

Special Issue

Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia

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ABSTRACT: Considerable attention has been focused on the role of gullies as a contributor to contemporary sediment loads of rivers in Australia. In southern Australia rapid acceleration of hillslope gully erosion has been widely documented in the post-European period (~ last 200 years). In the northern Australian tropics, however, gully erosion processes operating along alluvial plains have not been well documented and can differ substantially from those gullies eroding into colluvium on hillslopes. Aerial reconnaissance surveys in 2004 along 13 500 km of the main stem rivers that drain into the Gulf of Carpentaria (GoC), identified extensive areas of alluvial lands that have been impacted by a pervasive form of gully erosion. More detailed remote sensing based mapping within the 31 000 km² Mitchell River fluvial megafan has identified that active gullying into alluvium occupies ~ 0.4% (129 km²) of the lower Mitchell catchment. These alluvial gullies are concentrated along main drainage channels and their scarp heights are highly correlated to the local relief between the floodplain and river thalweg. While river incision into the megafan since the Pleistocene has developed the relief potential for erosion, other factors such as floodplain hydrology, soil dispersibility, and vegetation also influence the distribution of gullies. In this paper we present a conceptual model of alluvial gullies, and contend that they represent a distinct end member in the continuum of gully forms that have been described in the geomorphic literature. An understanding of the processes driving this form of alluvial gullying can only be gained when they are differentiated from widely described colluvial hillslope gully models and theories. We present evidence of type examples of alluvial gullying in the Mitchell, and through analysis of their distribution and morphology at different scales, highlight some of the key mechanisms that are potentially initiating these features and driving their expansion. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: alluvial gully erosion; fluvial megafan; relative relief; sediment budget; remote sensing

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, bio-

diversity 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 had an impact on 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 sub-

surface 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 gully erosion 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 paper 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 paper to present evidence to address this question; this will be addressed by upcoming research. As a more preliminary step, we describe alluvial gully forms and landscape positions, and develop a conceptual model of the evolution of these landforms to provide insights into the processes initiating and perpetuating the gullying, including human land use.

Hillslope and colluvial gullies

Gully erosion has been described in a large variety of landscapes throughout the world (e.g. Poesen *et al.*, 2003; Valentín *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).

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, we present a definition of an alluvial gully, and present 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 km²) 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 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 waterbodies such as lagoons or lakes (e.g. Figure 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 1).

By definition, alluvial gullies erode drainage networks into some form of alluvium, which is a time varying storage com-

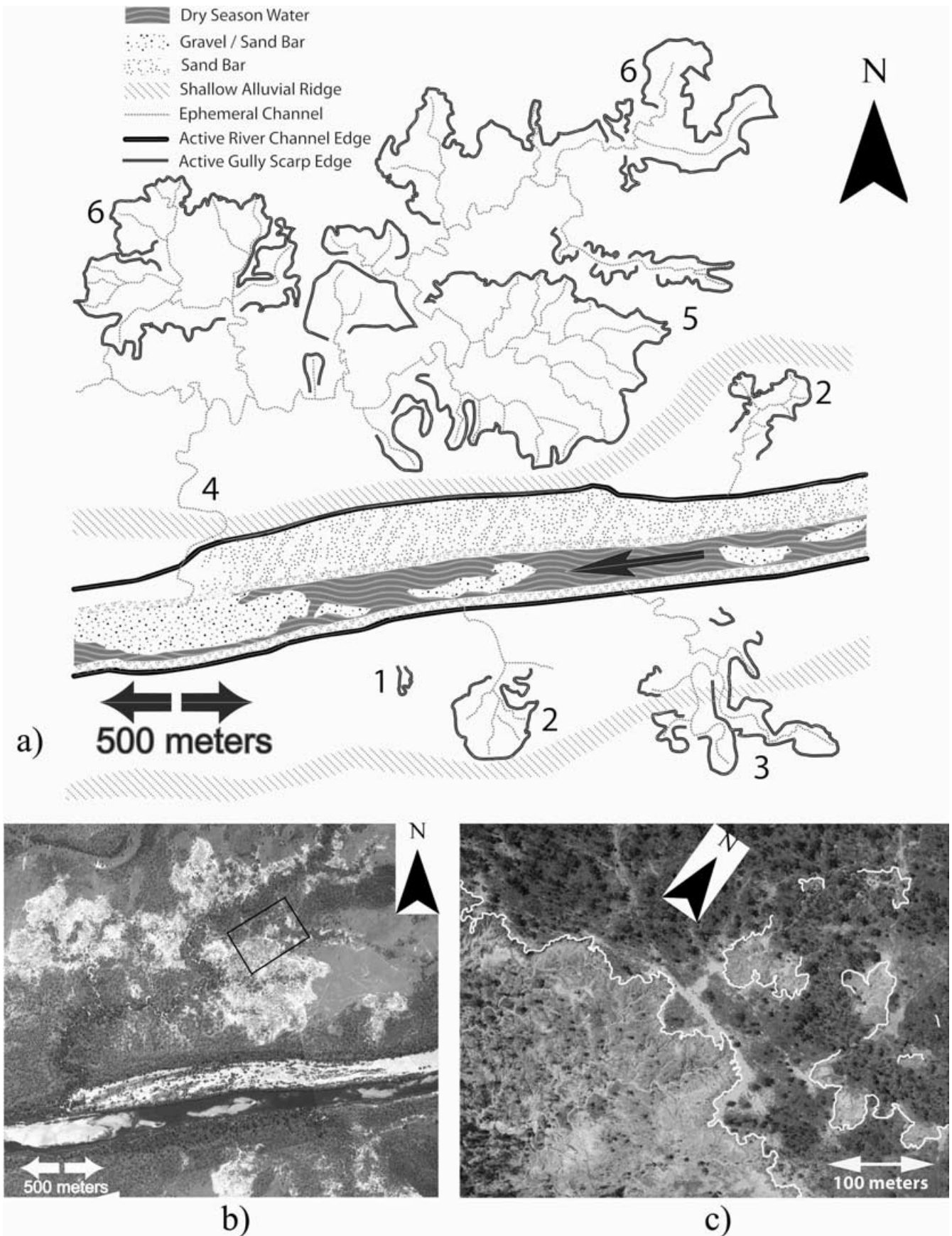


Figure 1. Histogram of gully pixel frequency from ASTER delineation in relation to pixel elevation determined from the 30 m SRTM DEM.

ponent 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 we outline the landscape context of the study area where we have described a type example of alluvial gullies and have mapped the extent of active gullies in a large savanna catchment.

Landscape Setting

Monsoonal climate and hydrology

The study area is located in the Mitchell River catchment (71 630 km²) 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 km² (Figures 2a and 3). The Mitchell River catchment has one of the highest mean annual discharge volumes in Australia (>8 000 000 ML/y, excluding

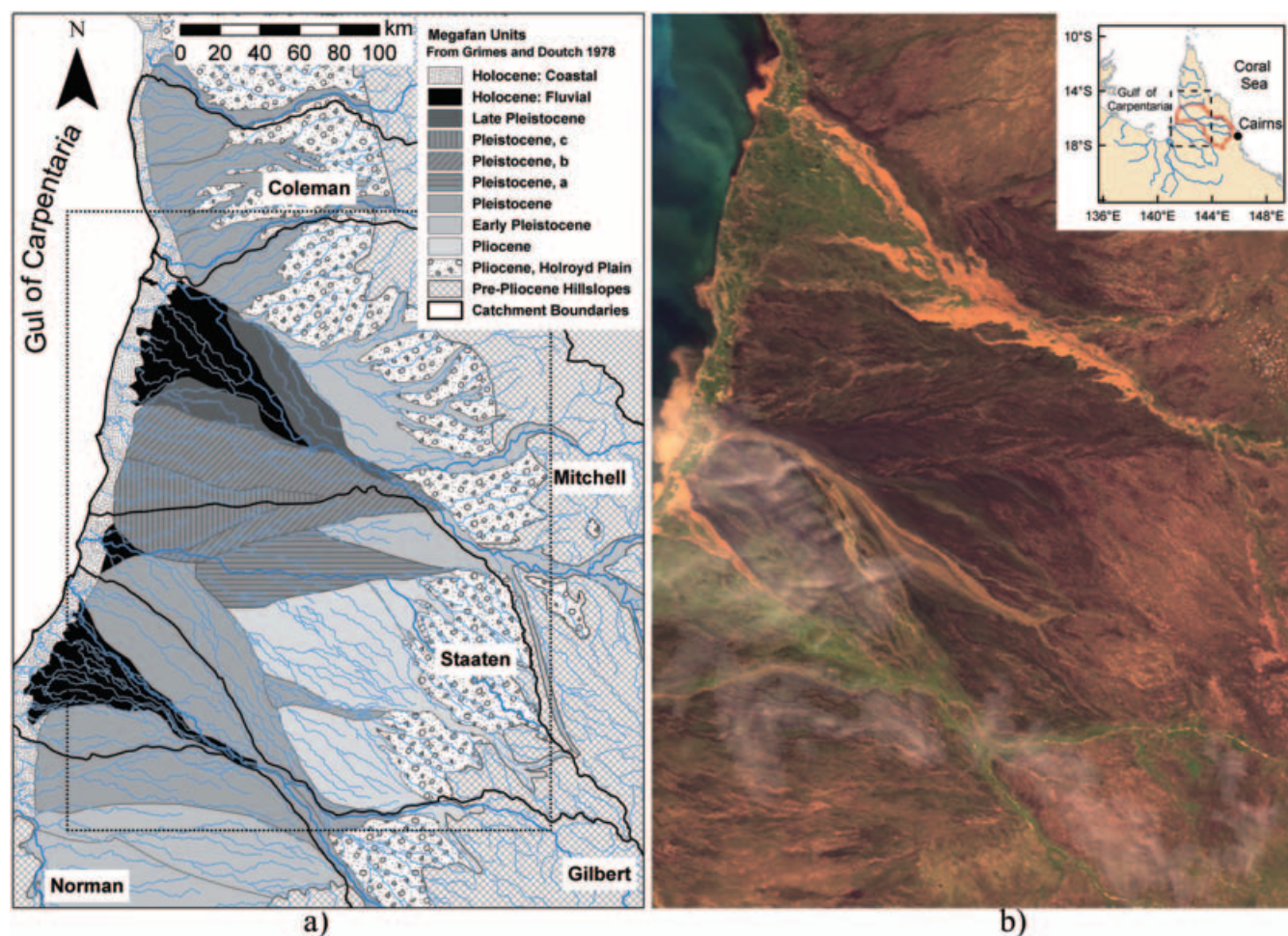


Figure 2. Longitudinal profile of the Mitchell River thalweg and adjacent megafan surface (floodplain or terrace). Locations of the key tributary confluences are noted as distances upstream (km) as are current and past fluvial megafan apexes.

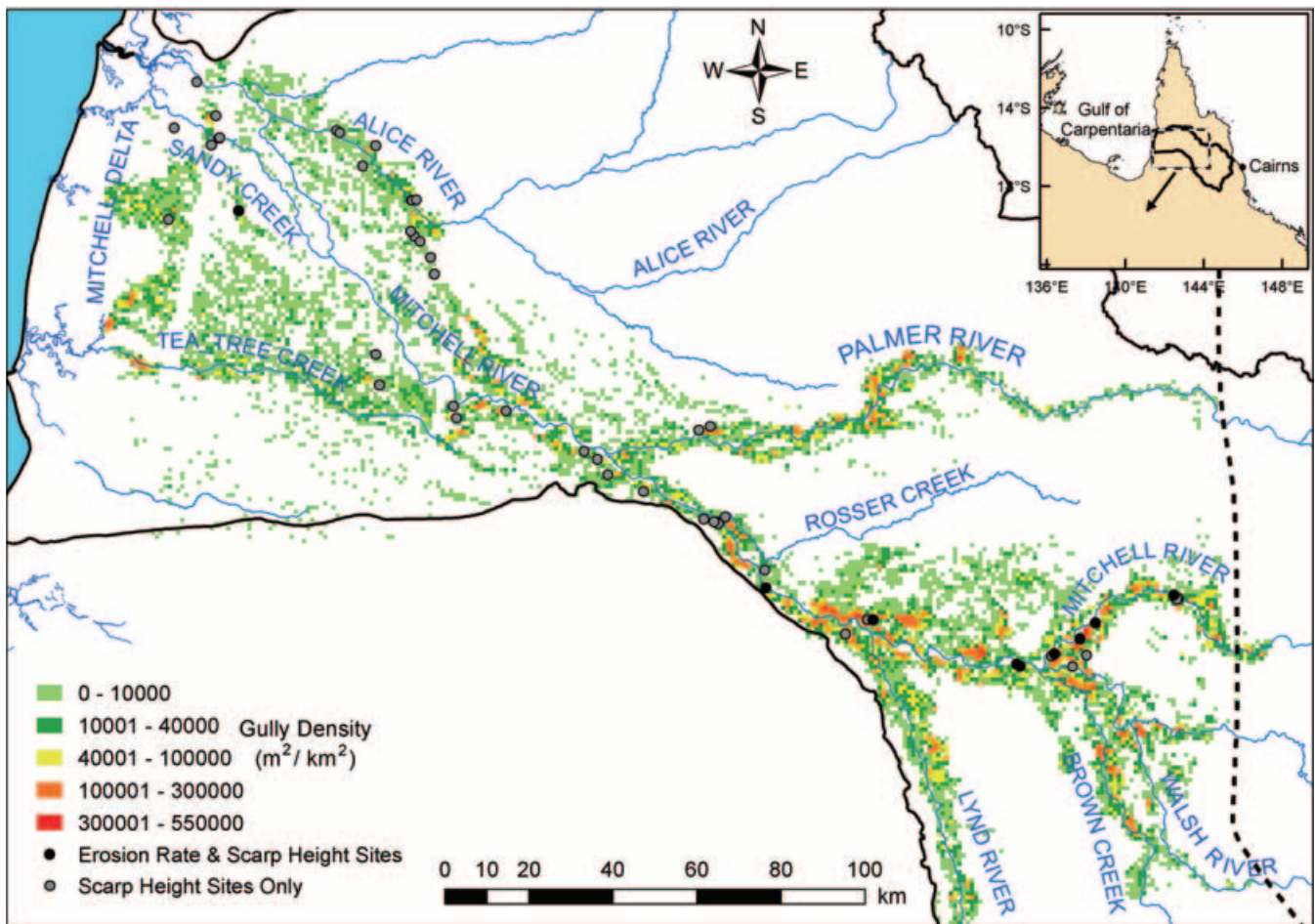


Figure 3. Relationship between measured gully head scarp height (SH) and adjacent floodplain surface elevation (E) as derived from the 30 m SRTM DEM.

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.

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 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 km². The Mitchell fluvial megafan was originally described in detail by Grimes and Douth (1978), who defined and delineated distinct fan

units from the Pliocene to Holocene (Figure 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.

Megafan morphology

The morphological apex of the entire megafan is located near the confluence of the Lynd and Mitchell Rivers (Figures 2a and 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 km²) 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 macrochannels (*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 its 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 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).

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).

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 hill-slope 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.

Methods

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.

Gully position in relation to megafan geology and soils

Mapped gully areas were additionally compared to mapped megafan geologic units (Grimes and Douth, 1978) and soil units (BRS, 1991). The frequency of mapped gully pixels (i.e. 15 m² pixels from the ASTER based mapping) in these units were analysed to gain insight into the units that were most sensitive to gully erosion.

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 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.

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.

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.

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 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.

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 I and Figure 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 I).

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 12). The same observations, coupled with survey data, indicate that due to the high rates of head scarp retreat (Table I, Figure 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).

Table I. Surveyed lengths and erosion rates at alluvial gully head scarps sites

Years	Site ID	Survey length (m)	Maximum retreat (m/y)	Mean retreat (m/y)
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		25485		
Median (50)			5.51	0.34
25th Percentile			2.91	0.15
75th Percentile			8.10	0.49

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 (rain-splash, 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.

Results

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 km².

After the initial validation exercise, roads (false positives) across the entire megafan were manually removed from the dataset, representing a 28 km² 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 km² gully density grids for final distribution map displayed in Figure 3. In total, the analysis identified 129 km² of active alluvial gullies within the Mitchell megafan (31 000 km²), 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.

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 Douth (1978) (Figure 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 Douth, 1978; Figure 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).

Gully pixel proximity to main channels

The proximity of gullies and mapped gully pixels to main channels is evident in the 1 km² density grid in Figure 3, where the largest concentrations of gullies parallels main channels. This relationship is quantified in Figure 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 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 airphotograph interpretation indicates that all gullies are associated with drainage channels of variable size.

Elevation at gullies pixels

The distribution of gully pixel elevations across the Mitchell megafan is complex, but generally follows a bimodal distribution (Figure 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.

Gully position in relation to megafan relief

From the spatial distribution of gullies (Figure 3), the elevational distribution of gullies along the Mitchell River longitudinal profile (Figure 5) and the evolution of megafan units (Figure 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

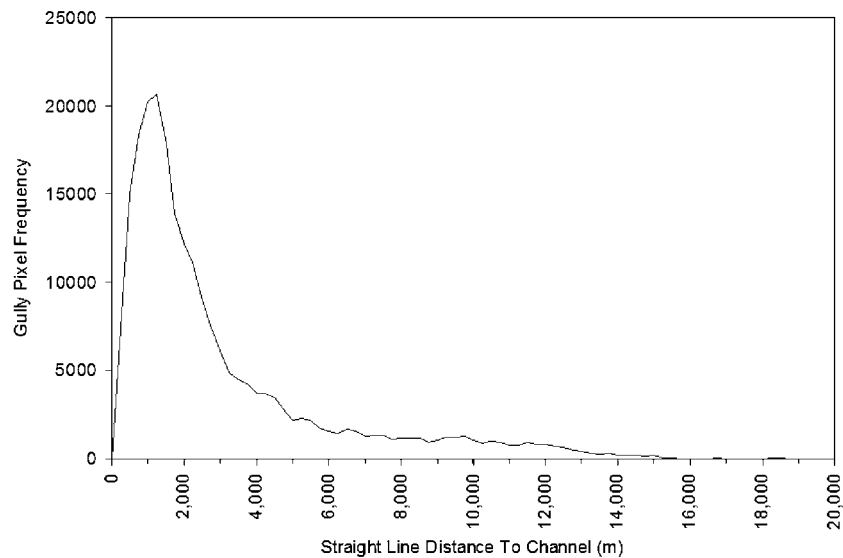


Figure 4. Longitudinal profiles of alluvial gully thalwegs between a main channel and adjacent floodplain. S = gully channel or floodplain slope. SH = scarp height.

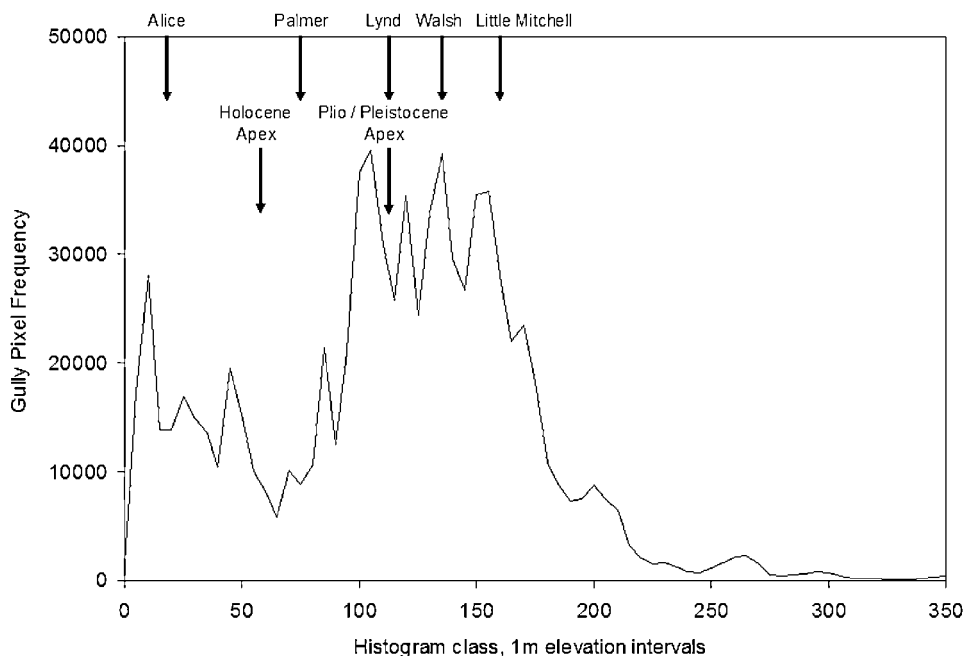


Figure 5. Gully pixel frequency from ASTER delineation in relation to pixel elevation determined from the 30 m SRTM DEM. Pixel elevation is closely correlated with distance from mouth, and hence this figure can be viewed as a type of longitudinal profile.

their difference in relative relief (Figure 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 (Figures 2a and 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 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 gully between 10 and 50 m elevation (Figure 5).

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 predictable pattern with floodplain elevation (Figure 7), and mimics the pattern of relative relief between the river channel and floodplain (Figure 6). Floodplain elevation (E_f) 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 7).

$$SH = 0.0004E_f^2 - 0.0509E_f + 1.8373 \quad (1)$$

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

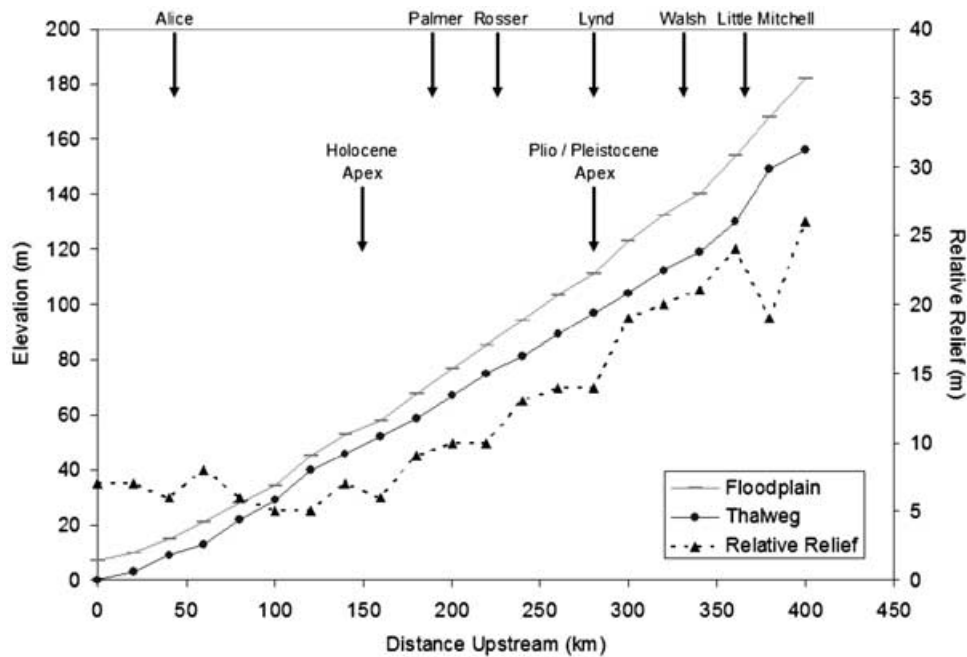


Figure 6. Longitudinal profile of the Mitchell River thalweg and adjacent megafan surface (floodplain or terrace). Upstream river tributary distances (in kilometres) are noted, as are current and past fluvial megafan apices.

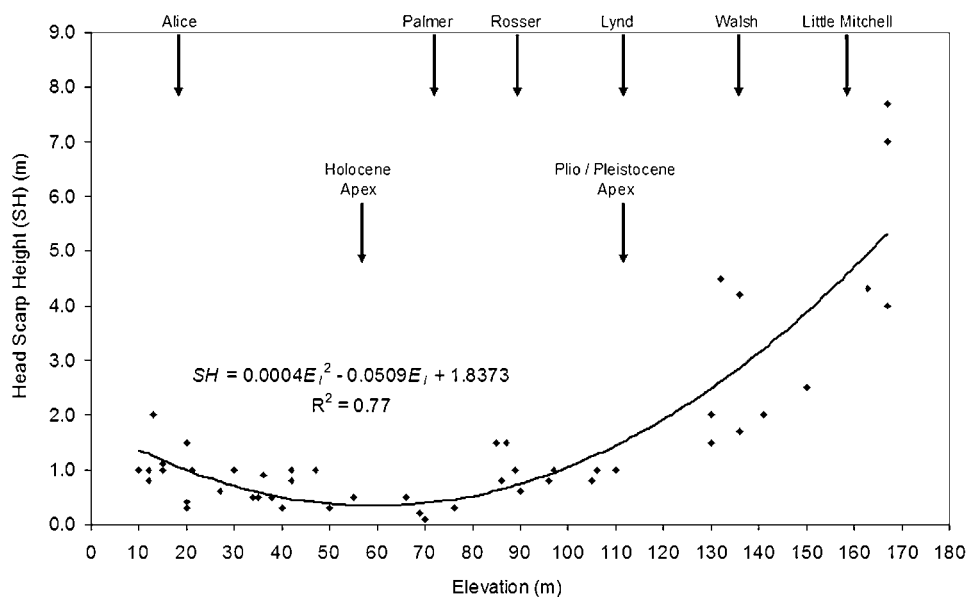


Figure 7. Relationship between measured gully head scarp height and adjacent floodplain elevation derived from the 30 m SRTM DEM.

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.

Longitudinal gully profiles

Examples of longitudinal profiles of gully channel thalwegs measured using LiDAR are displayed in Figure 8. These profiles of gully tributaries are distributed down the greater longitudinal profile of the Mitchell (Figure 6). The correlation between gully scarp height (SH) and floodplain elevations (E_i) is evident from these profiles (Figure 8), similar to Figure 7. The thalweg bed slopes of gully outlet channels also appear to decrease downstream (Figure 8). However, the true nature of the relationship between gully channel slope and landscape positions is likely influenced by individual channel slope dis-

tances 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 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.

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 I). Specific lobes displayed the greatest amount of retreat activ-

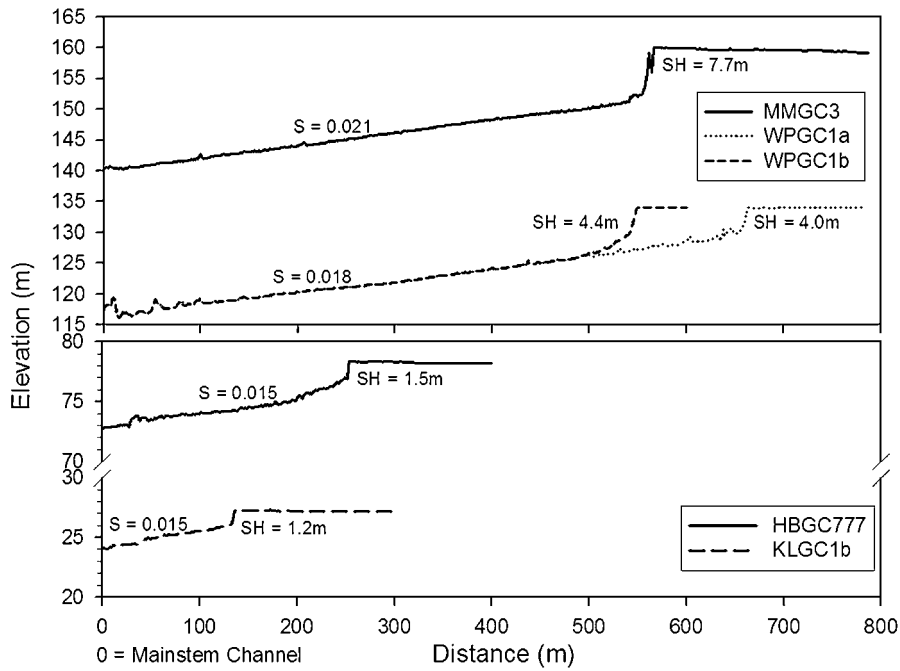


Figure 8. Longitudinal profiles of alluvial gully thalwegs between a main channel and adjacent floodplain. *S* = gully channel or floodplain slope. *SH* = scarp height.

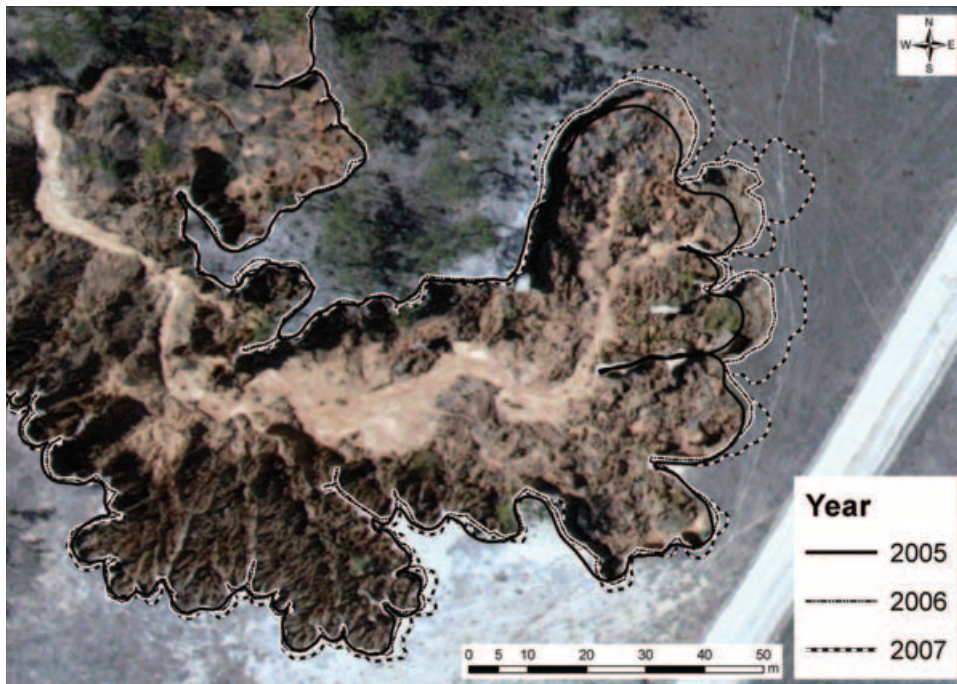


Figure 9. Annual gully scarp position between 2005 and 2007 at WPGC3. Note: cross over of some lines in inactive gully sections is due to measurement error, which is a combined function of limitations in the resolution of the Omnistar HP differential GPS survey technique, and the retracing of the survey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

ity, while a majority of the scarp length experiences less activity (Figure 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 I), 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.

Discussion

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.

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 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 interfluvies. The gully head is often indistinct, grading relatively gradually into the adjacent floodplain (e.g. Figure 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 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 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.

Further insight into the hydrologic processes driving alluvial gully erosion 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 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.

Hydrologic mechanisms for erosion

Largely depending on the gully position in the alluvial landscape and its connectivity with main channel hydrology

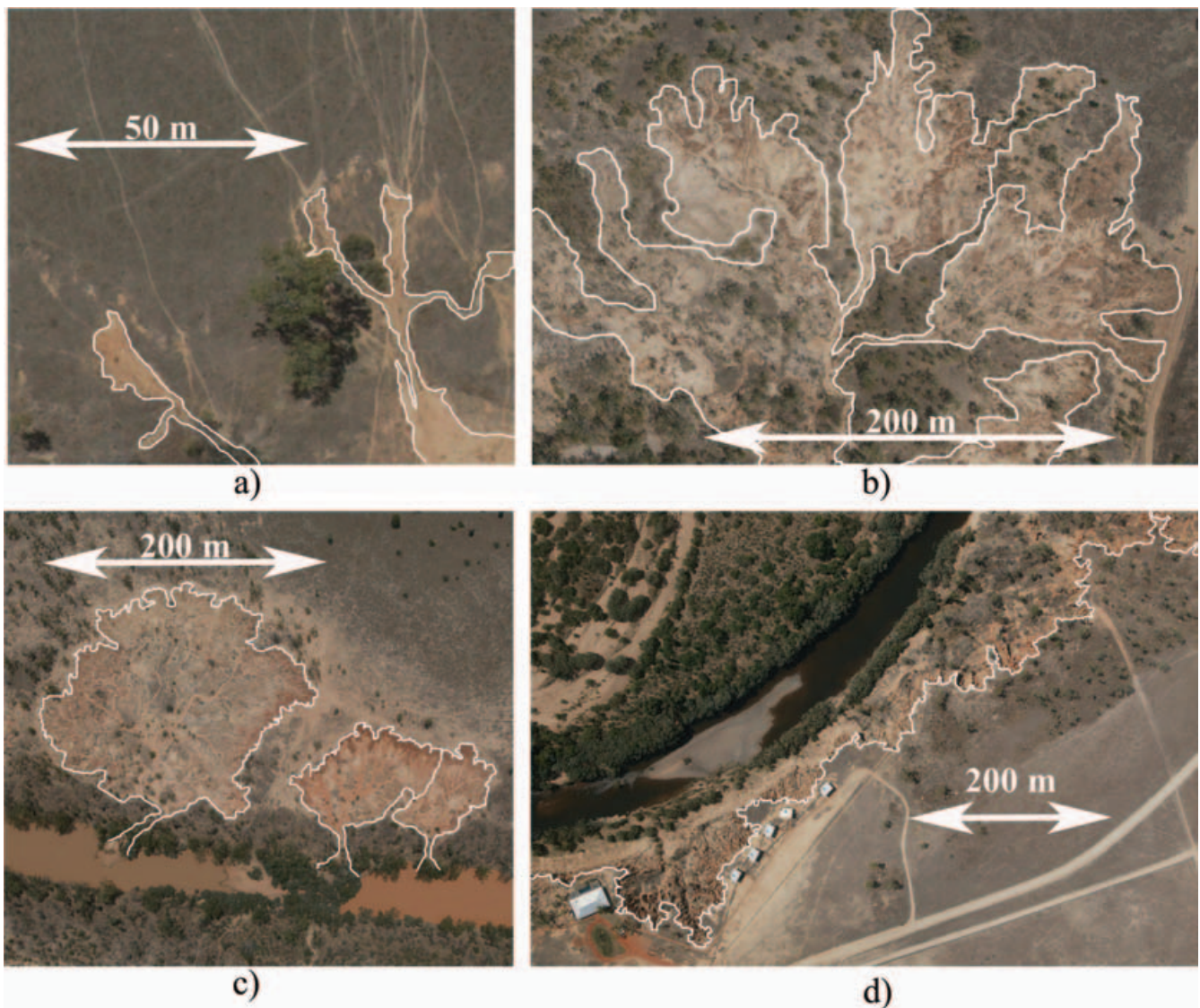


Figure 10. Examples of different planform morphologies of alluvial gullies: (a) linear; (b) dendritic; (c) amphitheatre; (d) continuous scarp front.

(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 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 11a). Sites with these

erosion mechanisms appear to have the highest erosion rates at active lobes (e.g. Figure 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 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 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



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

per decensum (Goudie, 1973; McFarlane 1991; Pain and Ollier, 1992).

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 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.

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 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 (M. Kirkby, personal communication, and this issue). 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 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.



Figure 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.

Conceptual model of alluvial gully

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 allu-

vial 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 13. While these two locations are quite different in terms of river connectivity, relative relief, and scarp height (Figures 13, 6, 7 and 8), they generally have similar stages of gully development. It is hypothesized that small incipient gullies on channel banks (1a in Figure 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

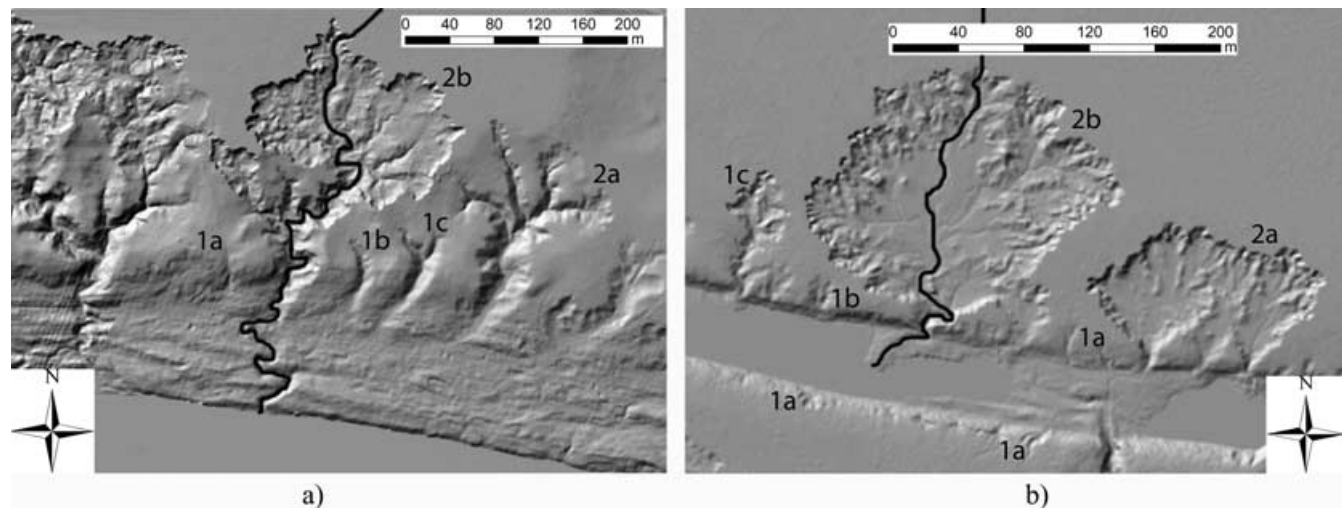


Figure 13. LiDAR DEM hillshades of alluvial gullies at different stages of evolution. (a) The Mitchell River at an upstream distance of 370 km (Figure 6) and floodplain elevation of 160 m (Figure 7). Note the longitudinal profile (MMGC3) in Figure 8 from the same area (black line). (b) A lagoon and palaeo-channel of the Mitchell River at an upstream distance of 210 km (Figure 6) and floodplain elevation of 85 m (Figure 7). Note the longitudinal profile (HBGC777) in Figure 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.

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 13, 1a) can develop further as they incise into alluvial banks and cut back into adjacent flat floodplains (Figure 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 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 13(a) 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 13). From field observations of these different gully stages (e.g. Figures 9, 11 and 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 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 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 1).

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 are imminent. 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. The second focuses on time and rates of gully erosion, in order to better understand the temporal evolution and genetic con-

nection of different gully types hypothesized in the discussion. 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 13). That is, the long-term evolution of the Mitchell megafan created the template for gully erosion potential, while shorter-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.

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 gully erosion 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. Furthermore, if realistic sediment budget models are to be developed for the catchments in the Australian tropical savanna, it is crucial that alluvial gully erosion be treated as a separate sediment source to colluvial gully erosion. The contrast between the two types of gully erosion is exemplified by the fact that alluvial gully erosion is located in parts of the catchment that are generally considered to be sediment sinks (i.e. floodplains).

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Erratum

ESPL

Earth Surface Processes and Landforms

Alluvial gully erosion: an example from the Mitchell fluvial megafan, Queensland, Australia

A.P. Brooks,* J.G. Shellberg, J. Knight and J. Spencer. *Earth Surface Processes and Landforms* **34**: 1951–1969. DOI: 10.1002/esp.1883

The publishers regret that due to a technical fault during production the figure captions were assigned to the incorrect figures in the published version of this article. This erratum corrects both the online and print versions of the article. Higher resolution versions of the figures, with their correct captions, are reproduced below.

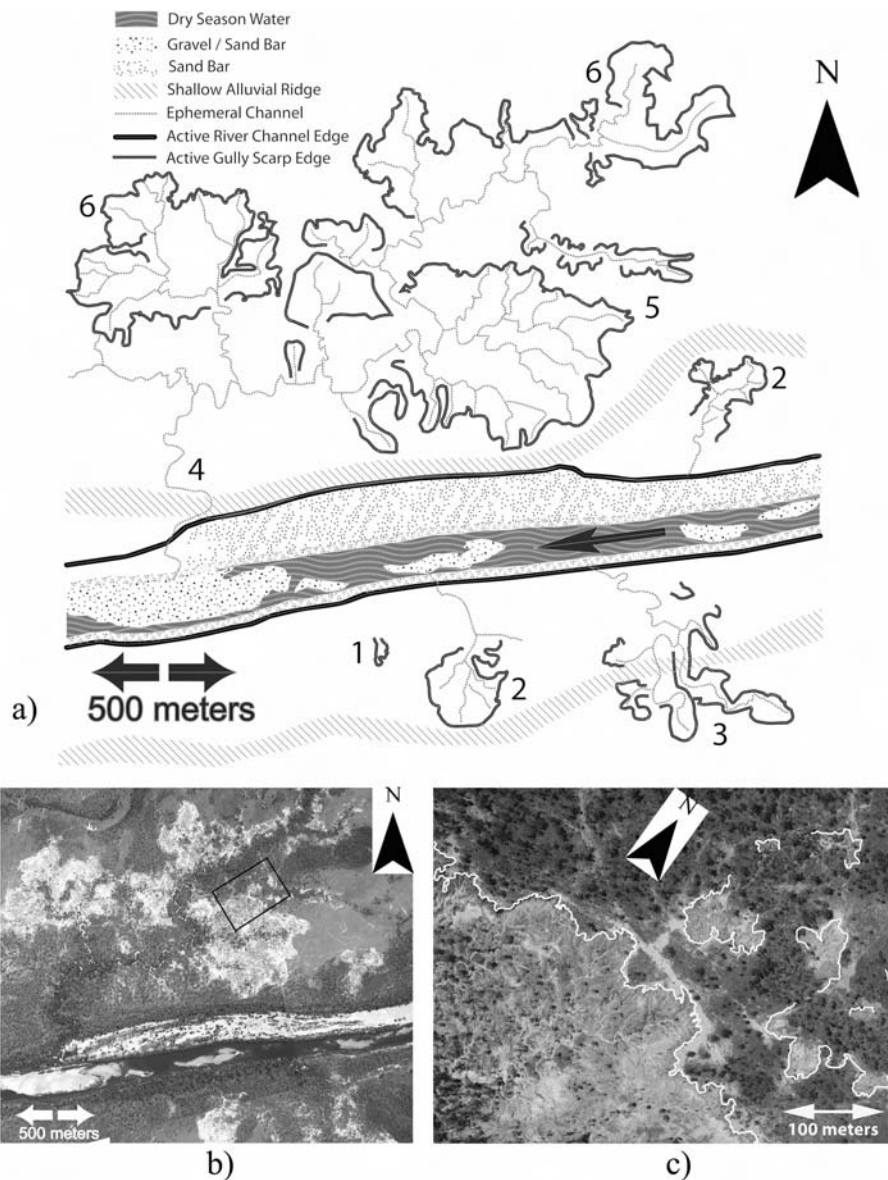


Figure 1. (a) Schematic of numerous alluvial gully complexes draining both proximal and distal portions of the Mitchell River floodplain near the Lynd River, (b) aerial photograph of the same area as (a) showing the white, bare portions of active alluvial gullies, (c) inset aerial photograph from (b). 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.

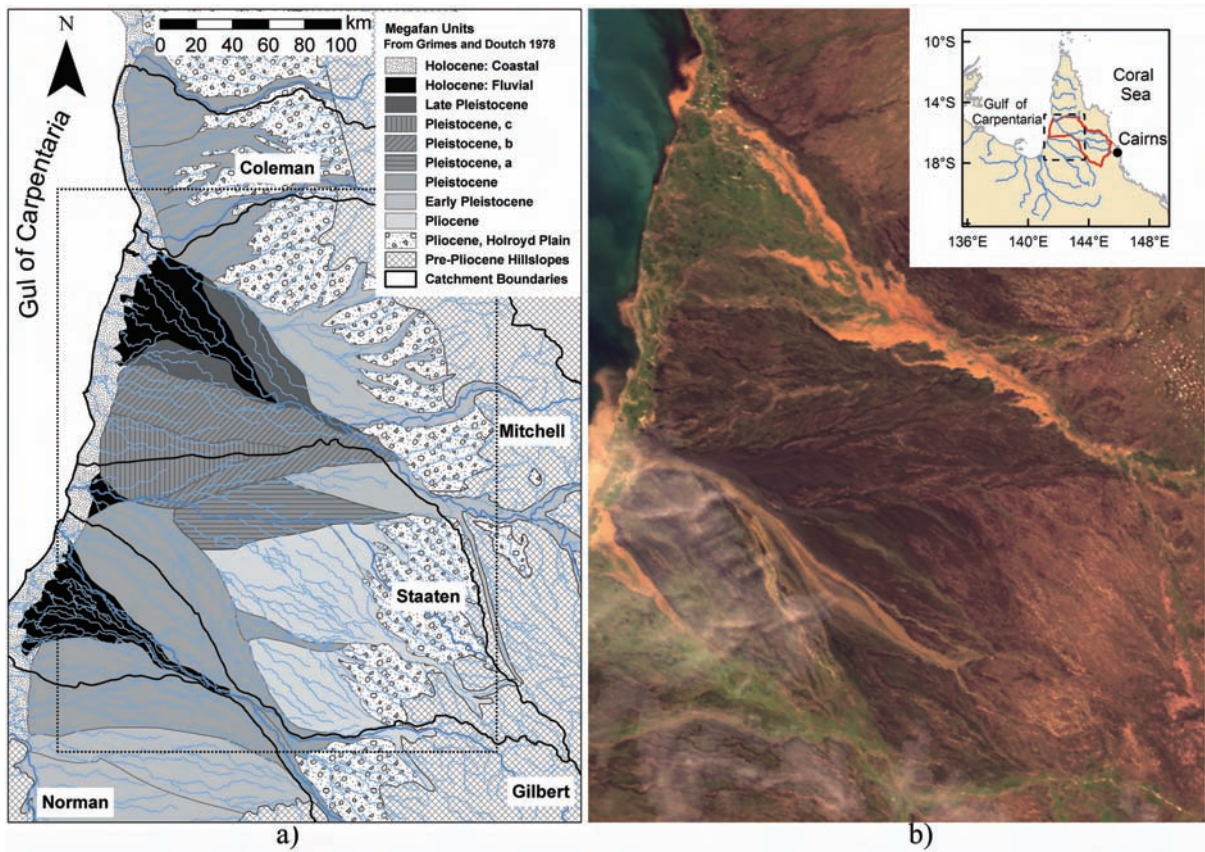


Figure 2. (a) Location and evolution of the Mitchell and Gilbert megafans from the Pliocene to Holocene [modified from Grimes and Douch (1978)], (b) MODIS image of the Mitchell/Staaten/Gilbert River megafans during flood, representing the inset dashed rectangular area in (a). Note partial cloud cover in lower left. Area represented in (b) is indicated by the box in the inset location map. This figure is available in colour online at www.interscience.wiley.com/journal/espl

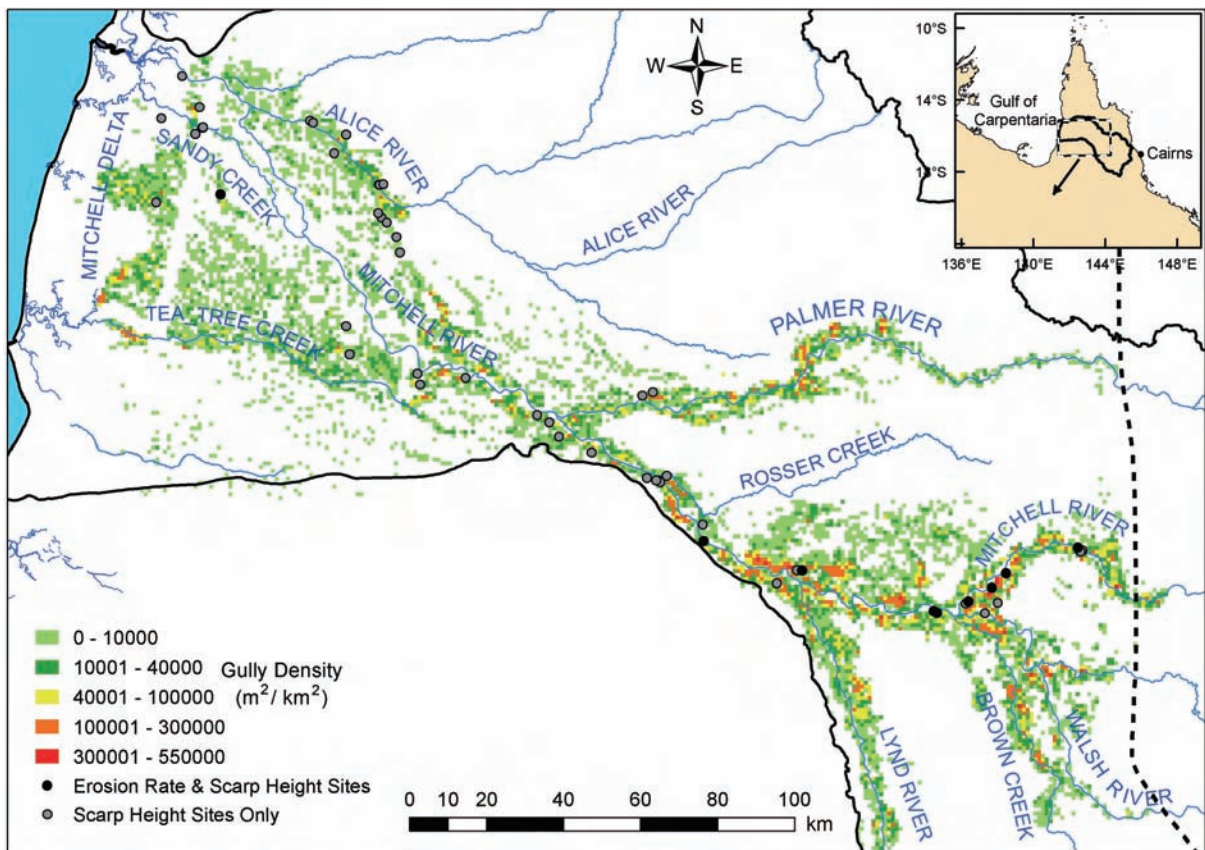


Figure 3. Alluvial gully distribution and density (in m^2/km^2) across the Mitchell fluvial megafan. The density grid resolution is $1 km^2$ pixels. Dashed line is the Palmerville fault.

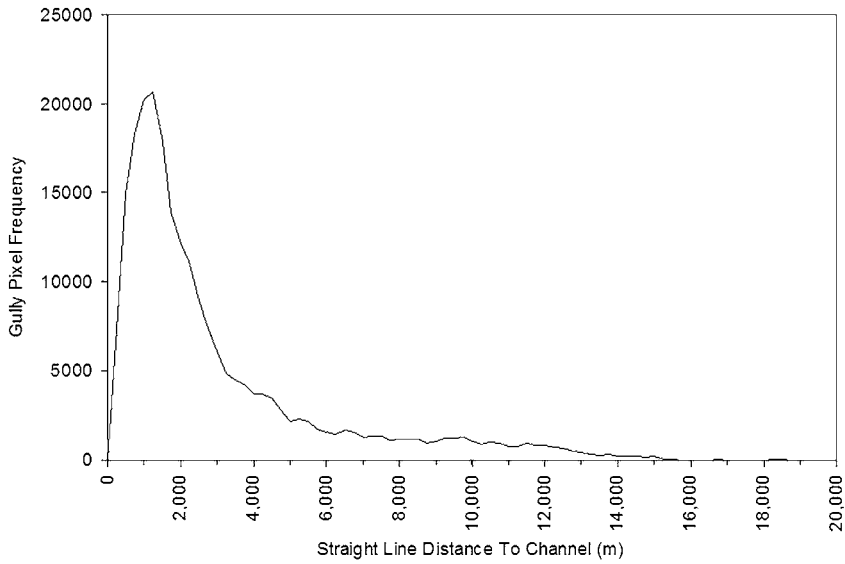


Figure 4. Gully pixel (15 × 15 m) frequency from ASTER delineation in relation to main channels.

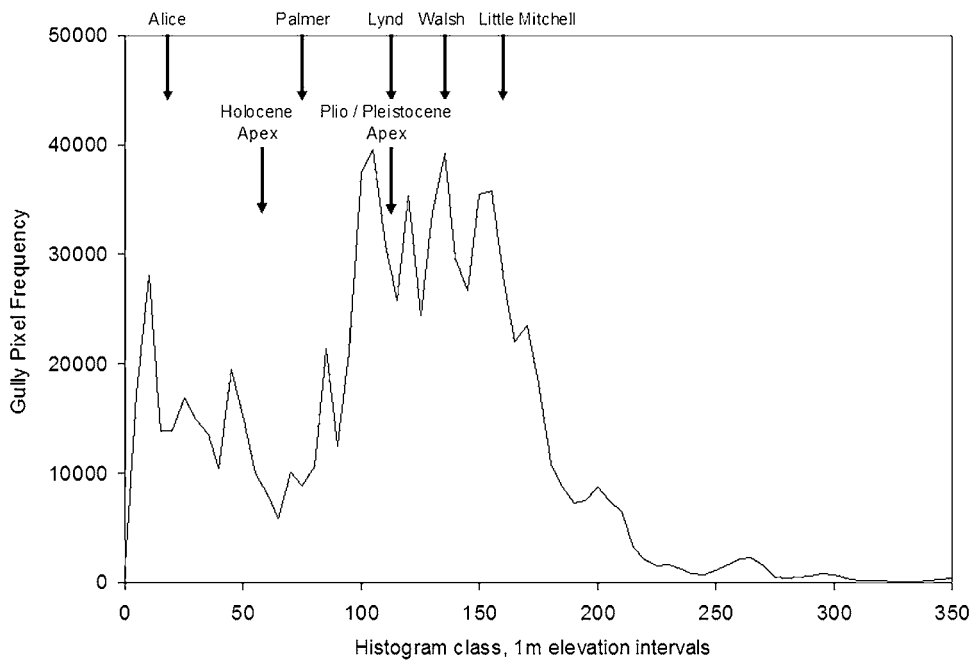


Figure 5. Gully pixel frequency from ASTER delineation in relation to pixel elevation determined from the 30 m SRTM DEM. Pixel elevation is closely correlated with distance from mouth, and hence this figure can be viewed as a type of longitudinal profile.

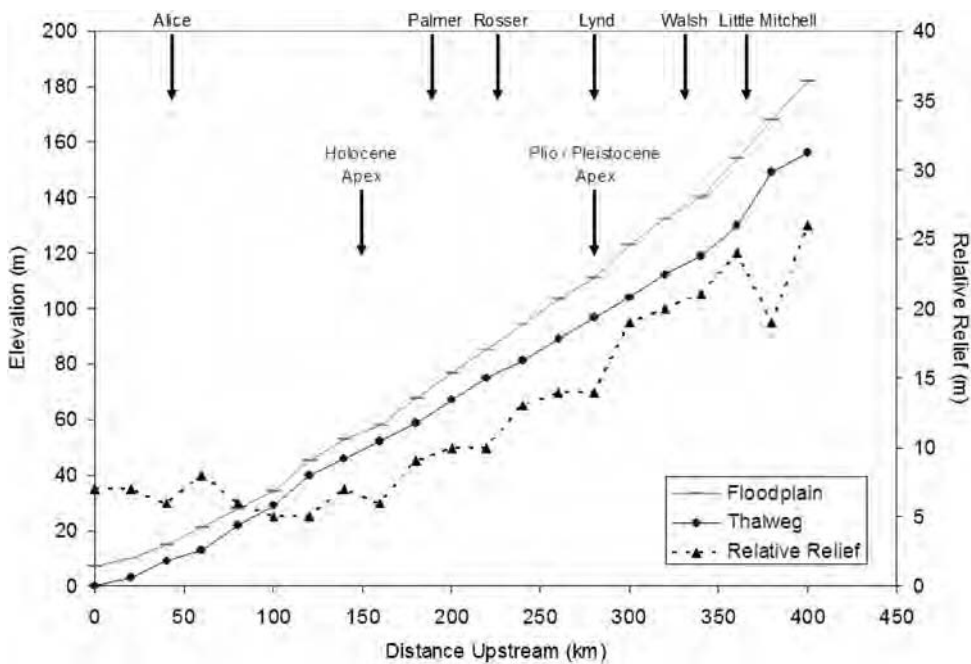


Figure 6. Longitudinal profile of the Mitchell River thalweg and adjacent megafan surface (floodplain or terrace). Locations of the key tributary confluences are noted as distances upstream (km), as are current and past fluvial megafan apices.

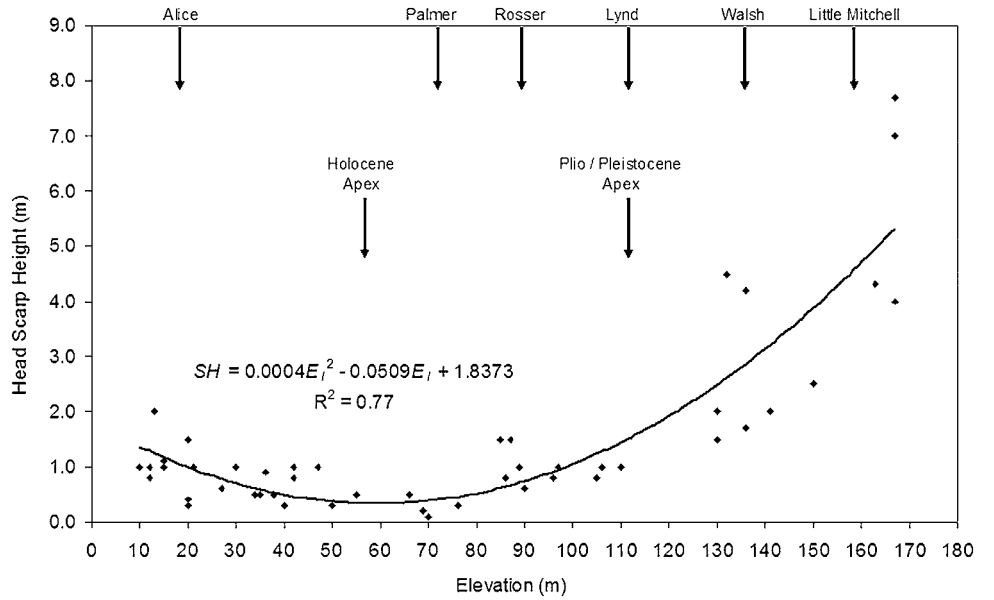


Figure 7. Relationship between measured gully head scarp height (*SH*) and adjacent floodplain surface elevation (*E_i*) as derived from the 30 m SRTM DEM.

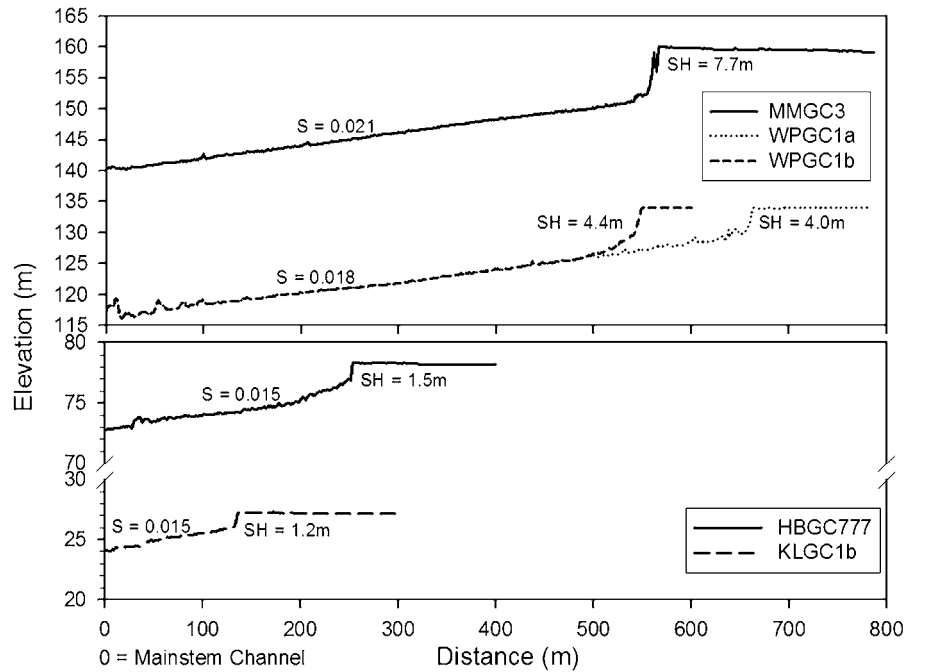


Figure 8. Longitudinal profiles of alluvial gully thalwegs between a main channel and adjacent floodplain. *S* = gully channel or floodplain slope. *SH* = scarp height.