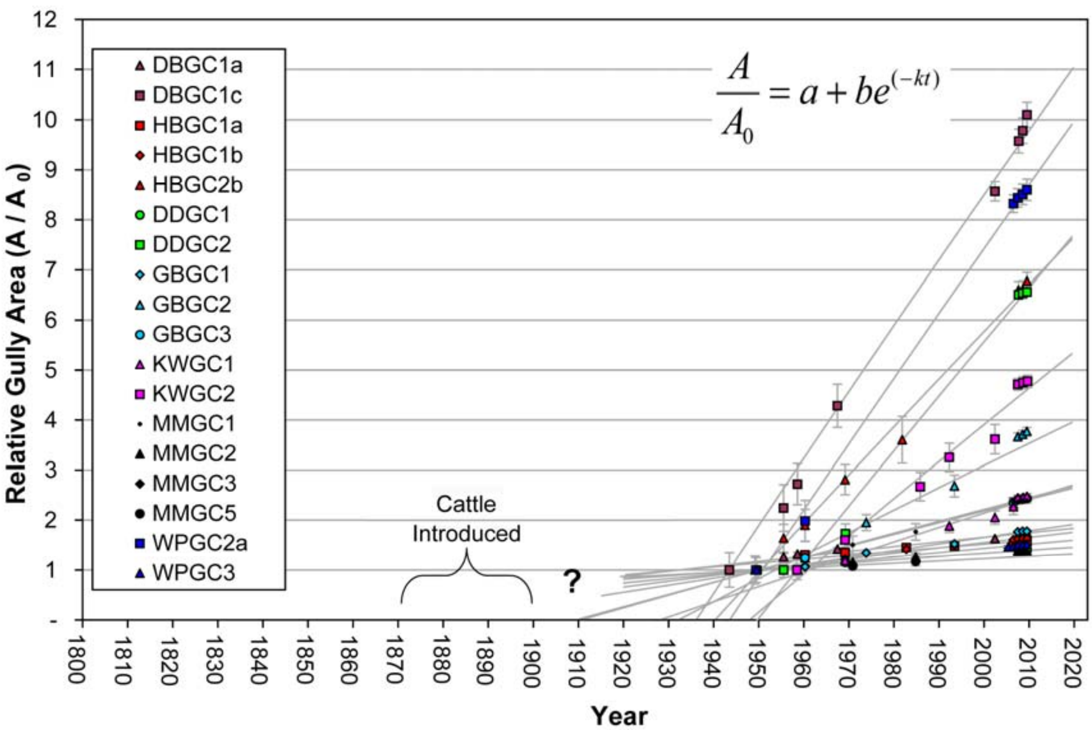


Figure 8 *Relative changes in gully area (A/A_0) over time at all 18 alluvial gully sites in the Mitchell catchment fitted with a negative exponential function (with near linear results).*

Initiation and acceleration by human land-use

Detailed reviews of the journals of historical explorers in the Mitchell (QLD)[19, 20] and Victoria (NT)[13] catchments indicate that severe gully erosion was not common nor widespread pre-European settlement, but that earlier forms of flood drainage channels[13] (FDCs), un-channelled floodplain hollows[19, 20], and old river paleo-channels did exist near the banks of floodplain rivers. Earlier phases of channel and gully network development into floodplain alluvium also exist in the Normanby catchment[5], but these features were largely rounded and quasi-stable upon the arrival of Europeans. These precursing drainage forms were often the locations where the current phase of extensive gully erosion initiated (Figure 9); however alluvial gullies have also initiated on steep river banks without associated drainage channels. The processes that created the *rounded* floodplain hollows and drainage channels were fundamentally different (slower surface erosion via local diffusion of soil) than the rapid expansion of *headcutting* alluvial gullies during historic times (faster channel incision leading to sediment advection and export).

a) *b)*

Figure 9 Examples of a) a small alluvial gully on a river bank eroding into b) an un-channelled floodplain hollow immediately upstream, that will eventually develop into a large alluvial gully similar to Figure 1.

In the Mitchell catchment, multiple lines of evidence indicate that the rapid historical rates (last 130 yrs) of alluvial gully expansion are unprecedented since the Pleistocene (>12,000 yrs). This assertion is supported by historical rates of expansion from air photos (Figure 8), young optically stimulated luminescence (OSL) dates of gully inset-floodplain deposits, LiDAR terrain analysis, historic explorer accounts of earlier drainage channel types, and archival records of cattle numbers and land management[19, 20]. Since the late 1880s, the introduction of hard-hoofed cattle and steady increases in herd sizes have fundamentally changed the way land is managed in northern Australia[7, 16, 19, 20]. From multiple lines of evidence, it is concluded 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, floodplain hollows and precursor channels[7,19,20]. This is a result of reduced native grass cover, increased physical disturbance of soils, and the concentration of runoff down cattle tracks over steep banks used to access water, which were possibly coupled with episodic drought, the invasion of exotic weed and grass species, fire regime modifications, and more recently road construction[4,7,13,19,20]. Or in other words, the natural factors mentioned above primed the floodplain landscape for erosion over long geologic time periods, but land-use change pushed the landscape across a threshold towards instability and triggered accelerated, widespread, and massive alluvial gully erosion (e.g., Figure 1).

The current management paradigm of grazing down grass cover to minimal levels in the late dry season near waterbodies (i.e., riparian zones), along with dense cattle pads cut into steep banks to access water and early wet season fire burning of remnant vegetation, results in exposed and disturbed erodible soils at the beginning of the tropical monsoon rains. Initiation and acceleration of alluvial gully erosion is the result. While native deep-rooted perennial grass is key to binding erodible soils together, dense networks of cattle pads (tracks) over steep banks to access water daily can overwhelm good vegetative cover by concentrating overland flow and initiating gullying (Figure 10a). Once the critical soil A-horizon is breached, exposing the dispersive and highly erodible sub-surface soils, there is little stopping the rapid development and propagation of alluvial gullies. A similar effect is caused by poorly located, constructed, and maintained roads (Figure 10b), which are rapidly becoming more common sediment sources as development advances across northern Australia.

a) b)

Figure 10 Examples of a) a cattle pad cut down a steep river bank that is rapidly being transformed into an alluvial gully, and b) an alluvial gully initiated by a poorly designed road crossing a river.

Sediment production from alluvial gullies

Alluvial gullies are highly concentrated, well connected, and major sources of sediment to river systems. Suspended sediment concentrations (SSCs) transported out of alluvial gullies in the Mitchell typically are > 10,000 mg/L and can exceed 100,000 mg/L from the largest gullies during peak runoff[20]. Similar concentrations have also been measured in Normanby gullies[5]. This is in contrast to SSCs measured in nearby river samples that are typically less than 1,000 mg/L, but with larger water volumes. The combination of highly erodible soils, rapid scarp retreat, intense tropical rainfall and runoff, and high sediment concentrations can lead to high local sediment yields (up to 80 to 350 t/ha/yr) [3,17,22], which are high by both Australian and world standards for soil and gully erosion[20].

Distributed measurements of scarp retreat rates, scarp heights and soil bulk densities along with remotely mapped distributions of alluvial gullies can be used to estimate sediment production from alluvial gullies at the catchment scale. 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[3,4,17,20], with slightly faster rates possible during the initial phases of disturbance[20]. These erosion rates are higher than sediment transport rates measured at downstream river gauges (<2 Mt/yr[17,20]), indicating that much of this eroded sediment is deposited locally or along long lengths of river channel. This is supported by observations of lagoon and channel infilling (Figure 11; Figure 12; Figure 13) and measured sedimentation rates exceeding 2 kg/m^2/yr on river inset-floodplains and benches.

Across northern Australia, sediment tracing research of fine suspended sediment suggests that sub-surface erosion sources (gully, bank, and deep rill erosion) dominate the overall sediment budget[5,6,24,25]. In the Mitchell at the catchment scale, alluvial gully sediment sources likely dominate the fine sediment budget[17], however bank erosion cannot be discounted[3] and other significant sources of sediment from mining, agriculture, and roads remain poorly quantified[17]. Sediment budget estimates for the Normanby catchment indicate that bank erosion from small alluvial channels and alluvial gullies together dominate the overall sediment budget, in contrast to sediment loads from hillslopes that are several orders of magnitude lower[5].

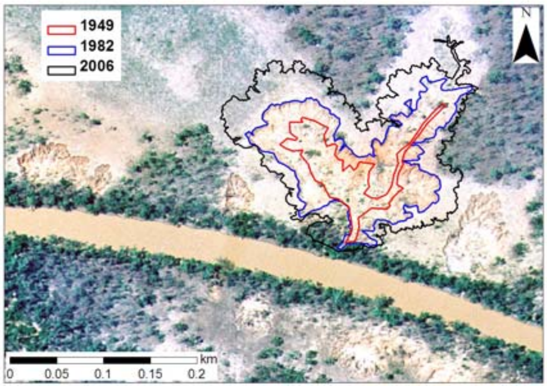
Impacts on riparian, aquatic, and cultural resources

Alluvial gully erosion can impact local terrestrial and riparian vegetation habitat and degrade cultural sites and human infrastructure (e.g., roads, yards, dams, buildings)[4]. The sediment pollution of local and downstream waterways can seriously degrade water quality (e.g., excess suspended sediment and nutrients), freshwater and marine aquatic habitat and ecology (e.g., habitat volume, fish production, coastal and reef ecosystems), and Indigenous cultural uses of the landscape (e.g., subsistence use of waterholes; degradation of ceremonial sites)[16]. Excess sediment impacts on aquatic ecosystems can be direct such as with fish gill abrasion and reduced clarity for visual feeding organisms, or indirect such as with smothered or infilled habitat and altered food productivity for fish or humans.

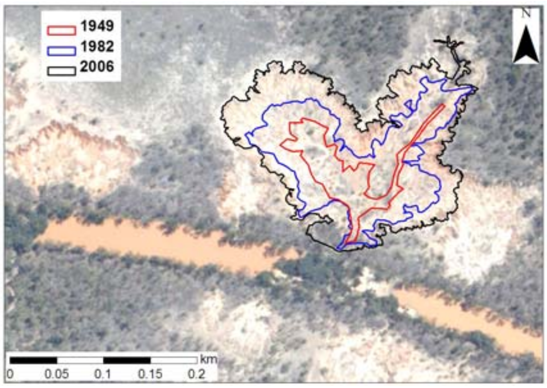
Since alluvial gully erosion is often concentrated along the riparian margins of major river channels and floodplain waterbodies (e.g., lagoons and billabongs)[4,7,13,16,20], the effective sediment delivery to water bodies is high and the local damage to eroded riparian vegetation and habitat can be enormous. For example, Figure 11 displays a sand slug from a cattle-impacted alluvial gully infilling a floodplain lagoon that is >20,000 years old. Over time as alluvial gullies continue to grow once initiated and consume local riparian zones, this type of sediment infilling can completely bisect local lagoons and reduce their habitat volume and connectivity with main river channels (Figure 12)[20]. If left unchecked, this type of erosion and sedimentation can completely infill ancient lagoons at accelerated rates, eliminating habitat for fish species such as barramundi or other native species[16] and reducing future water supplies for human needs.

Further downstream, sand slugs from thousands of cumulative alluvial gullies (and other mixed sediment sources) can result in the infilling of major river channels with sand[3,17]. This can reduce the in-stream pool habitat that aquatic species depend on, alter and reduce human fishing opportunities, and degrade riverine infrastructure and navigability (Figure 13). Meanwhile, the excess fine sediment (silt and clay) from alluvial gullies can wash into estuaries, coastal habitat, and off-shore reef environments, further degrading ecosystem processes there.

Figure 11 Example of a sand slug from an alluvial gully infilling a floodplain lagoon.



a) 1982 Photo



b) 2006 Photo

Figure 12 Changes in gully scarp location from a) 1982 to b) 2006 at a Mitchell floodplain lagoon with 1949 area for reference. Note how the floodplain lagoon has in-filled from sediment derived from the expanding alluvial gullies.

a)

b)

Figure 13 Changes in a) pool habitat and b) fishing opportunities as a result of river sedimentation.

Land management recommendations

There is now substantial evidence that the introduction of cattle into the tropical savannah landscapes of northern Australia has pushed the landscape across a stability threshold along many floodplain river systems, triggering a massive phase of alluvial gully erosion[5,7,13,15,19,20]. The mobilisation of millions of tonnes of sediment that would not otherwise have been eroded at current rates has elevated sediment loads in rivers and other water bodies with consequences that we are only just beginning to understand.

A paradigm shift in land management and cattle grazing practices is needed to ensure that no new gullies are initiated and to slow gully erosion rates where already initiated. Cattle should be managed more cautiously within riparian zones and along steep banks of river, creeks, and other water bodies across large areas of floodplain landscape. Complete cattle exclusion should be considered in the most erosion-prone floodplain areas to reduce new gully initiation and promote vegetation recovery. However in northern Australia, it is as yet uncertain the degree to which stock exclusion and passive vegetation regeneration will slow alluvial gullies once initiated, but success has been documented internationally[20].

Rehabilitation recommendations

Australian and international gully literature indicates that different *direct* intervention and *passive* rehabilitation actions using biological, chemical, and physical methods are available to rehabilitate gully erosion[20].

Direct Intervention: All too often, direct intervention in gully erosion follows an engineering paradigm that uses “technological fixes” to overcome and control natural processes, rather than working with natural processes to address the causes of erosion instead of the symptoms. The failure of many gully rehabilitation projects is common[20] due to naive attempts to fully engineer nature, lack of initial rigorous experimentation, poor design and implementation, and lack of adaptive management or maintenance. For the simpler form of colluvial/hillslope gullies in southern Australia, experience with trying to engineer stability in gullies over the past five decades has proved to have mixed results at best[20]. For the more complicated alluvial gully situation, it is unlikely that direct intervention to slow or halt erosion will be a viable option physically or economically across large areas of riverine landscapes.

Direct intervention will only be viable in the more strategic or important cases (i.e., buildings, yards, roads, dams, key waterholes, biodiversity hotspots, cultural sites). Examples of direct intervention include creating berms above gully heads to frequently divert excess water runoff to safe disposal locations, installing drop and grade control structures, filling and slope battering, adding gypsum to sodic soils, adding organic material, and revegetating with native and exotic grass species, often in combination for best results. For these applications, trial *direct* intervention programs with detailed scientific monitoring are needed across northern Australia to identify the most process-effective, cost-effective, and practical methods to stabilise alluvial gullies using a suite of biological, chemical, and physical tools. This is partially underway in the Normanby catchment using both direct and passive approaches.

Passive Rehabilitation: Due to the widespread extent of alluvial gully erosion across northern Australia, passive rehabilitation programs along river corridors are likely the most practical and cost-effective in reducing gully erosion and elevated sediment yields. Natural vegetation is often resilient following disturbances, and natural regeneration is often the result of managing or removing chronic disturbance agents such as cattle that cause or trigger erosion. Better management of cattle through fencing and excluding cattle from riparian zones, steep banks, and local floodplain catchment areas around alluvial gullies can reduce chronic soil disturbance and cattle pad density and increase vegetative cover, which can protect soils from rainfall and reduce excess water runoff[21]. However, caution is needed when locating fences (preferably on the flat high floodplain) and in constructing and maintaining them to minimize the initiation of rill and gully erosion.

In northern Australia, eucalyptus and acacia trees and native and exotic grasses can readily and progressively recolonise alluvial gully floors once eroded[20]. Exotic weed species can also invade these disturbed riparian habitats, and need to be controlled at the local and catchment scales if native species are to be encouraged for improved soil protection. Regardless, revegetation roughness can promote bed aggradation and gully stabilisation. However, revegetating harsh, nutrient poor, sodic sub-soils will be problematic unless organic matter and soil development is allowed to cumulatively and progressively improve over time. Alternatively, specific grass and tree species are better adapted to growing in harsh sodic soils, which could be utilised and spread more proactively along gullied river corridors to stabilise gully slopes. Proactive vegetation seeding and planting of appropriate species in gullied catchments has proven to be an effective management approach to stabilising large areas of alluvial and colluvial gullies around the world (i.e., India, China, Africa, New Zealand, USA, and to a less extent Australia[20]).

In northern Australia, a high priority should be the initiation of several large-scale trials of complete stock exclusion from intensively gullied lands, to test passive and proactive revegetation techniques and monitor over the long-term (10+ years) the potential reductions in erosion rates and yield from a more passive management approach. Along with direct intervention trials at more localised sites, passive and direct intervention outcomes need to be synthesised into best management practices (BMP) guidelines for alluvial gullies that can be utilised by the regional pastoral community and natural resource management groups for rehabilitation and soil conservation actions.

Further reading

1) Brooks, A.P., Knight, J.M. and Spencer, J., 2006. *A Remote Sensing Approach for Mapping and Classifying Riparian Gully Erosion in Tropical Australia*. Milestone Report 1 to Land Water Australia for project GRU 37, Australian Rivers Institute, Griffith University, Nathan, Qld, Australia.

2) Brooks, A., Spencer, J. and Knight, J., 2007. Alluvial gully erosion in Australia's tropical rivers: a conceptual model as a basis for a remote sensing mapping procedure. In: A.L. Wilson et al. (Editors), *Proceedings of the 5th Australian Stream Management Conference*, pp. 43-48. http://www.csu.edu.au/research/ilws/news/events/5asm/docs/proceedings/Brooks_Andrew_43.pdf

3) Brooks, A.P., Spencer, J., Shellberg, J.G., Knight, J. and Lymburner, L., 2008. Using remote sensing to quantify sediment budget components in a large tropical river - Mitchell River, Gulf of Carpentaria. *Sediment Dynamics in Changing Environments* (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). IAHS Publication, pp. 225-236. http://www.mitchell-river.com.au/news-and-issues/SedimentBudgets_RemoteSensing_IAHS_2008_Brooks_et_al_Final_Published.pdf

4) 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, + 2010. Erratum. *Earth Surface Processes and Landforms*, 35: 242–245.

5) Brooks, A., Spencer, J., Olley, J., Pietsch, T., Borombovits, D., Curwen, G., Shellberg, J., Howley, C., Gleeson, A., Simon, A., Bankhead, N., Klimetz, D., Eslami-Endargoli, L. and Bourgeault, A., 2013. *Sediment sources, sinks and drivers in the Normanby catchment, Cape York.*, Griffith University, Australian Rivers Institute, Draft Final Report for Australian Government Reef Rescue Program, October 2012.

6) Caitcheon, G.C., Olley, J.M., Pantus, F., Hancock, G. and Leslie, C., 2012. The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers. *Geomorphology*, 151-152: 188-195.

7) Condon, R.W., 1986. *A Reconnaissance Erosion Survey of Part of the Victoria River District, N.T.*, Hassall & Associates, Canberra.

8) Crouch, R.J., 1990. Rates and mechanisms of discontinuous gully erosion in a red brown earth catchment, New South Wales, Australia. *Earth Surface Processes and Landforms*, 15(3): 277-282.

9) Erskine, W.D. and Melville, M.D., 1984. Sediment movement in a discontinuous gully system at Boro Creek, Southern Tablelands, N.S.W. In: R.J. Loughran (Editor), *Drainage Basin Erosion and Sedimentation: A Conference on Erosion, Transportation and Sedimentation in Australian Drainage Basins*. University of Newcastle and the Soil Conservation Service of N.S.W., pp. 197-204.

10) Galloway, R.W., Gunn, R.H. and Story, R., 1970. *Lands of the Mitchell-Normanby Area, Queensland*. CSIRO, Land Research Series 26: 1-101.

11) Hancock, G.R. and Evans, K.G., 2006. Gully position, characteristics and geomorphic thresholds in an undisturbed catchment in Northern Australia. *Hydrological Processes*, 20: 2935-2951.

12) Knight, J., Spencer, J., Brooks, A. and Phinn, S., 2007. Large-area, high-resolution remote sensing based mapping of alluvial gully erosion in Australia's tropical rivers. In: A.L. Wilson et al. (Editors), *Proceedings of the 5th Australian Stream Management Conference*, pp. 199-204. http://www.csu.edu.au/research/ilws/news/events/5asm/docs/proceedings/Knight_Jon_199.pdf

13) McCloskey, G.L., 2010. *Riparian Erosion Morphology, Processes and Causes along the Victoria River, Northern Territory, Australia*. Charles Darwin University, PhD Thesis, pp. 200.

14) Medcalff, F.G., 1944. *Soil erosion reconnaissance of the Ord River valley and watershed*. Report to the Department of Lands and Surveys, Western Australia.

15) Payne, A.L., Kubicki, A., Wilcox, D.G. and Short, L.C., 1979. *A Report on the Erosion and Range Condition in the West Kimberley Area of Western Australia*, Department of Agriculture of Western Australia, Technical Bulletin No. 42., pp. 52.

16) Pusey, B. (Editor), 2011, *Aquatic Biodiversity in Northern Australia: Patterns, Threats and Future*. Charles Darwin University Press, Darwin, N.T., Australia, pp. 5-22.

17) Rustomji, P., Shellberg, J., Brooks, A., Spencer, J. and Caitcheon, G. 2010. *A Catchment Sediment and Nutrient Budget for The Mitchell River, Queensland*. A report to the Tropical Rivers and

Coastal Knowledge (TRaCK) Research Program. CSIRO Water for a Healthy Country National Research Flagship. 119 pp. http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-Mitchell-River-sediment-nutrient-budget.pdf

18) Sattar, F., 2011. *Geoinformatics Based Framework for Three Dimensional Gully Mapping and Erosion Volume Calculation*. PhD Dissertation, School of Environment and Life Sciences, Charles Darwin University, Australia, 191 pp.

19) Shellberg, J., Brooks, A. and Spencer, J., 2010. Land-use change from indigenous management to cattle grazing initiates the gullying of alluvial soils in northern Australia. *Soil Solutions for a Changing World, 19th World Congress of Soil Science*, 1 - 6 August 2010. Brisbane, Australia, pp. 59-62. http://www.mitchell-river.com.au/news-and-issues/MitchellCattleAnd%20ErosionShellberg.pdf

20) Shellberg, J.G. 2011. *Alluvial Gully Erosion Rates and Processes Across the Mitchell River Fluvial Megafan in Northern Queensland, Australia*. Griffith University, PhD Thesis, Brisbane, Australia, November 2011, 283pp.

21) Shellberg, J.G., Brooks, A.P., Spencer, J. and Ward, D., 2013a. The hydrogeomorphic influences on alluvial gully erosion along the Mitchell River fluvial megafan, northern Australia. *Hydrological Processes*. DOI: 10.1002/hyp.9240.

22) Shellberg, J.G., Brooks, A.P. and Rose, C.W., 2013b. Sediment production and yield from an alluvial gully in northern Queensland, Australia. *Earth Surface Processes and Landforms*, DOI: 10.1002/esp.3414.

23) Skinner, A.F., Gillies, C.C. and Milton, L.E., 1972. *An Erosion Survey of the Upper Nogoa River Catchment*. Division of Land Utilisation, Queensland Department of Primary Industries, Technical Bulletin No. 6, 23 pp.

24) Wasson, R.J., Furlonger, L., Parry, D., Pietsch, T., Valentine, E. and Williams , D., 2010. Sediment sources and channel dynamics, Daly River, Northern Australia. *Geomorphology*, 114: 161-174.

25) Wilkinson, S.N., Hancock, G.J., Bartley, R., Hawdon, A.A. and Keen, R.J., 2013. Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia. *Agriculture, Ecosystems and Environment*. DOI: 10.1016/j.agee.2012.02.002.