Alluvial gully erosion in Australia's tropical rivers: a conceptual model as a basis for a remote sensing mapping procedure

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Abstract

In 2004, an aerial reconnaissance survey of Gulf of Carpentaria rivers identified alluvial gully erosion as a likely key sediment source into many rivers. The process is found to varying degrees within alluvial river types along most Gulf rivers, and is more extensive in the larger, steeper gradient rivers. It is hypothesised that the high connectivity between alluvial gullies and trunk streams makes these features a significant sediment source to the Gulf. The process appears to differ significantly in scale and process from the well documented, largely colluvial, gullies that abound in southern Australia. New conceptual models of the processes driving these gullies, and controls on their morphology and spatial distribution, are required if this process is to be adequately parameterised into existing sediment budget models, such as SedNet, in northern Australia. It is likely that similar features exist in eastern draining tropical rivers, suggesting existing SedNet models may need to be adjusted to account for this different style of gully erosion. Our model suggests that morphological variability can largely be explained by the relative dominance of the two main processes driving gully headward retreat: basal sapping and overland flow driven knickpoint retreat. The model suggests that gully initiation, rate of activity and morphological variability can be explained by the interplay between soil type, floodplain relief, vegetation, climate, fire regime, grazing pressure, river flow regime and local rainfall within the context of these two primary driving processes.

Keywords

Alluvial gully erosion, tropical rivers, northern Australia, basal sapping

Introduction

Gully erosion has been identified as a dominant sediment source in many regions within Australia and internationally (Gobin *et al.,* 1999; Olley & Wasson, 2003; Prosser *et al.,* 2001), locally contributing up to 90% of the total sediment yield (Olley & Wasson, 2003). The majority of gully erosion process studies and associated models tend to be derived for incisional features in erodible hillslope colluvium that are driven by the exceedance of a critical flow shear stress on the soils surface (*sensu* Montgomery & Dietrich, 1988). A notable exception is the large literature on arroyo development in valley fills (Cooke & Reeves, 1976; Graf 1983), and similar valley fill incision phenomenon in semi-arid Australia (Fanning *et al.,* 1999). Recent aerial and ground reconnaissance through the Gulf of Carpentaria (GoC) has identified extensive gully erosion within alluvium along many of the large rivers draining into the GoC. These gullies have some of the characteristics of the arroyos in the American southwest and the bank gullies described by Vandekerckhove *et al.,* (2000), but differ in that the gullies are eroding perpendicular to large main stem river channels (catchment area $10^3 – 10^5$ km^2) into low gradient alluvium. Preliminary assessments of gully activity on the Mitchell River shows rates of headwall retreat up to 10m/yr, generating specific sediment yields of 1250T/ha (Brooks *et al.,* 2006). These rates are comparable with sediment yields from gullies on the Chinese Loess plateau (Hessel & van Asch, 2003), which are generally regarded as the highest rates recorded on the planet. Similar gully processes have also been identified in the Savannah regions of the NT and WA, particularly the Victoria and Ord Rivers. Preliminary assessment suggests they are found along some of the eastern draining tropical rivers, such as the Burdekin and Fitzroy, as well. It has been suggested that broad scale gully erosion of this type and associated local scale denudation is a fundamental control on vegetation community dynamics in areas affected by this phenomenon (Pringle & Tinley, 2003), which until recently was not accommodated into rangeland vegetation ecosystem models (Pringle *et al.,* 2006). Fundamental questions persist concerning this widespread phenomenon. Particularly, is widespread gully erosion an inherent characteristic of this landscape associated with base level adjustments and long-term landscape evolution, and has it been accelerated by land-use changes (e.g. cattle grazing and altered fire regimes) or external drivers such as climate change? A crucial step in unravelling the causal mechanisms underpinning this process is the mapping of gully distribution and severity and placing them within a broad landscape context. All the Natural Resource Management groups in this region have identified understanding and managing this erosion process as a high priority.

The first step in developing a remote sensing based procedure for mapping alluvial gully erosion in Australia's tropical rivers, is the development of a morphologic typology with an underlying process basis, that can be adapted to an image based assessment schema. As such, it is necessary to keep the typology as simple as possible, while enabling the mapping procedure to capture the inherent variability of gullying across large areas. The remote sensing approach being adopted is reported elsewhere (see Knight *et al.*, in these proceedings). The typology has been derived from field and airborne remote sensing data in five focal river systems in Queensland and Northern Territory (the Mitchell River in the north-eastern Gulf; the Leichhardt, Gregory and Nicholson Rivers in the southern Gulf; and the Victoria River in the NT).

Alluvial gully erosion processes and typology as a basis for remotely sensed mapping
Based on field survey and air photo interpretation of 53 gullies in the Gulf River catchments, we have identified four primary gully morphological variants, which we hypothesise to have different formative processes. As with many natural systems, a complex continuum of gully forms exists, and invariably most gullies will have elements of more than one of the primary variants. Following is a description of the four key gully types identified.

Amphitheatre form
Defining characteristics
- Broad amphitheatre or teardrop planform with a relatively narrow outlet to the main-stem channel or distal floodplain creek (Figure 1).
- Gully head is in the form of a distinct vertical or undercut scarp face.
- Often exhibit pipe erosion – indicating the presence of sodic soils and dominance of a basal sapping process (i.e. the preferential erosion of the sub-soil by dissolution weathering and positive pore pressures).
- Often occurring on both the distal and proximal margins of an alluvial ridge adjacent to the main-stem channel.
- Not dependent on upslope catchment area to progress. Given that the process is apparently driven by groundwater flow, once initiated it will proceed until no material is left to erode, provided there is sufficient groundwater available. Groundwater recharge is likely dominated by river flood flows (not necessarily overbank). See Figure 1
- Often exhibit highly complex fluting and an extensive lag of calcrete nodules on the eroded surface.
- Vegetation in the gully is generally not well developed –indicating high rates of gully progression.
- Drainage network may be evident within the gully complex, but the interfluves between drainage lines are subtle – being significantly lower than the former floodplain level.

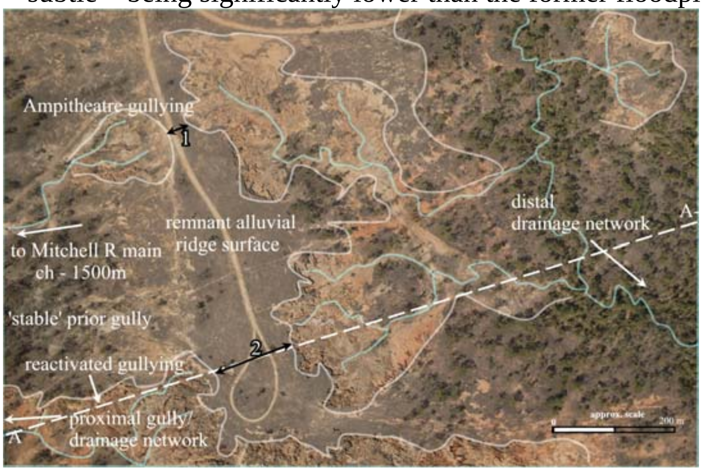

Figure 1. (Left) Example of amphitheatre gully form on the mid Mitchell River. Figure 2. (Right) On ground photo of the same general area. Note how the gullies are progressing towards the highest ground (as represented by the remnant alluvial ridge surface – depicted by the loop road) from both sides, and the very small "upslope" contributing catchment area adjacent to each gully (indicated with the arrows 1 and 2).

Key processes

- Basal sapping is much greater than surface erosion or overland flow driven knickpoint retreat.
- Basal sapping processes leads to undercutting and then block mass-failure, likely occurring in the draw down phase after flooding.
- Surface erosion associated with local surface runoff and rain splash is an important secondary process in the breakdown of mass wasted material.
- Important interaction with flood flows – most significantly from the perspective of saturation of floodplain soils and then post flood draw down as a primary mechanism driving the gullying.
- Fluvial scour in high magnitude flows along preferential flow paths in the riparian zone may play an important role in the initiation of gullies, however, once initiated fluvial scour is not necessary to perpetuate the erosion process.
- This process occurs on highly dispersible deep alluvial sodic soils – often with high carbonate content.

Continuous scarp front form

Defining characteristics

- Relatively linear gully complex running parallel with the main stem channel of major rivers. This appears to be a (possibly more mature) variant of the amphitheatre form, whereby a sequence of amphitheatres coalesces to form a continuous gully scarp front (Gully sidewall retreat greater than headwall retreat). Common in multi-channel rivers with extensive in-channel vegetation (see Figure 3).
- As with the amphitheatre form, the gully head tends to be in the form of a scarp face, however, variants exists where the scarp is relatively indistinct, possibly due to the role of fluvial scour/stripping during flood flows.
- As with the amphitheatre form, pipe erosion is also common– indicating the presence of sodic soils and occurrence of a basal sapping process.
- Generally (but not exclusively) confined to the proximal floodplain margins of the main-stem channel (i.e. not on the distal margin of alluvial ridges – if they exist).
- Not dependent on upslope catchment area to progress – and as with the amphitheatre form once initiated, will continue to migrate across the floodplain for as long as there is sub-surface saturation.
- Relative rates of lateral gully expansion in this form of gully are much greater than headward retreat.

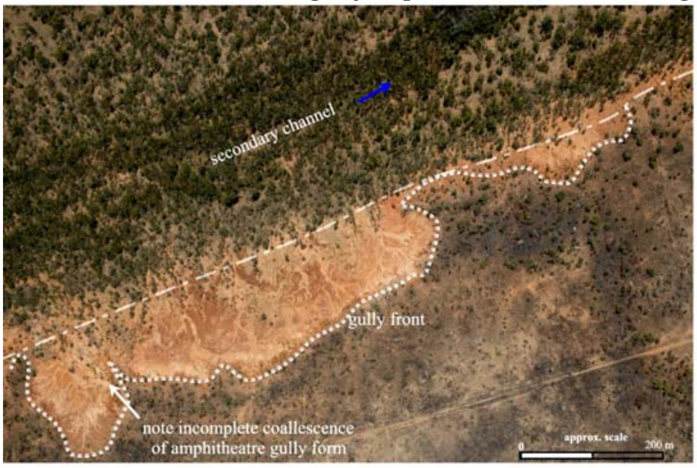

Figure 3. (Left) Example of gully scarp front form on the Nicholson River. Note the incomplete coalescence of the amphitheatre gully on the far left, and the remnant drainage pattern of the pre-existing separate amphitheatre gullies can still be discerned. Figure 4. (Right) On-ground shots of the same gully scarp.

Key processes

- Two key variants: 1) Basal sapping much greater than surface erosion results in the scarp front variant; 2) Fluvial scour & overland flood flow greater than basal sapping. Both forms are a function of multiple initiation points where the adjacent gullies coalesce to form a continuous front
- Variant 1 forms as a result of highly efficient sapping driven lateral expansion, whereas in variant 2 the process of gully coalescence is accelerated by flood scour of the gully sidewall interfluves – i.e. a form of floodplain stripping (*sensu* Nanson, 1986).

- It is likely that fluvial scour plays a role in the initiating process as well as the process leading to coalescence of individual amphitheatre gullies into the continuous scarp (see Figure 3). Fluting is less evident than in the amphitheatre form, possibly a function of the higher lateral expansion rates.
- Surface erosion associated with local surface runoff and rain splash is an important secondary process in the breakdown of mass wasted material. Flood flow interactions are critical from a fluvial scour perspective and an alluvial aquifer recharge perspective.

Dendritic form

Defining characteristics

- Tend to have an elongate dendritic planform, with the gully complex forming a well defined drainage network, separated by interfluves which often extend to the former floodplain level (Fig 5).
- Gully head is often indistinct, grading relatively gradually from the adjacent floodplain to the gully network (Fig 6). These gullies tend to have a distinct appearance of a micro-drainage network. Seldom exhibiting pipe erosion – sub-soils are far less dispersible than amphitheatre and scarp front forms.
- Calcrete nodules are evident but not to the same extent as in the amphitheatre form
- Occurs on both the distal and proximal margins of an alluvial ridge adjacent to the main-stem channel, but contingent on “upslope” catchment area.
- Gully network progression is dependent on upslope catchment area, be it generated by overbank flood flows or local storm flow. Seldom exhibiting extensive fluting. Active dendritic gullying often appears to be inset within *prior* “stable” gully network
- Often has a well developed vegetation community within the more mature part of the gully drainage network (see Figure 5). Relatively steep long profiles

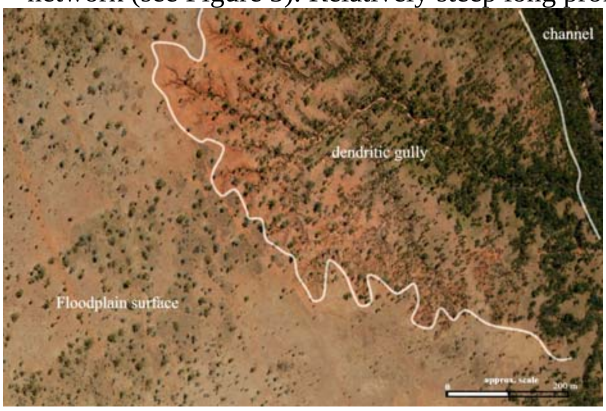

Figure 5. (Left) Dendritic gully form on Leichhardt River. Note well established vegetation community within the lower part of the gully complex, indicating the gully’s long evolutionary history. Dendritic gully activity commonly occurs within a much older prior gully network. Figure 6. (Right) On ground photo showing the dendritic gully form headwall

Key processes

- Gully network development is driven by overland flow generated by either local stormflow (without associated flooding in the mainstem channel), or return flow associated with overbank flooding on the receding limb of the hydrograph

Figure 7. (Left) Aerial photograph of a linear gully formed along a river road crossing. These sparsely vegetated riparian margins are highly sensitive initiation points for gully erosion. Figure 8. (Right) An example of linear gullies associated with the concentration of flow along graded roads.

Linear form

Defining characteristics

- Elongate planform morphology without a well developed secondary drainage network. This gully type is often associated with anthropogenic disturbances such as roads, stock tracks, or other linear disturbances that tend to concentrate flow. Depth along profile can vary significantly depending on site-specific circumstances. This gully type is in all likelihood an incipient phase of one or all of the other gully types.

Key processes

- Linear incision is likely initiated by excess shear stress associated with flow concentration along preferential flow paths, such as wheel tracks, stock tracks or fence line grader tracks. Subsequent form is then dictated by the dominance of processes driving head and sidewall retreat.

Table 1. Formative processes of tropical alluvial gullying - Gully type and process conceptual model. Legend: +++ = highly significant factor in formation, magnitude and perpetuation of this gully type; ++ = important factor in most cases; + = moderately important in many cases; - = not required.

	Gully Types			
Controlling factors	***Amphitheatre***	***Scarp Front***	***Dendritic***	***Linear***
Broad scale Controls				
Catchment morphology				
Width of alluvial surface	++	+++	++	+
Presence of alluvial ridge	++	-	+	-
spatial location within alluvial fan	+++	++	-	-
Regional hydrology: seasonal flood inundation	+++	+++	+++	+
Connected regional shallow groundwater aquifer	+++	+++	+	+
Climatic regime	+++	+++	+++	+
Local scale controls				
Dispersible subsoils	+++	+++	+	++
Soil porosity (infiltration capacity)	+++	++	+	++
Depth of alluvium	+++	++	++	++
Local topography – i.e. elevation difference between main-stem channel bed and floodplain/alluvial ridge surface	+++	++	++	+
River reach type				
multi-channel with extensive in-channel vegetation	+	+++	-	-
single thread/wandering	++	++	-	-
Initiating/driving Mechanisms				
Flow concentration (stock tracks, wildlife tracks, roads)	+++	+++	+++	+++
Riparian surface groundcover at onset of wet season (as a function of cattle grazing, burning, wildlife herbivory)	+++	+++	+++	+
Storm intensity at onset of wet	+++	+++	+++	+++
Flood hydrograph (duration of high flow and draw down rate)	+++	+++	++	+
Bank mass failure due to rapid drawdown	+++	++	+	-
Fluvial scour (sub bank full flow)	-	+++	++	-
Fluvial scour (over bank flow)	+	+++	+++	+++
Mechanisms Perpetuating gully activity				
Riparian ground cover vegetation	+	+	+++	+
Riparian mid & over storey vegetation	+	+	++	+
Local storm induced overland flow	+	+	+++	++
Stock compaction	+	+	+++	+
Overbank flood flows	++	+++	+++	+++
Sub-bankfull flood flows	++	++	++	+
Local rainfall intensity (rain splash erosion)	++	++	++	+
Alluvial groundwater flow	+++	++	-	+

Discussion and conclusion

Having described the key characteristics of the identified alluvial gully types encountered in the Gulf region, Table 1 is a synthesis of what we hypothesise are the key factors giving rise to the different gully forms and the factors that are likely to be perpetuating their expansion. At present this compilation can be regarded as a preliminary conceptual model that still requires field validation. The table includes a range of natural controls that are an inherent feature of this landscape. However, it also includes a number of other parameters that are a function of land-use activity (or can potentially be). Existing theoretical models of gully initiating and perpetuation highlight the importance of ground cover and flow concentration, and clearly these are parameters that are potentially affected by land-use. There is little doubt, however, that this type of gullying is an inherent feature of the Gulf Savannah landscape, given that there is extensive field evidence of palaeo gullies, some of which contain well developed soils profiles within the eroded portion of theses gullies. Even before absolute dating results have been obtained, it is clear that some of these incisional features pre-date the implementation of European land management practices. Nevertheless, anecdotal evidence from most of the landholders consulted during the 2005 and 2006 field seasons, suggests that in gully prone areas, the extent of land impacted by gullying is increasing, not decreasing. It is also likely that land management practices have increased rates of gully erosion. The introduction of roads, in particular, has introduced an initiation mechanism never seen before in this landscape. In areas prone to this type of erosion, roads without some form of associated incipient gully erosion appear to be rarer than those with them. Hence it would appear likely that the increase in initiation points is an important mechanism that may be contributing to the increase of gullying in the Gulf region. The conceptual model presented here provides a critical first step in developing hypotheses regarding changes in the rates of gully initiation and activity.

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