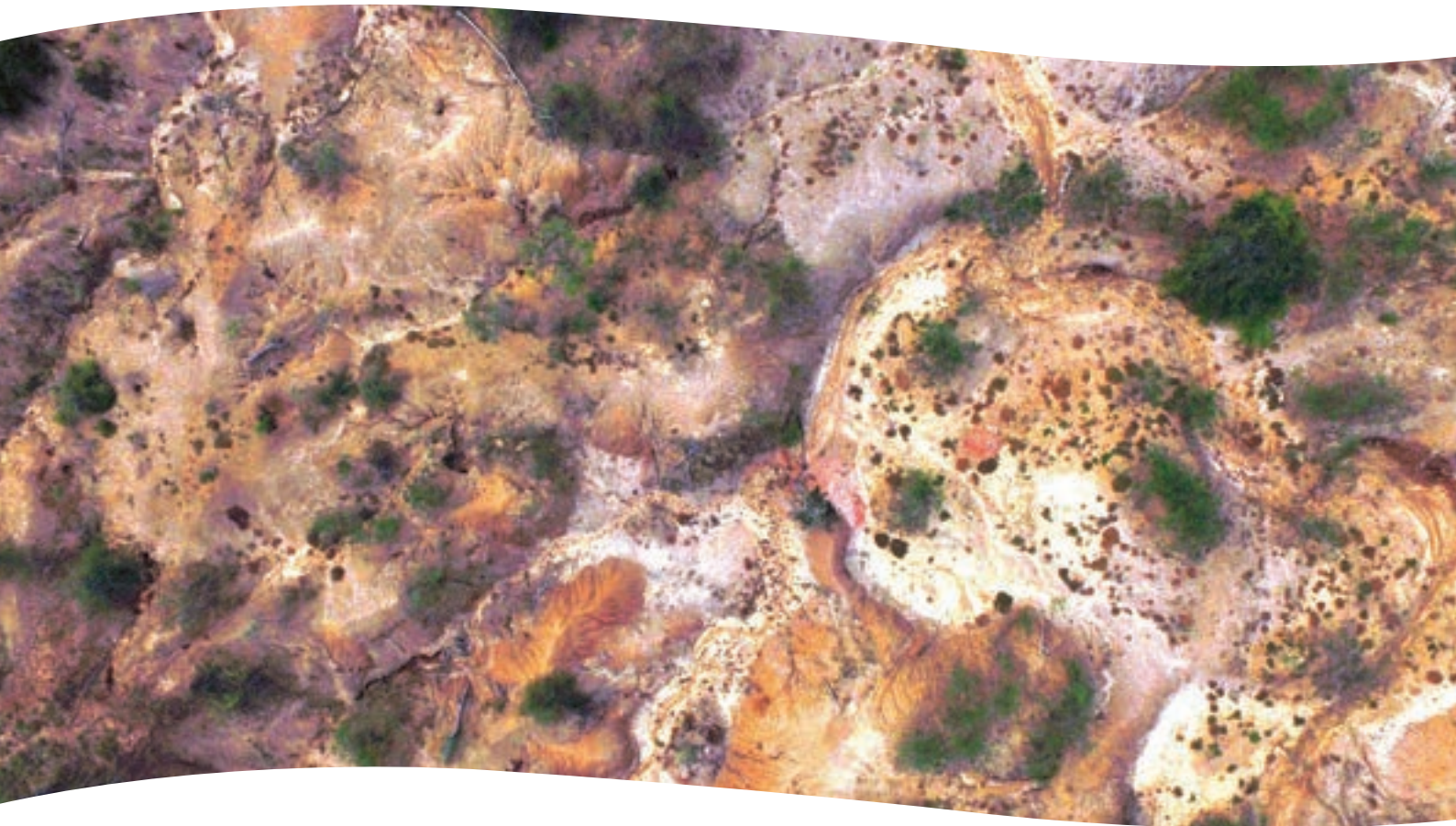


A Gully Classification Scheme to Underpin Great Barrier Reef Water Quality Management: 1st Edition

Andrew Brooks, Robin Thwaites, John Spencer, Tim Pietsch and James Daley



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Andrew Brooks, Robin Thwaites, John Spencer, Tim Pietsch and James Daley
Griffith Centre for Coastal Management, Griffith University



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Project 4.9 Gully Characterisation Framework to underpin GBR Catchment Water Quality Management

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ACRONYMS

AG	 Australian Government
BBB	 Bowen, Broken, Bogie Rivers, Queensland
CCA	 Contributing Catchment Area
CSIRO	 Commonwealth Scientific & Industrial Research Organisation
DtD	 Distance to Divide
DEM	 Digital Elevation Model
DME	 Distance-measuring equipment
GBR	 Great Barrier Reef
GIS	 Geographic Information System
GPS	 Global Positioning System
Lidar	 Light Detection and Ranging also LiDAR
MIP	 Major Integrated Project
NERP	 National Environmental Research Programme
NESP	 National Environmental Science Program
NRM	 Natural Resource Management
PrESM	 Precision Erosion & Sediment Management Research Group Griffith University
SALI	 Soils And Land Information
TRaCK	 Tropical Rivers and Coastal Knowledge Programme

AUTHOR ATTRIBUTION

Andrew Brooks was the project leader, and a report author, along with Robin Thwaites. Andrew was responsible for the final report structure and production, the initial concept, the workshop discussion document, leading the workshop, and keeping the project on track.

Robin Thwaites was responsible for the production of the Gully Classification conceptual model, following from a conceptualisation and framework workshop with Andrew Brooks and John Spencer. He was responsible for much of the research into gully classification and characterisation, the workshop planning, the detail in the classification manual, glossary, and the majority of the conceptual figures. He was also responsible for (several) drafts of the field data sheets with John Spencer.

John Spencer was responsible for the gully database and for designing the data entry spreadsheets. He has contributed to numerous discussions about all aspects of gully morphometrics and classification.

James Daley and Tim Pietsch contributed to the gully classification workshop and the discussion about the differences between gullies and channels.

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EXECUTIVE SUMMARY

Gully rehabilitation and management is a high priority activity across key Great Barrier Reef (GBR) catchments. Both the Queensland and Australian Government have recently invested significant resources into major gully rehabilitation programmes, through the Reef Trust II and IV Programmes and the Queensland Government's Major Integrated Project (MIP) in the Bowen, Broken, Bogie (BBB), the Springvale Station Erosion Management Plan, and the Strathalbyn Gully Innovation Project (with Greening Australia). With these major investments (which in total amount to around \$60m) there is a pressing need amongst all parties to identify different types of gullies in the landscape, and to prioritise management effort and resources such that the appropriate treatments are applied to different gullies in the most cost-effective manner.

As more groups become involved in gully rehabilitation, and gully mapping, often involving people with little background in geomorphology, soil science or soil conservation, it has become obvious that before we develop gully management guidelines (the ultimate goal) we first need to ensure that we have a common language to describe the variety of gully types that exist in landscape and how active they may be. This is important for developing management strategies, as well as for mapping and prioritising gully management efforts.

Catchment-wide gully mapping has been undertaken in each of the Natural Resource Management (NRM) regions, often using different criteria for what a gully is, and with no differentiation between different gully types. With additional information about different types of gullies in different parts of the landscape, resources can be much more efficiently targeted to the areas where they are most needed for water quality improvement. When coupled with detailed mapping of gullies using LiDAR data, there is also the potential for significantly improving catchment models.

Effective gully remediation planning requires knowledge and understanding about a range of gully characteristics, including: the potential sediment yield coming from each gully or gully system, the sediment particle size and nutrient status of the sediments derived from the gully/system, some information about the soil/sediment chemistry, and the gully/system scale and geometry. At present most of these necessary parameters require field assessment, including laboratory analysis of soil materials. Gathering such data for every gully in the field is an expensive exercise. However, we can try to identify sub-sets of the overall gully population that have similar characteristics i.e. 'gully types' which means that we can collect detailed data on just a sample of each gully type, and make reasonable estimates of the characteristics of the rest of that gully type within a local area, and then better predict sediment yields based on a simple set of broader proxy data such as rainfall, landscape position and vegetation cover, along with detailed metrics about each gully.

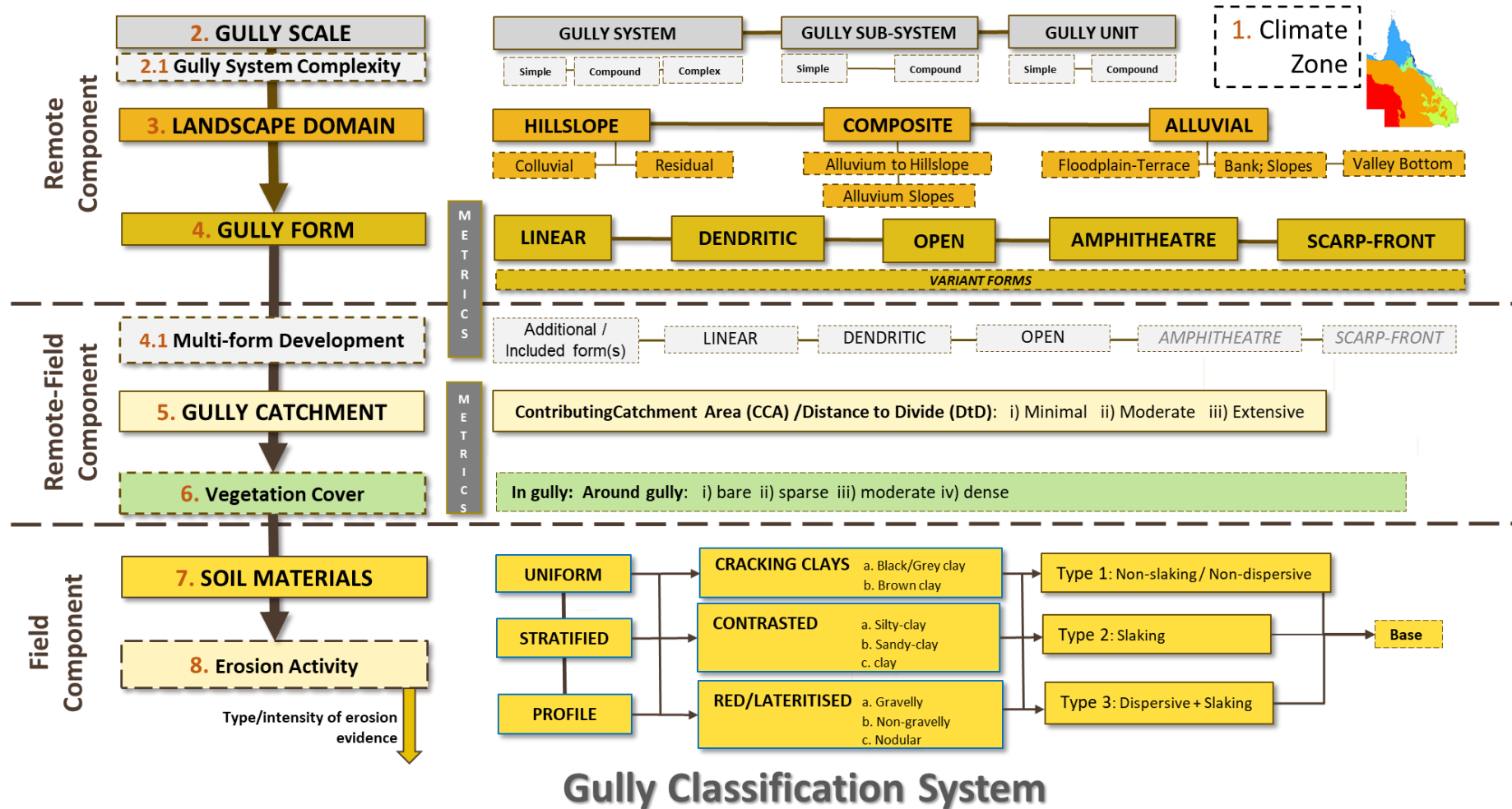
The holy grail objective is to come up with a spatial model that accurately predicts sediment yield from gullies, but until we better understand empirically some of the variability in the field and the key drivers of that variability, it is futile to attempt to derive such a model. A fundamental prerequisite for deriving a useful catchment scale model is to first compile a high-resolution spatial map of gully distribution that will enable us to identify in detail the characteristics of each gully. Such a dataset will then form the basis for a catchment model.

At present the Queensland Government is committing significant resources into mapping the locations of gullies, so we can better plan the resources and effort required to remediate the major sediment producing gullies, and to parameterise gully sediment sources within catchment models better. However, when applied to the models, the current presence/absence mapping data is effectively considered as all gullies being a standard type with a standard cross-sectional profile and a consistent age. A selection of gullies are being field-assessed for basic dimensions. The current mapping provides no breakdown of gully type, even at the most fundamental level between hillslope gullies and floodplain alluvial gullies (*sensu* Brooks et al., 2009), or between gullies and stream channels.

To address this shortcoming and to provide a basis for future planning, we propose a framework for classifying gullies across the state of Queensland. This report presents a summary of the first iteration of this classification framework. It must be stressed that this should be regarded as a **First Approximation**, or a **Beta-Version only**, and we fully expect that it will evolve over time as more data becomes available, and more importantly as more people use the classification in different areas and suggest modifications to the approach. Whilst the focus for this project was on the Great Barrier Reef (GBR) catchments, a Gully classification system has been designed that should be applicable anywhere across Queensland, or indeed, across Australia.

The classification framework outlined in this report is intended to be carried out by a technical extension officer with at least some background in soil conservation and/or land management. Whilst there are many technical terms used in the report, we have focused significant effort on providing detailed glossaries and explanatory material so that the intended meaning of the terminology is clear to the typical user.

The proposed classification has been developed from a literature review of gully descriptions worldwide, but particularly in Australia. It is intended to be applied at various scales using both field and remotely-sensed data. The conceptual diagram shown here (below), is then explained in detail throughout the report.



To facilitate the systematic collection of data on gullies, we have also developed a gully database, along with purpose-built Excel-based data entry forms to allow for easy data upload to the centralised database. These will be made available through the NESP Tropical Water Quality Hub website www.nesptropical.edu.au and the eAtlas www.eatlas.org.au.

We also outline a range of metrics that will be used in future numerical analysis of gully types. As the use of the gully database expands, and we start to accumulate a larger dataset on a wide range of gully types, we expect to be able to develop a data-driven classification that will highlight what the key variables differentiating the key gully types. In time, this should enable us to rationalise the number of metrics that we need to collect to drive the classification. Hence, this classification should be considered the first iteration of a few in continuing to refine the database and classification system.

The database has also been designed to accommodate a core set of field data and remotely-sensed data, that we believe is the minimum for determining the gully type, but there are also fields for more detailed research studies which may require more detailed data and diligent collection.

PART 1

1.0 INTRODUCTION

Fine sediment sourced from gully erosion is estimated to contribute around 40% of the sediment load delivered to the Great Barrier Reef (Wilkinson, et al., 2015), and in other drainage divisions in Queensland, such as the Gulf of Carpentaria, it likely represents an even larger proportion of exported sediment (Caitcheon et al., 2012). We also know that there is a very large diversity of gully forms and types occurring within all regions of the Queensland landscape, with a broad range of sediment yields, particle size and nutrient characteristics, as well as different evolutionary trajectories (Figure 1). Given the great diversity in gully types, a broad array of management strategies, or combinations of management strategies, are required to remediate these different types of gullies. Hence, as we now move towards managing this sediment source at scale in Queensland, it is essential that we have an appreciation of the diversity of gully types in the landscape to underpin the remediation planning, design and investment. At a more fundamental level, it is important that we have a common language when communicating the nature of the problem amongst landholders and remediation practitioners.

Effective gully remediation planning requires that we know something about a range of gully characteristics, including: the sediment yield derived from each gully or gully system, the sediment particle size and nutrient status of the sediments derived from the gully/system, some information about the soil/sediment chemistry, and the gully/system scale and geometry. At present most of these parameters require field data collection or high-resolution survey data. Whilst it is becoming more feasible to characterise morphometric gully parameters using remotely sensed LiDAR data, many of the other parameters currently require field measurement. Hence gathering such data for every gully in the field is an expensive exercise. However, if we can identify sub-sets of the overall gully population that have similar characteristics i.e. gully types' it may mean that we can collect detailed data on just a sample of each gully type, and make reasonable estimates of the characteristics of the rest of that gully type within a local area, and then better predict sediment yields based on a simple set of broader proxy data such as rainfall, landscape position and vegetation cover, along with detailed metrics about each gully. The holy grail objective is to come up with a spatial model that accurately predicts sediment yield from gullies. However, until we better understand empirically some of the variability in the field and the key drivers of that variability, it is futile to attempt to derive such a model. A fundamental prerequisite for deriving a useful catchment scale model is to first compile a high-resolution spatial map of gully distribution that will enable us to identify in detail the characteristics of each gully. Such a dataset will then form the basis for a catchment model. We can also then better predict sediment yields based on a simple set of broader proxy data such as rainfall, landscape position and vegetation cover, along with detailed metrics about each gully.

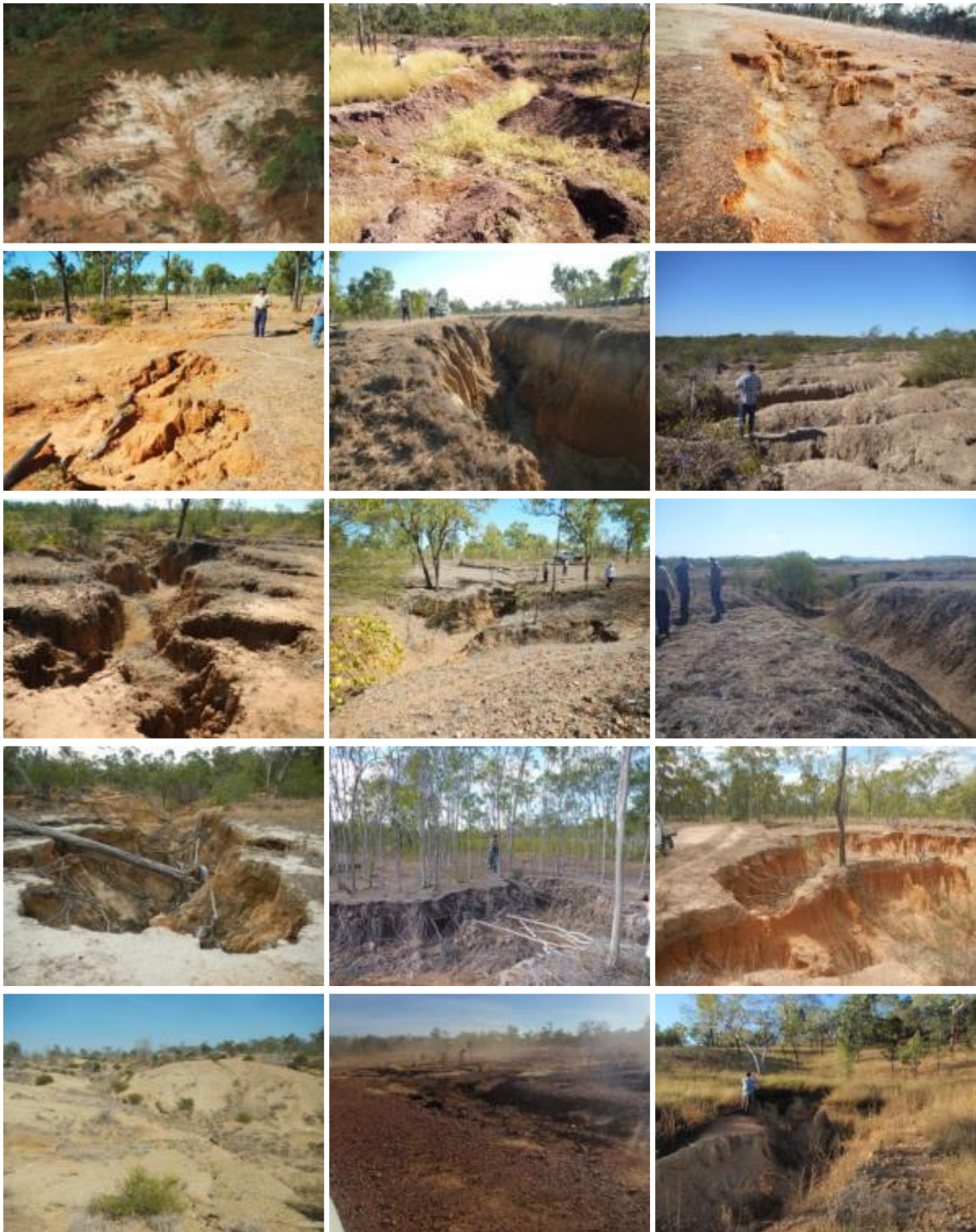


Figure 1: A sample of the large diversity of gully forms found throughout Queensland. The variety of major gully erosion factors that are apparent in these examples helps demonstrate the shortcomings of assuming that there is a single ‘unit’ gully erosion rate that can be applied to all gullies. Those variable erosional factors include the erosional forms, the soil materials being eroded, erosion activity intensities and type of erosion, and established vegetation cover. NB – gullies at top right, bottom centre and bottom right are hillslope gullies, all others are alluvial gullies.

At present the Queensland Government is committing significant resources into mapping the locations of gullies, so we can better plan the resources and effort required to remediate the

major sediment producing gullies, and to parameterise gully sediment sources within catchment models better. However, when applied to the models, the current presence/absence mapping data is effectively considered as all gullies being a standard type with a standard cross-sectional profile and a consistent age. A selection of gullies are being field-assessed for basic dimensions. The current mapping provides no breakdown of gully type, even at the most fundamental level between hillslope gullies and floodplain alluvial gullies (*sensu* Brooks et al., 2009).

To address this shortcoming and to provide a basis for future planning, we propose a framework for classifying gullies across the state of Queensland. This report presents a summary of the first iteration of this classification framework. It must be stressed that this should be regarded as a **Beta-Version only**, and we fully expect that it will evolve over time as more data becomes available, and more importantly as more people use the classification in different areas and suggest modifications to the approach.

1.1 Gully classification

Given the diversity of gully form and processes in the GBR catchments and across Queensland more generally, the aim of this project is to develop a generic gully classification framework that is applicable across the main rural land uses (excepting mined land and urbanised or constructed environments). Such a framework will then help to guide a stratified approach to collect data according to gully type, enabling us to analyse gully soil geochemistry, age, gully morphology and activity to develop a decision support tool for designing gully specific management strategies. Necessarily this will be an iterative process, whereby the classification method evolves as more data is collected on different types of gullies. Ultimately, once sufficient data is available on a broad range of gully types, we would hope to derive a completely data-driven classification. However, such an approach is not possible at this point since we have very little data on individual gullies, nor do we have a standardised approach for collecting data on gullies. Hence a key aspect of this project is to design a database, along with data collection protocols, to enable us to standardise data on gullies across Queensland. This is similar to the approaches that have been in place for many decades in soil and land resource assessment.

1.2 The scope for a gully classification

The original intention to produce a 'Gully Typology' for rehabilitation and management prioritisation and rehabilitation methods could not easily be achieved without first considering an overall classification framework. The scope for the classification was modified and enhanced from discussions during and after the workshop held at Griffith University in September 2018.

A 'Gully Classification' is necessary to accommodate all gully systems that may exist in Queensland from a scientific and technical viewpoint. A functional, management-oriented Gully Typology can then develop from this. The Gully Classification, however, must be comprehensive enough to include those attributes and criteria that are relevant to gully management as well as their basic morphological and process-based (genetic) factors. The

initial, overarching Gully Classification is seen to be a morpho-genetic concept, which then can provide for a more functionally-based Gully Typology.

As more groups become involved in gully rehabilitation, and gully mapping, often involving people with little background in geomorphology, soil science or soil conservation, it is becoming increasingly obvious that before we can begin to develop gully management guidelines (the ultimate endpoint) we first need to ensure that we have a common language to describe the variety of gully types that exist in landscape. Not only is this important for developing management strategies, but it is important for mapping and prioritising gully management efforts. Catchment-wide gully mapping has been undertaken in each of the Natural Resource Management (NRM) regions, often using different criteria for what a gully is, and with no differentiation between different gully types. With additional information about different types of gullies in different parts of the landscape, resources can be much more efficiently targeted to the areas where they are most needed for water quality improvement. When coupled with detailed mapping of gullies using lidar data, there is also the potential for significantly improving catchment models.

2.0 THE CONCEPTUAL BACKGROUND UNDERPINNING THE GULLY CLASSIFICATION

2.1 Gully evolution states in time and space

Colloquially, gullies have been informally classified with reference to the concept of Davisian cycles in classical geomorphic theory (Davis, 1899), which uses their developmental maturity or stage of development as an indicator of sediment yield and as a predictor of future trajectory and recovery potential. Whilst there has been merit in this maturity concept to interpreting landscapes, it has fallen from favour in recent decades because of the over emphasis on the uniformity of the time component to interpret form, and the poor understanding of tectonics, climate cycles, and environmental thresholds (Orme, 2007).

We believe it can be more helpful to understand the evolution of similar types of gullies at a local scale, where one can judge all other controls to be approximately equal, or at least account for variability. Nonetheless, it is highly problematic to attempt applying a similar conceptualisation of sequential growth stages in landscape development across variable regions and indeed across climatic zones, variable geology, soils and sediments, and land use patterns over the whole state of Queensland (1.85M km²). For example, in landscapes subject to extensive hillslope gullying it is possible to predict the maximum headward limit of gully extension as a function of the contributing catchment area (Dietrich et al., 1993). Hence one can gain some understanding of whether the gullies are likely to continue delivering sediment as they have done through recent historical times, and whether such gullies may only require fairly minimal intervention to help them on their recovery trajectory. However, applying such concepts across regions when there are so many other variables at play, including completely different gully types, variable soil material type, depth and erodibility, potentially only serves to confuse the understanding of what the real controls are on gullies in each local region.

In large alluvial gully systems such as in some of the examples shown in Figure 1, sediment yields may just keep increasing for several decades, or centuries, as the gully area increases. Hence the notion that such gullies might be in a mature stage (i.e. near exhaustion of its potential sediment supply and/or decreased supply rate), and therefore not worth rehabilitating, is unlikely to apply. Indeed, there are examples of large alluvial gullies that are expanding exponentially with an unpredictable end state.

The concept of development from 'youthful' stages to 'mature' stages in some form of linear temporal fashion does not convey the potential for the amount of material to be eroded and in what time-frame. If the primary objective of managing gully erosion is to limit inputs of sediment and nutrients into freshwater and marine systems, then the current sediment yield, as well as the projected future sediment yields, are both critical elements.

Erosion gullies do not all follow a simple pattern of youthful form and process towards a predictable mature form and process that can be determined in the field by classifying the 'development stage' of gully development. This assumes a predestined form, process, and state of gully systems over time. Gully development is dependent on a broad range of

variables, including soil material type, volume of available material, local hydrology, climate, land use history, potential energy, alluvial sedimentology, vegetation as well as time since gully initiation. While time is one variable, the current and potential future sediment yield is a function of all the controlling variables together. Not all small gullies we find in the field today will evolve into large gully complexes over time, nor will gullying in river floodplain alluvium develop into the massive alluvial gully complexes that are found in some areas.

It is important to resist the temptation to substitute time for space in characterising gully forms as we do not have a good indication of how long individual and collective systems have taken to develop and we are seeing systems in a snapshot in time (although we may have visual evidence for 60 - 70 years, and anecdotal evidence going back a bit further). We may recognise patterns of development in space, but we may not invoke a reasoning that simply replaces space for time for forms of similar development over time from an inference of observed forms over space. The causative and modifying factors (such as land clearing, extreme flood events, and soil material changes) are too variable, and we have no temporal models to support this at present.

It may be appropriate to identify 'states' of gully development in much the same way as fluvial landforms develop. For example, an expansive amphitheatre gully system may be seen to be at a 'diminished state' of development from a small dendritic system after many years of evolution (i.e. reduced energy, lowered base level, exhaustion of erodible material). However, another alluvial gully system may be at its peak of sediment yield 'intense state' (high energy, downcutting/lateral cutting, large supply of material) after 100 years and showing no signs of slowing down, depending on all of the other variables controlling that gully.

Similarly, many systems may appear to be in a low-erosion, stabilised state but can then rejuvenate in part or in the whole, owing to the tipping of internal or external thresholds that initiate a phase of secondary incision.

We therefore suggest that applying notions of morphodynamic 'state' rather than linear 'evolutionary stage' to gullies is more helpful when comparing different types of gullies. This more fruitful approach focuses on current form, material composition, and invoked process from our extensive understanding of erosional processes and materials behaviour.

2.2 What is a gully?

Across Queensland, most available evidence points to the fact that gully and channel erosion combined, typically represent the source of 90% or more of the contemporary sediment load in our rivers (Caitcheon et al., 2012; Olley et al., 2013; Wilkinson et al., 2015). However, the drivers of gully and stream erosion can be quite different, and rehabilitating gullies successfully is a very different activity to rehabilitating streams. Thus, having a clear understanding of precisely what proportion of the erosion problem is coming from which source is a critical question for setting policy, allocating resources, and undertaking on-ground works. From a practical point of view, if we are mapping the distribution of gullies in the landscape from aerial imagery, it is important that we map gullies, not small streams. If these data are being used to set up programmes addressing sediment sources from gullies, we need to know that what has been mapped as a gully, actually is a gully. Hence, for these various reasons it is crucial that

we have a common understanding of exactly what a gully looks like, in all its myriad forms, and how we can distinguish these from stream channels, ephemeral or otherwise, and be able to communicate it in standardised terms.

There are also legislative reasons e.g. Queensland's Water Act why it is important to distinguish between a gully and stream, which are often both mapped as part of the stream network on drainage network maps. The problem with confusing them in this context is that there is a range of regulations that come into play as soon as a feature is mapped as a channel of a certain size. This identification dictates, for good reason, what sorts of management activities can be undertaken in a channel, particularly regarding things like in-stream works, riparian vegetation, and fish passage. However, fish passage is not relevant in gullies, so if the two features are confused, a range of potentially unnecessary regulations may end up being applied to gullies where they are of little value, potentially preventing the types of gully rehabilitation necessary from being undertaken.

2.2.1 Distinguishing gullies from stream channels

A commonly accepted definition of gullies is that they are erosion features larger than rills (erosional features < 0.3 m deep which can be ploughed out or easily crossed (Poesen *et al.*, 2003; NCST, 2009), but smaller than streams, creeks, arroyos, or river channels (Graf, 1983; Wells, 2004). The Australian Soil and Land Survey Handbook (NCST, 2009, p.39), the Australian standard for landscape description, defines a gully as a Landform Element that is, (an) open depression with short, precipitous walls and moderately inclined to very gently inclined floor *or small stream channel, eroded by channelled stream flow* [emphasis added] and consequent collapse and water-aided mass movement .

These definitions are not very helpful for distinguishing between a gully and a small, ephemeral stream line, which might also be referred to as a first- or second-order channel. It is also important to determine at what point a gully transitions to something that is better defined as a stream or channel. Some gullies can also be substantially larger than the channels into which they feed, so size alone is a poor discriminator. The following definitions attempt to clarify the difference between a channel (or stream) and a gully. But it should also be stressed that the boundary between gullies and channels can be a fuzzy one, although a simple (thick) line may still have to be drawn on the map or in the landscape to distinguish one from the other. Often this boundary may have to be viewed as a transition one'

2.2.2 Characteristics of low-order ephemeral channels

Low-order streams and ephemeral channels have several characteristics that, combinations taken together, provides a weight of evidence to categorizing a stream channel as distinct from a gully (Figure 2). These characteristics are:

- Small ephemeral low order channels (i.e. first- or second-order streams *sensu* Strahler, 1957) are characterised by the fact that they have a defined bed and banks.
- This differentiates them from zero-order drainage basins which do not have a defined channel (Montgomery & Dietrich, 1989; Dietrich & Dunne, 1993).



Figure 2: Examples of low-order ephemeral *stream channels* that are not *gullies*. Note that these features tend to be elongate features with a defined bed and banks, which are not always alluvial (i.e. they can be bedrock). They typically have banks that are lower than they are wide (width/depth ratio > 1) and they have bedload deposits that are coarser than the bank sediments. Small ephemeral channels tend not to have a distinct riparian vegetation community.

- These small channels can have some similar characteristics to gullies, such as vertical banks, but they are differentiated from gullies in that they may show signs of meandering, they are dynamic and are both erosional and depositional systems

(comprising both autochthonous (internally sourced) and allochthonous (externally sourced) sediments - Figure 3) without an active upslope headscarp.

- Many complex gully networks will transition to a stream channel at some point, but the transition point may be difficult to identify precisely (i.e. they have a fuzzy, or transitional, boundary). Furthermore, as the gully network develops this transitional zone may change. Key features that indicate the gully may be viewed as transitioning to a channel, are:
 - The presence of a self-formed floodplain;
 - A distinct assemblage of fluvially derived depositional geomorphic units, e.g.
 - point bars,
 - lateral bars,
 - benches.
 - Bed material load that is distinctly different to the locally available sediment source (i.e. from bank erosion)
 - A width/depth ratio > 1
 - Meander development

Not all these attributes are required to define a stream channel, nor is each characteristic in isolation a defining feature of a channel. Definition is by weight of evidence.

2.2.3 Characteristics of a gully

A persistent erosional landscape feature > 0.3 m deep that has multiple modes of expansion, but always including headward retreat into an otherwise un-dissected landscape since land use intensification (typically ~ 150 – 200 years in Australia). A defining feature of an actively eroding gully is that it has an active headscarp at the upslope limit of the gully, or sometimes a series of headscarps. A scalded area (i.e. an area stripped of its topsoil with degraded vegetative cover) may often fringe the upslope area of the headscarp.

Evidence of these features, though less obvious, are also evident in less active, or stabilised gullies.

In many cases the land upslope of, or beyond, the gully may be a swamp or drainage depression in keeping with the incisional caveats above.

Gullies are typically driven by ephemeral flows (i.e. associated with direct rainfall on the gully and in the gully catchment), although there are some alluvial gullies that can experience overbank flooding or backwatering from river channels to which they are connected (*sensu* Brooks et al., 2009; Shellberg et al., 2013).

While gullies can have temporary depositional units within the gully floor, comprising materials predominantly eroded from within the feature i.e. an 'autochthonous' source they are not as spatially organised as the depositional features within the channel bed that also have materials that can be identified as deriving from outside the feature location 'allochthonous' sources

There is a wide diversity of gullies, differentiated into two fundamental types: alluvial and hillslope (residual/colluvial) gullies (as well as their possible intergrade - combination type). They are also found in a wide variety of soils, soil materials, and sediment types.

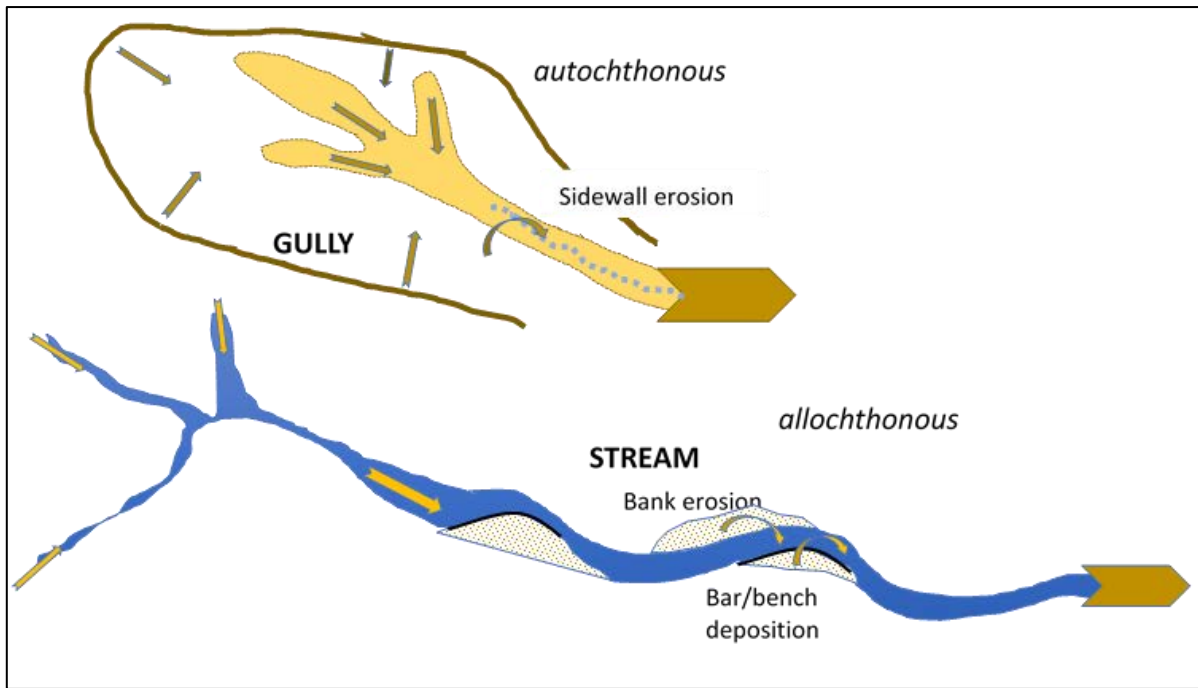


Figure 3: Schematic diagram to explain the difference between a small ephemeral channel and a gully in terms of the dominant source of the transported sediment that exits the gully or stream channel. In a gully the autochthonous sources (locally derived sediment) is much greater than the allochthonous sources (sources derived from upstream of the observed reach). The reverse is the case for a stream channel.

2.3 The definition of gully process-form

2.3.1 The gully margins

Defining what the actual margin of the gully that is being classified is not always straightforward in gully systems that have multiple erosional phases. This is particularly the case when automated tools are used to delineate gully boundaries from lidar data.

As can be seen from Figure 4, this gully has two distinct boundaries, or *margins*, both of which are important for describing the attributes of this gully system, and for grouping with other like gullies that might have similar characteristics. In many cases the outer 'soft margin' of these gully systems, where they occur, are not the location of active erosion, and can often be deemed to be at least semi-stabilised, although they have eroded in the past. This soft margin, which is the margin of a former erosion feature and current slope processes, represents the *gully process* margin. It will be an important parameter when defining the longer-term behaviour and evolutionary trajectory of this gully, and for gully management and rehabilitation purposes. The inner 'hard margin' in this example bounds the gully void and probably best represents the edge of present-day active erosion and is the *gully form* margin.

For these reasons, both boundaries should be defined.

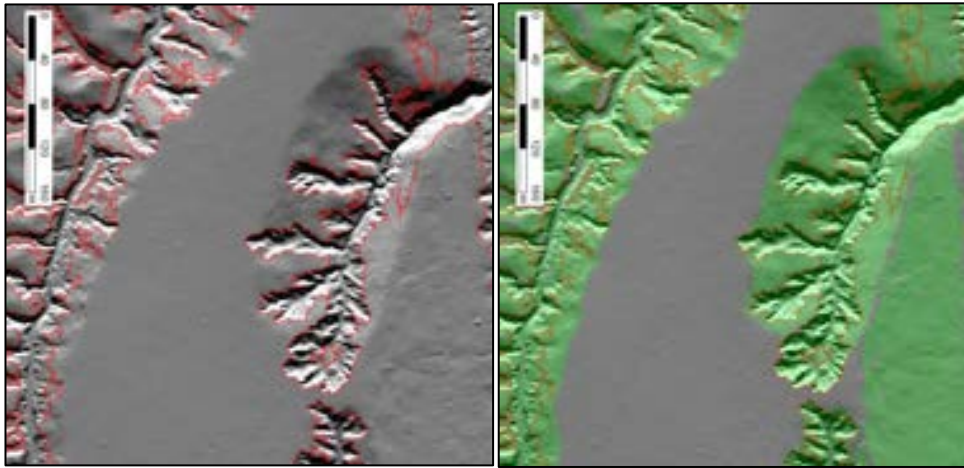


Figure 4: Diagram showing different gully margins. Left: inner 'hard margins' around the gully void. Right: Outer 'soft margins' with the zone including the gully void shaded green.

2.3.2 Gully R-E-D Zones (*Residual – Erosional – Depositional*)

These are definitions used primarily for mapping gully systems and the constituent soil materials (see Figure 5). It is a modified form for soft regolith mapping from the Bureau of Mineral Resources (BMR) scheme for landscape regolith mapping (Pain *et al.*, 1991; Anand *et al.*, 1993; Anand & Smith, 1993). This has yet to be included in the classification scheme explicitly, if it is required in this form. However, the concepts outlined here underpin the process aspect of the classification and provide a basis for defining gullies and gully types, as well as linking the process aspects to gully mapping. R-E-D zones is a novel approach to aid identification of gully form and process for automated mapping and field mapping purposes and is still in development as an automated mapping process.

Residual Zone (Land surface):

Moderately dynamic to static processes; enduring features.

Uneroded/intact land surface unaffected by gully erosion process. Exhibits a largely intact soil profile, except for eroded and deposited material by surface wash. Part of the landscape into which the gully is eroding, and it is currently only affected by hillslope and surface processes.

Erosional Zone:

Dynamic processes; temporary features.

Actively eroding gully head(s), walls and pediment(s), if present. The eroding zone is dominated by evidence of current or prior erosion processes, but it can also be subject to localised deposition and residual lag material development (e.g. nodules, gravels). Dominated by mass movement, surface wash, dispersion and slaking, tunnels. Small, localised areas of temporary deposition in eroded pockets can also occur in this zone

Depositional-Erosional (D-E) Zone:

Dynamic processes; temporary features.

Actively depositional features (fans/cones) of coarser colluvial/alluvial wash load, i.e. temporary, unconsolidated materials. Rarely vegetated with grasses, herbs, or shrubs. Can show evidence of erosion (e.g. rilling, sheet wash, and tunnelling).

Depositional-Transfer (D-T) Zone:

Dynamic processes; temporary features.

Dominantly flat, or gently sloping, planar features below Erosional or Erosional-Depositional (D-E) zones. The local gully floors. Characterised by accumulation of coarser materials with finer sediment layers and micro-fluvial features and evidence of flood flow or drainage flow as sediment transfer processes to a stream. Rarely vegetated with grasses, sedges, reeds. Maybe divided into separate floors by rejuvenation knick-points but is continuous to the gully outlet/terminus.

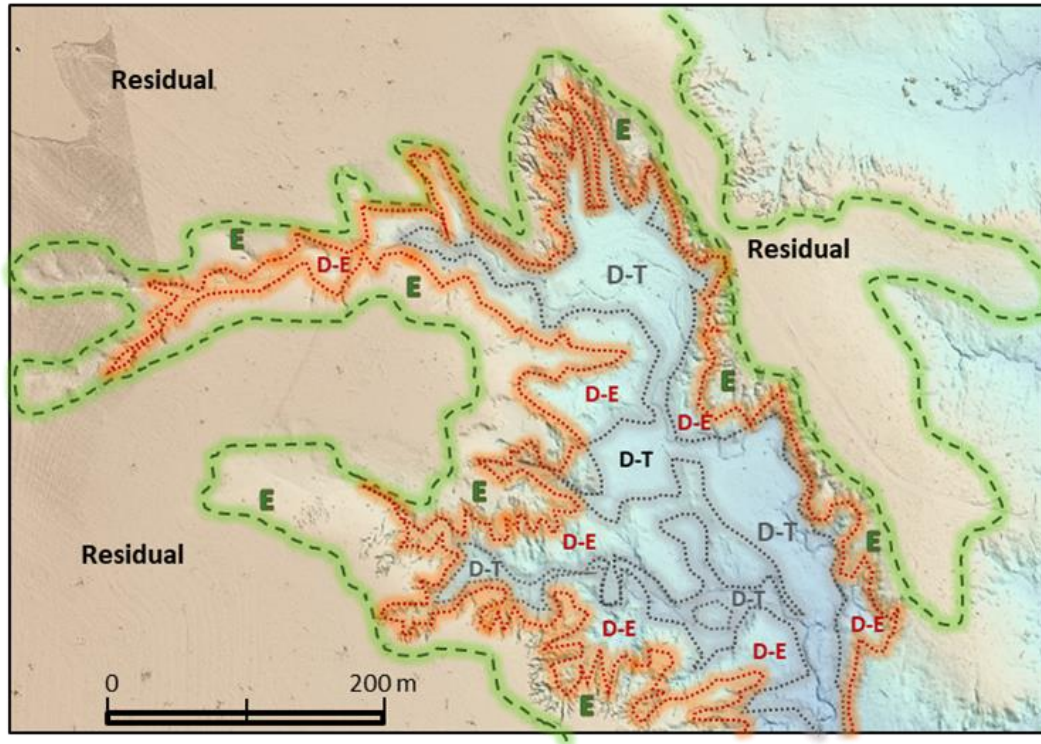


Figure 5: A simplified differentiation of R-E-D Zones in an alluvial gully landscape setting. Automated mapping will pick out greater detail.

2.3.3 Relative Locations

Proximal end

For gullies: Close to or at the point of origin of the gully erosional feature. Usually, the end near the outlet where the feature is assumed to have originated.

For sediment erosion/transport processes: Close to or at the point of origin of the material erosion (i.e. the gully head, walls, eroding in-gully features).

Distal end

For gullies: Close to or at the point furthest from the origin of the gully erosional feature, i.e. the actively eroding head(s) or scarp walls, adjacent to the residual/uneroded land surface.

For sediment erosion/transport processes: Close to or at the point furthest from the origin of the material erosional, i.e. end of the transporting outlet or point of measurement usually the catchment egress to the sea, lake, or impoundment.

2.3.4 Relevant gully features

Features within the gullies are often referred to while describing gullies and describing the attributes within gully classes. Some important terminology used in the classification is defined and explained here. Field and lidar image examples of the terms outlined above and below are shown in Figure 6 to Figure 8.

- **Distal end:** where the gully starts (usually a headscarp or knick-point).
- **Terminus:** where the gully ends. This is a problematic concept (see earlier discussion on definitions of a stream channel and a gully). Usually it is the outlet to a stream, unless the outlet to the stream or drainage network is definitively a stream in itself (see Section 2.2). Often, gully drainage *transitions* to a stream channel before it joins the greater drainage network. This **transition zone** can be deemed to be the terminus of the gully, although judgement must be applied. In some cases, it is not clear if there is a transition, so it may be best to consider the 'drainage' flowline to the confluence as the outlet of the system and, therefore, the terminus also. Defining the terminus of the gully system will also then determine the length of the gully, whether by length of flowline from the furthest head or the length of the longitudinal axis.
- **Proximal end:** The outlet of the gully drainage system to the local drainage network. In the case of discontinuous, or disconnected gullies then the proximal end is where the gully feature loses its defining criteria, and presumably it is where the eroded sediment is depositing. Gully system **boundaries**, or **Margins:** All measurement related to the active eroding eroded eroded eroded hard margins' the outer soft margins of gully systems and individual gullies vary considerably in their shape, character, and relationship to the erosion processes of the gully (see Section 3.2.1). For a functional classification of gully systems for erosion management the inner 'hard margin' is used for the boundary of the gully system as the zone of active erosion and sediment supply.
- The soft margins need to be considered for rehabilitation and management purposes. Reasons for using soft margins/hard margins, where relevant, needs to be stated. Gully **trunk:** the main body of the gully system, subsystem, or gully void (in Linear and Dendritic Forms and variants only). This is where the main drainage flows and may be connected by **Branches** and **Lobes** as tributary gully units. This concept is scale dependent.

Other terms are used in the Classification for Erosion Activity and can be found in the Glossary (Appendix 4).

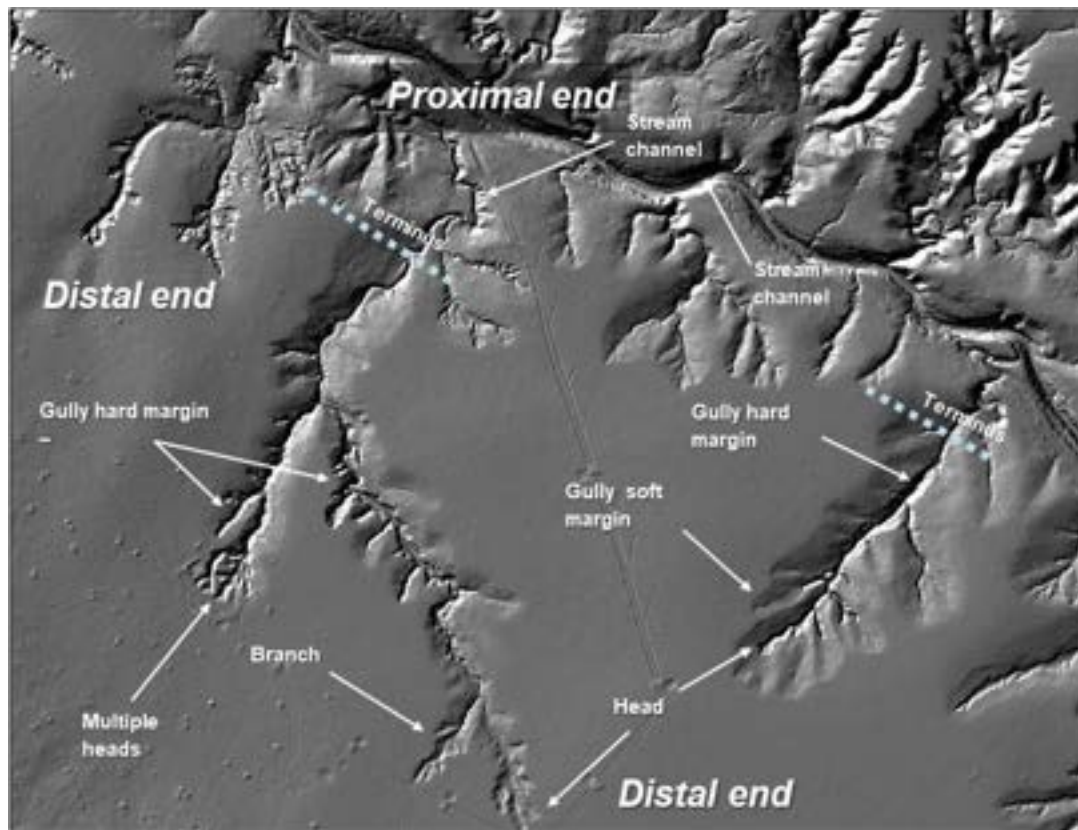


Figure 6: LiDAR hillshade DEM of an alluvial gully system highlighting key features discussed in the text.

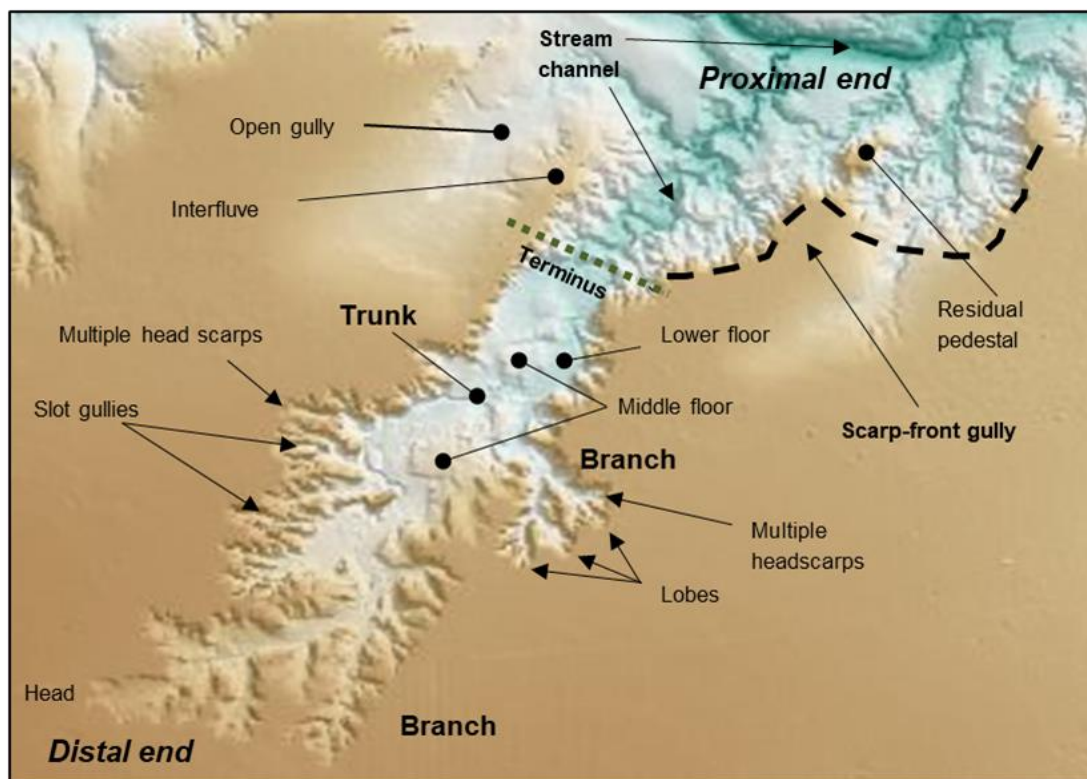


Figure 7: Type gully showing highlighting various terms outlined in the text

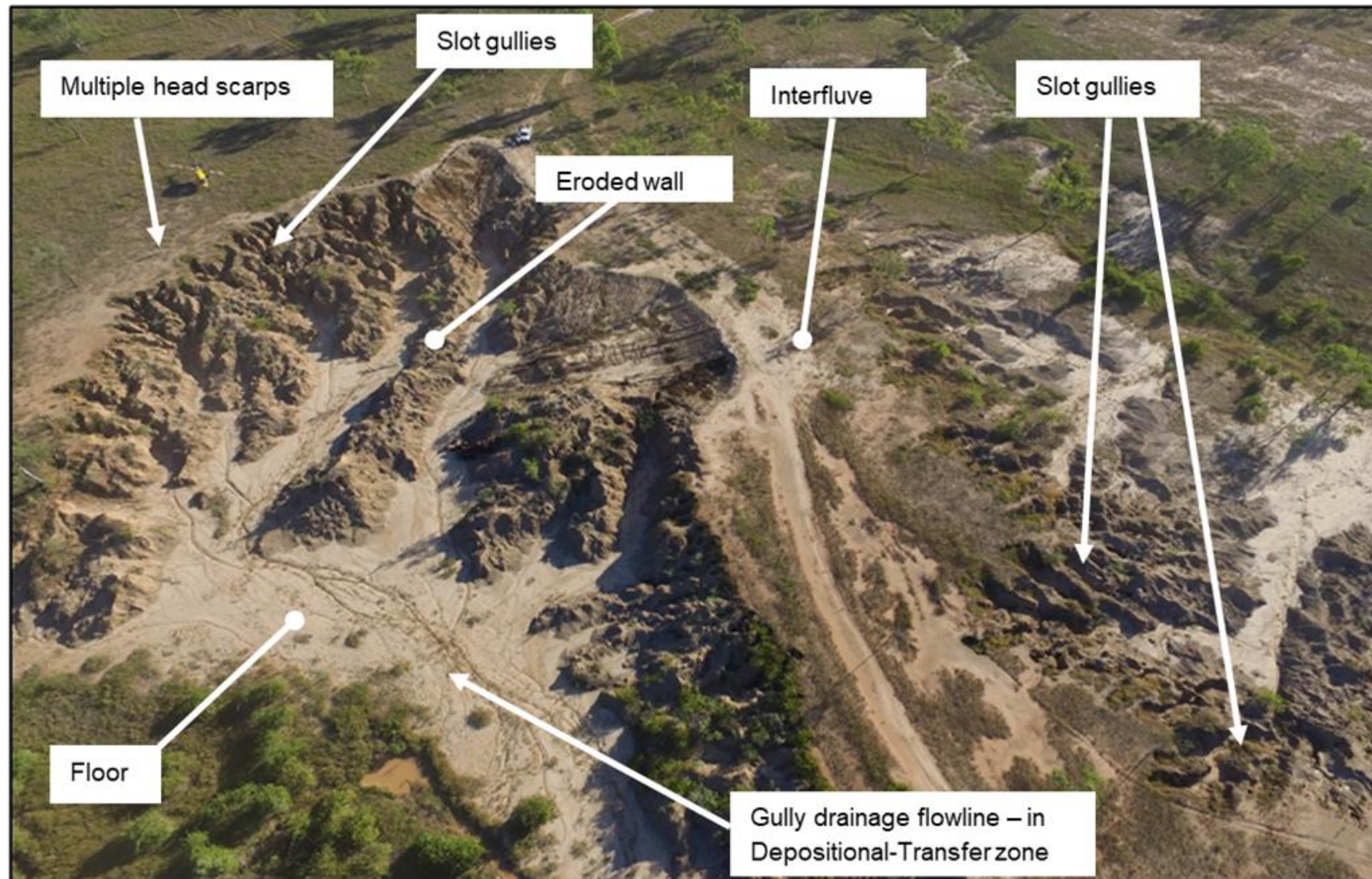


Figure 8: Oblique aerial photograph, showing key alluvial gully features.

3.0 BACKGROUND TO THE GULLY CLASSIFICATION SYSTEM

3.1 A schema for gully scale and complexity

Gully classification is a multi-dimensional process that combines a range of spatial characteristics of a gully that are best determined from remotely-sensed data for ease and precision of measurement, such as plan-form shape, gully area, width, depth and slope, catchment area, landscape setting. A range of non-spatial, field parameters such as soil material and vegetation characteristics, also then must be considered. The parameters relevant to classification can be determined using either field or remotely-sensed data, depending on the nature, resolution and availability of the remotely sensed data (e.g. high-resolution lidar). The schema presented here is an initial draft of the classification process.

3.1.1 About gully scale

A critical aspect of classifying gully systems is to establish the scale (extent) and resolution (detail) at which a gully or gully system is being assessed at the initial stage of the process. Gully systems develop different characteristics as they expand in scale. Hence, an assessment and evaluation of gullies must be conducted and presented at the appropriate process-sensitive scale.

Most linear hillslope gullies and smaller alluvial gullies can be observed, or followed, in full in the field, and hence the gully unit that is being classified is relatively straight forward. However, many large hillslope and river alluvium gully systems can be tens of hectares in area, comprising multiple, nested units that make up the whole system (Figure 9 and Figure 10). Decisions as to what features to investigate for characterisation and managing gullies need to be made at the field observation scale as well as via remote imager. In such systems it is important to identify that scale of the gully unit that is being classified. Hence, clear statements need to be made as to the definition of the gully systems or subsystems being classified, e.g. complete gully systems defined from the outlet to the fluvial drainage system to the head(s), or for all systems in a tributary river system (Figure 10). This sets the scale level and resolution of the assessment for classification.

3.1.2 Defining gully scale

The example shown in Figure 11 and Figure 12 is a large alluvial gully complex on the Leichardt River comprising multiple coalesced gully systems (note this image is around 500 m wide). How such a system should be classified is very much a function of the scale of observation. Therefore, it is critical that the scale at which the classification is being applied is defined, before any sense can be made of such a highly complex system.

The sinuous channels exiting the gully system would be better described as stream channels at this point and so this whole complex *gully system* is comprised of an array of *unit gullies*, within *gully subsystems*, connected by channels into a whole *gully system*. The differentiation between a stream channel and a gully is discussed in some detail below. The enlargement in Figure 12 shows the different nested gully features that are apparent at different scales.

As a general guide, the gully unit is the sort of feature that you would be observable if standing at its margin in the field, whereas to observe the Gully Subsystem or Gully System would require a birds-eye view typically gained from remote sensed data. Some gullies only exist at the Gully Unit scale and are therefore much easier to define. However, most alluvial gullies require that they be considered at multiple scales. In the examples shown in Figure 9 to Figure 10, the gully type would change with gully scale. So, the Gully Units might be classified as Open Form, whereas the Gully System would be described as a Scarp-front. *Depending on the purpose for the classification*, it may not be necessary to classify the system at all three scales, but it is important to define the scale so that another person using the system can understand the decision-making process leading to the adopted classes. Further examples in which there are multiple gully types, depending on the scale of observation, can be seen in Figure 11 through Figure 13. Detailed descriptions of each level of scale of gully features are explained further in Section 3.1 below.

Once the appropriate scale of observation has been established, the following provides some guidance regarding the various steps through the classification procedure shown in Figure 5. The conceptual diagram provides an overview of the classification at the highest level but underpinning each level of the classification process are a number of more detailed metrics that can be used to provide a deeper level of understanding of the gully in question.

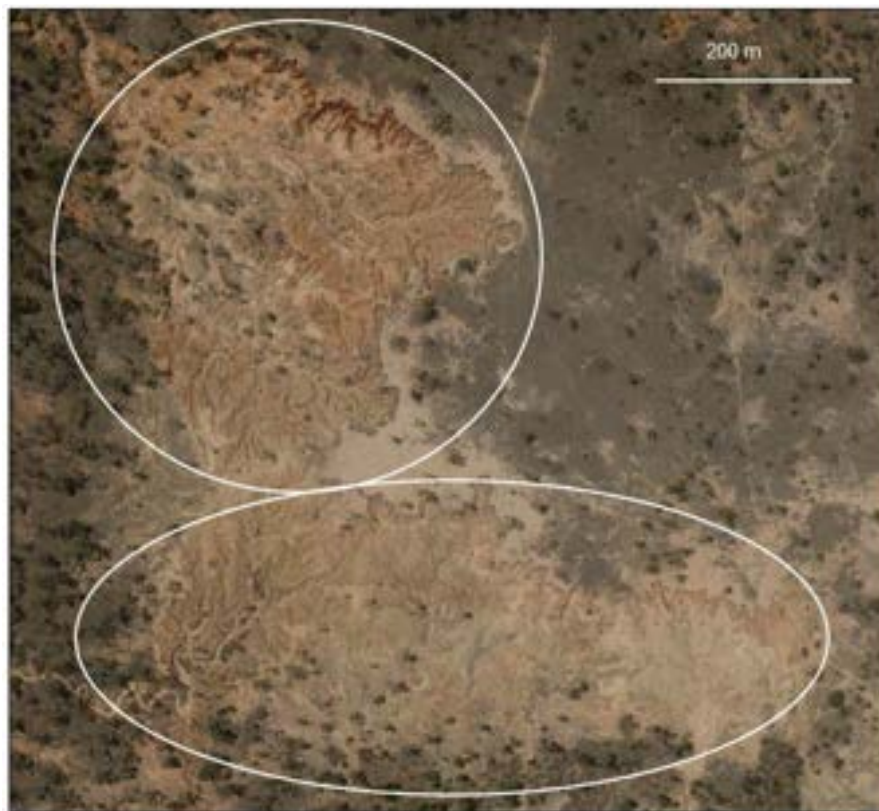


Figure 9: Examples from aerial imagery of alluvial gullies where the decisions as to what features to investigate for characterisation and managing need to be made initially at the remote stage – if whole systems are to be characterised and classified, or only selected subsystems within them.

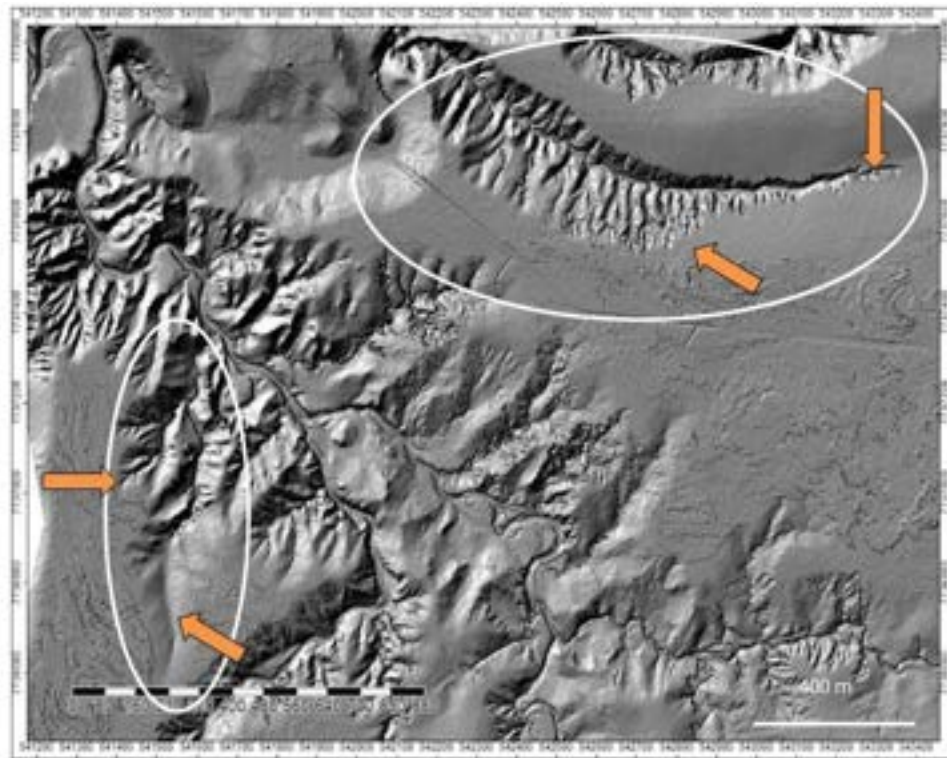


Figure 10: Examples from LiDAR of alluvial gullies where the features indicated with arrows are all essentially simple gullies of different scales but are part of much larger gully systems (circled).

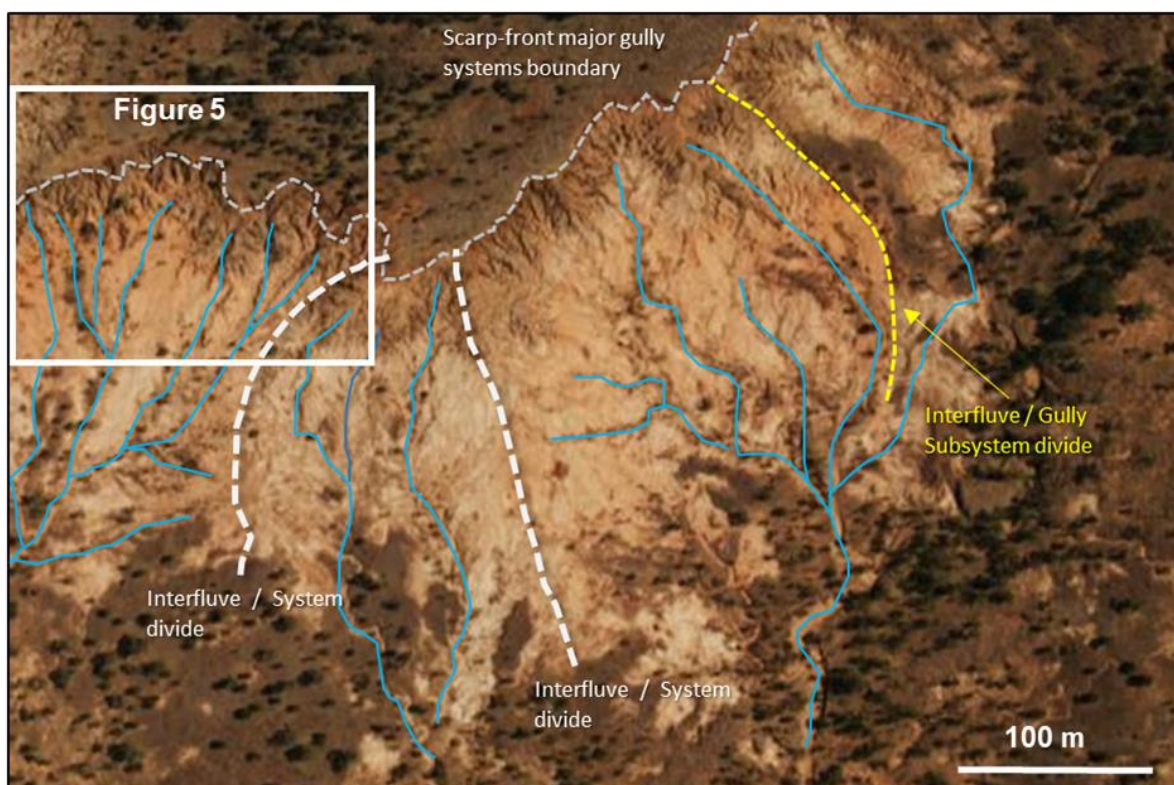


Figure 11: A large alluvial gully complex on the Leichardt River comprising multiple coalesced gully unit systems. Identifying the scale at which to apply the classification is important in complex systems.

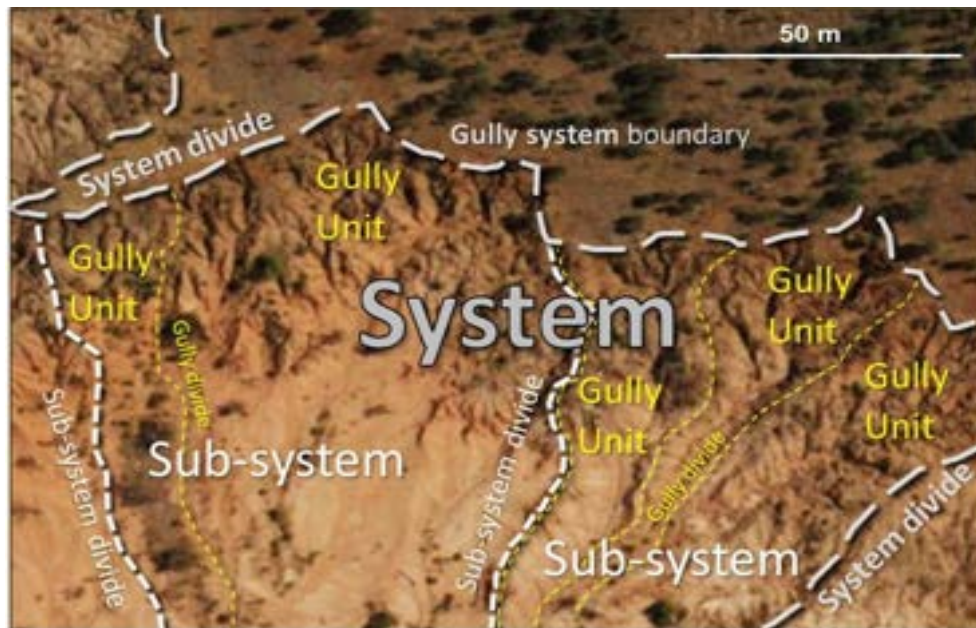


Figure 12: Enlargement of the box in Figure 11 defining the scale of analysis in a large alluvial Gully System.

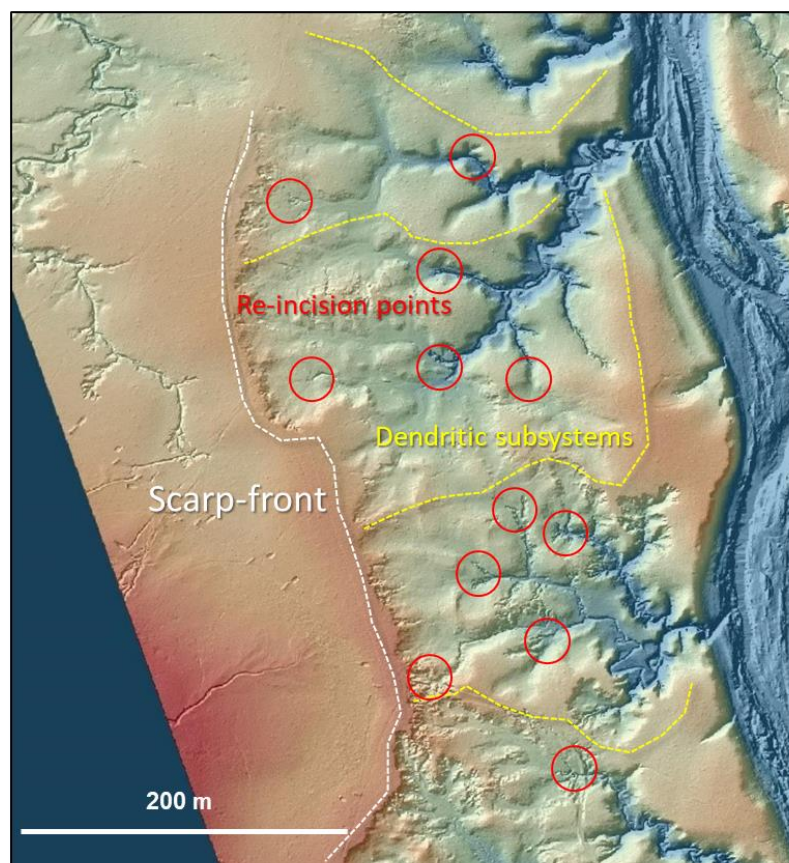


Figure 13: Another example of a Gully System (broad process-network scale) that can be described as a Scarp-front type System in an advanced state, and has formed from an incisional gully phase comprising linear gullies at a finer process Gully Unit scale that have rapidly expanded (in different soil materials) and formed a dendritic network at an intermediate, Gully Subsystem scale.

SYSTEM

A group of gullies (including channels) with a common outlet or with related outlets (e.g. in coalesced gully systems), in close proximity to the drainage network or common depositional landform (Figure 14). A distinct grouping of gullies, and possibly stream channel, that operate as an integrated hydrological and erosional system. The system can be of one main gully form or of a variety of forms. Includes stream channels if they are part of the stream-line to the outlet.

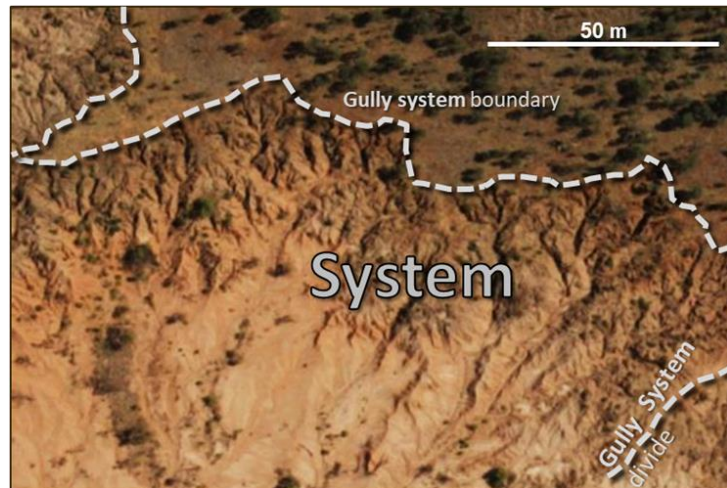


Figure 14: Example of a large gully system

Subsystem

A subset of the identified gully system, with a *single* outlet or end-point, that is an identifiable unit for assessment or management purposes (excluding stream channels). It can be a series of similar or disparate gullies in a connected network, that consist of more than one gully unit but constitutes only part of a gully system (Figure 15). The sub-system is probably the typical scale that a gully would be managed as a discrete unit.

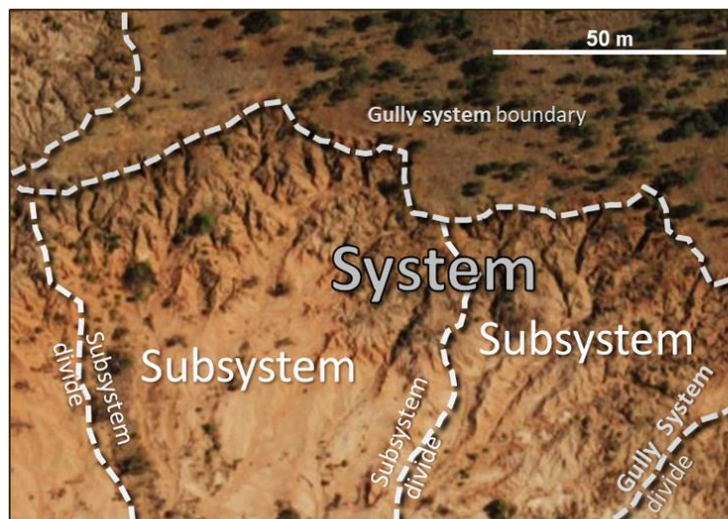


Figure 15: Example of two gully sub-systems, making up the gully system (Figure 14).

Gully Unit

A simple unitary gully form that is not easily subdivided, that is identifiable as a single type in the field or on imagery, and is not a stream channel (see gully – stream channel’ definition above). The fundamental gully unit. Gullies can be subdivided into Branches, Lobes, Heads, and Scarps (Figure 16).

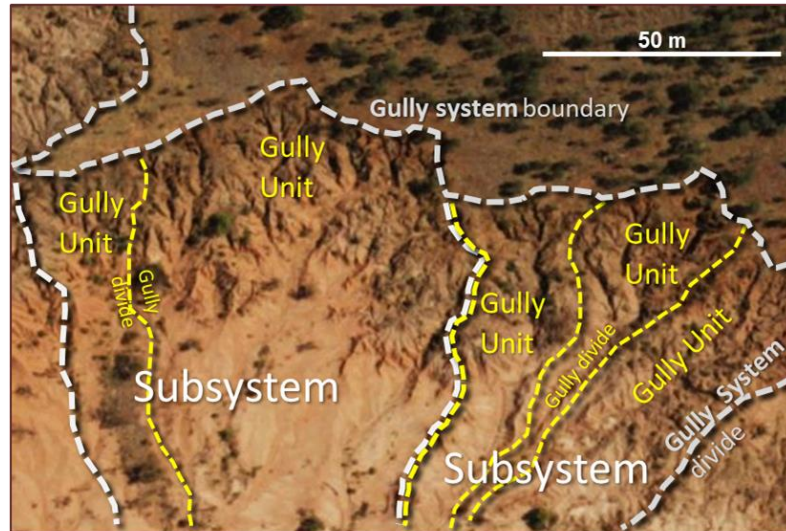


Figure 16: The relationship between a) a Gully system, b) Gully Subsystems, and c) Gully Unit.

3.1.3 Complexity

Identification of Simple or Complex systems (depending on scale and resolution of investigation), can be established from DEMs, imagery, lidar DEM, and morphometric analysis.

Simple

A uniform type of Gully System, Subsystem, or Gully Unit based on morphology and gully-type 'Form' (see Gully Classification below), even at field scale of observation. Individual gully units may also be simple gully systems.

Where the Gully System, Subsystem, or Gully Unit appears to be of one form and shows no change in floor or base level or nick points. The gully can be described as one 'Form' as a whole (see Figure 17).

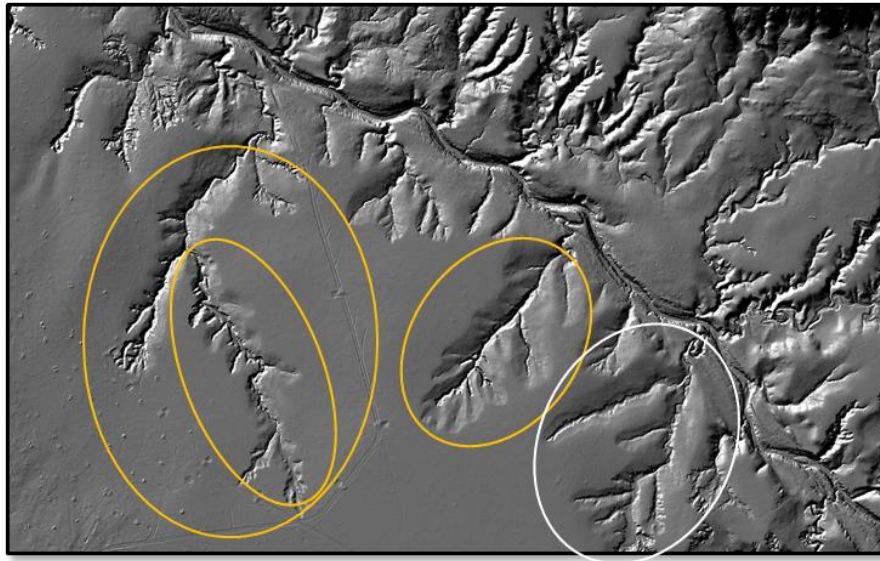


Figure 17: Simple linear Gully Units in Linear Subsystems (orange), and in a Dendritic Subsystem (grey)

Linear and Dendritic gullies and some Open gullies can be identified as Simple systems, some of these and Amphitheatre and Scarp-front gully systems would not fall into this Simple class of complexity.

Compound

Where the Gully System or Subsystem appears to be of more than one form and shows change(s) in floor or base level and/or knick points. The system may be nested, and/or each form and gully type can be identified and defined at a field scale of observation and assessment. The system may show simple difference in erosion forms by varying erosion processes and variable eroded materials. The gully can be described as one or more Forms as a whole (Figure 18).

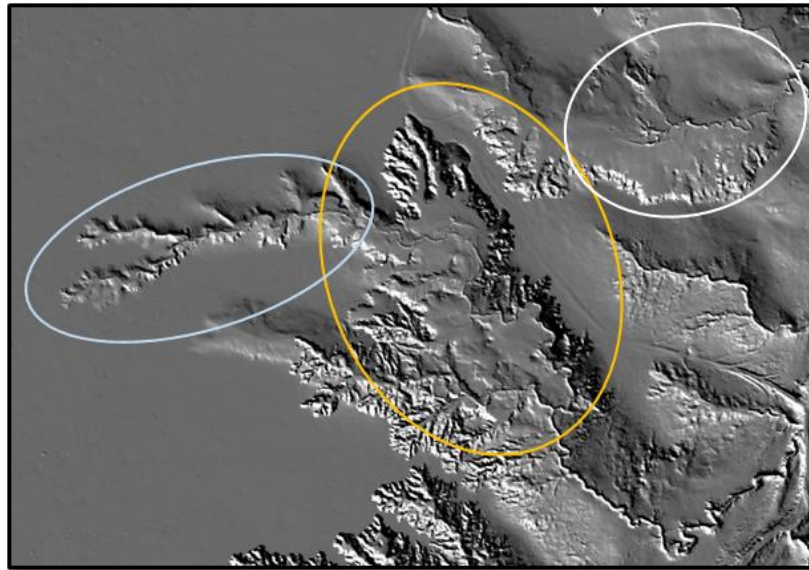


Figure 18: Example of a Compound gully system – A Linear Gully Unit (grey) branching from an advanced state Open gully (orange). Also, a Linear re-incision within an Open Gully Subsystem (white).

Each subsystem form and gully type can be identified and defined as one of the five Gully Forms in this classification at a more detailed level of description and assessment. The gully system can be described as a set of one or more Forms as a whole. Many Amphitheatre and Scarp-front gully systems would fall into this Compound class of complexity (otherwise into the Complex class) along with some Linear, Dendritic, and Open systems.

Complex

A multi-form Gully System whereby the arrangement or Form of (sub)systems is not possible to ascertain at finer levels of observation.

Where the gully or gully system appears to be of more than one form and shows changes in floor or base level and/or knick points.

The system may be nested or show differences in erosion forms by varying erosion processes and variable eroded materials. Each gully form, or subsystem of forms cannot be practically identified and defined as one of the five Gully Forms in this classification at a more detailed level of description and assessment. The associations are too complex to describe simply or clearly. The gully system can be described as a complex of more than one Form as a whole (Figure 19).

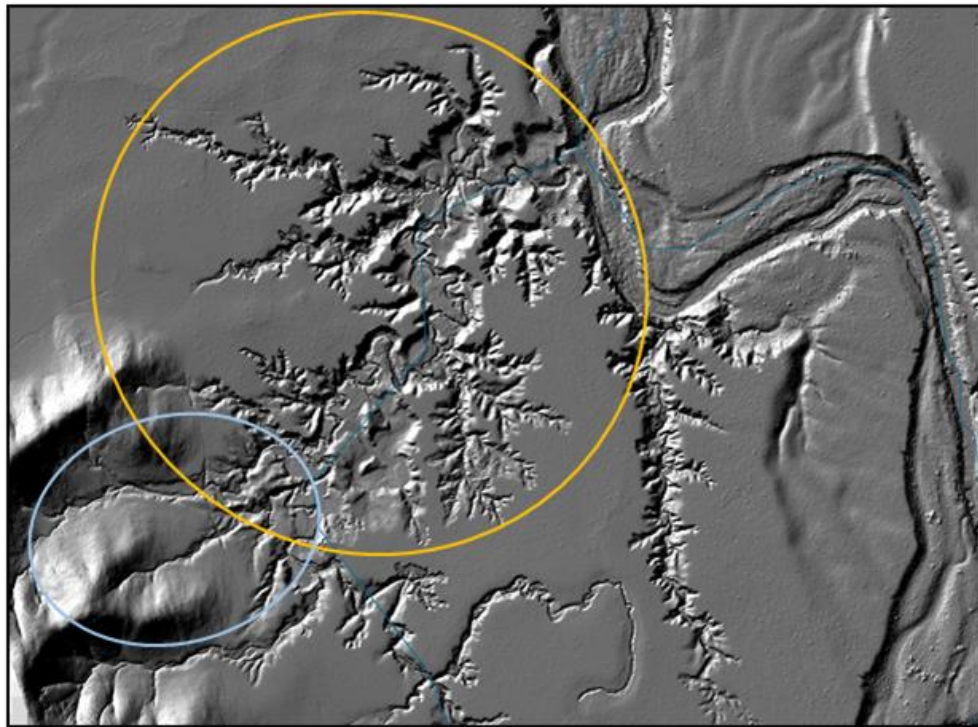


Figure 19: Complex gully system which are usually only found in Gully Systems such as this Alluvial Domain where Linear and Dendritic gullies are developing from an advanced eroded state subsystem of indeterminate with multiple floors and re-incision (orange), which has also developed from Hillslope Domain gullies (grey).

3.1.4 The Landscape Domain

The **Landscape Domain** describes the context of the gully system by way of physiographic setting and geomorphological material and process. It includes the nature of the dominant erodible material in which the system has formed and the physiographic forms of hillslopes and alluvial plains. It includes an intergrade class where the landscape position and type of host material is in question, or in complex association (Figure 20).

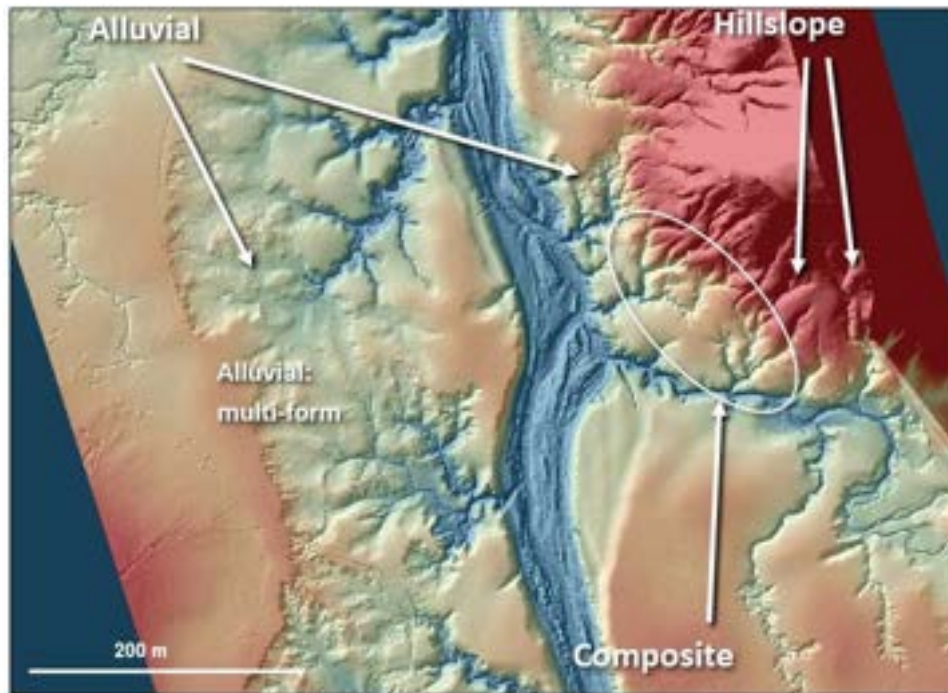


Figure 20: Example of the different landscape domains within which gullies have formed at Crocodile Station research area, Cape York Peninsula, Queensland. Gullies on the right-hand side of the image have been initiated in alluvium and have eroded into the adjoining hillsides

HILLSLOPE DOMAINS

The Hillslope Domain gully systems initiate and develop in hills, low hills, pediments, and rises (*sensu* NCST, 2009) in residual soil-bedrock material, or transported colluvial material, i.e. away from the alluvial floodplain and terrace deposits of moderate to major drainage systems (high order creeks and rivers) (Figure 21). Gullies usually initiate by headward erosion upslope from initial in-slope knick points or breakaways. Gullies may be ancient (i.e. > 200 years old), stabilised features reactivated by clearing, cattle movement, or rare major surface flow events. Hillslope gullies are commonly Linear, Dendritic, and Open Gully System Forms.

Colluvial

Those systems and individual gullies that have developed in, and are eroding, soil materials that are largely transported: consolidated or unconsolidated, or both; stratified or unstratified; colluvium, with little or no evidence of bedrock constraint to vertical or lateral development.

Residual

Those systems and individual gullies that have developed in and are eroding soil materials that are largely residual and have developed in situ from bedrock weathering and pedogenic processes. Evidence of bedrock constraint to vertical or lateral development may be common.

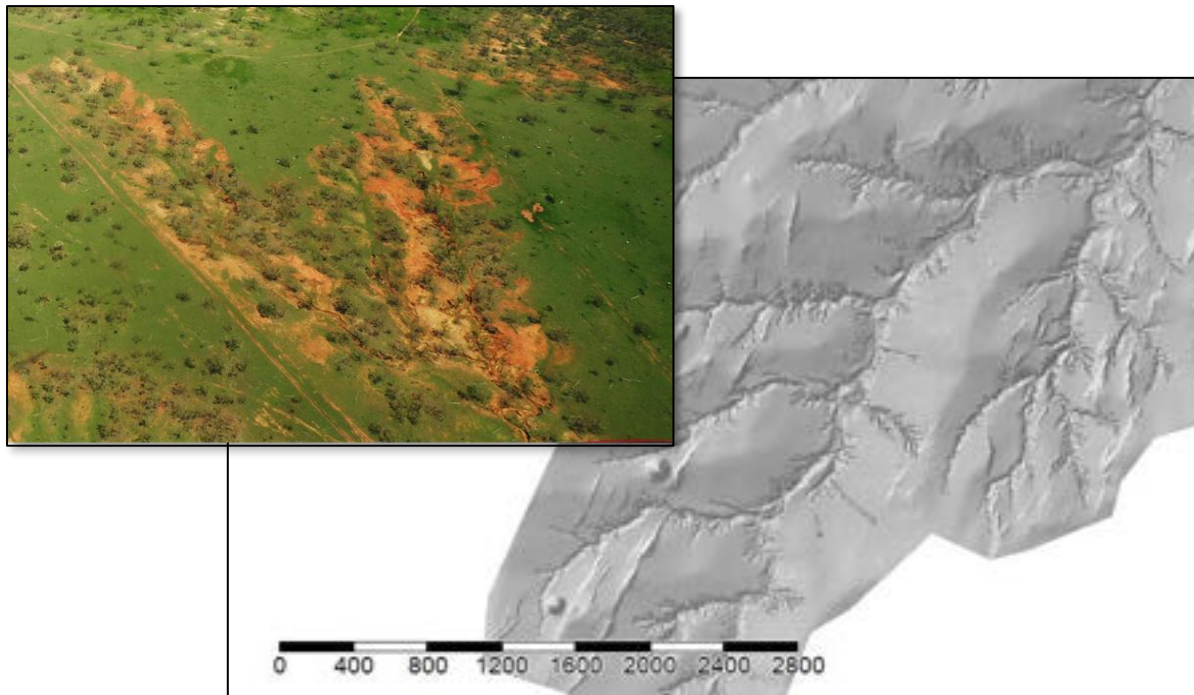


Figure 21: Example of Linear and Open forms of hillslope gullies.

ALLUVIAL DOMAINS

The Alluvial Domain here refers to floodplains (*sensu* NCST, 2009) and terraces (*sensu* NCST, 2009) (relict floodplains and terraces included), and alluvial plains (*sensu* NCST, 2009) associated with current or prior stream channels to major drainage systems (usually of a stream order of 3 or higher). Alluvial gully systems (Brooks et al., 2009) develop usually as floodplain drainage and streambank erosion features and headward development is away from the stream channel. Some gullies on alluvial slopes may develop in a manner that is similar to hillslope gully processes (i.e. headward erosion from knick points initiated by streambank erosion, or from bank disturbances such as cattle tracks). Gullies may be ancient, stabilised features reactivated by clearing, cattle movement, or rare major surface flow events. All Gully System Forms occur: Linear, Dendritic, and Open, with common Amphitheatre and Scarp-front forms formed from coalescence of prior gully forms.

Floodplain; Terrace

Small to very extensive gully systems of all forms often eroding saline and sodic materials that may become dispersive. Alluvial materials deposited by overbank flows either currently or in the past capable of high sediment loads. May be part of past swamps, or very broad, extensive alluvial systems (e.g. anastomotic plains, covered plains, alluvial fans or megafans (such as the Gulf of Carpentaria catchments), and sheet flood fans (*sensu* NCST, 2009)). Often extensive features rapidly developing in exposed dispersive substrates (Figure 22). Often bounded by colluvial hillslopes in more confined alluvial settings, where gullying may continue.

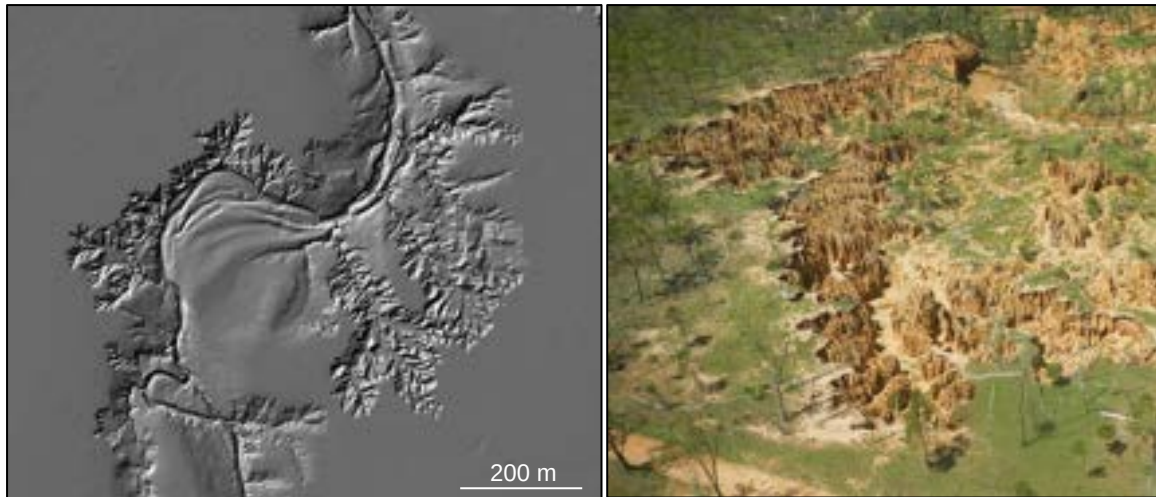


Figure 22: Examples of Terrace Alluvial Domain gully systems.

Bank Gullies; Terrace Slopes

Proximal gullies that form in the levees and floodplain banks that drain and flow directly into the main drainage system (stream, river, or major river) without eroding into the floodplain or terrace material to any extent.

Some recent and relict floodplains and terraces exhibit sloping surfaces, and terraces can often be bounded by low bluffs of moderate slopes at their base. Increased kinetic energy from sloping terrain can initiate gully erosion into susceptible alluvial materials by hillslope gully processes (i.e. headwards erosion from in-slope knick points).

Valley Bottom

Within hill terrain and smaller river valleys, gullies can form in the valley fill. In hill terrain the materials may be uniform alluvial materials or alluvial soils, whereas in the small river valleys, the material is more likely to be alluvial soils on stratified sediments.

COMBINATION DOMAINS

There will always be intergrades of these two main Hillslope and Alluvial Domains where the landscape position and type of host material is in question, or in complex association. Two main Combination Domain scenarios are defined here.

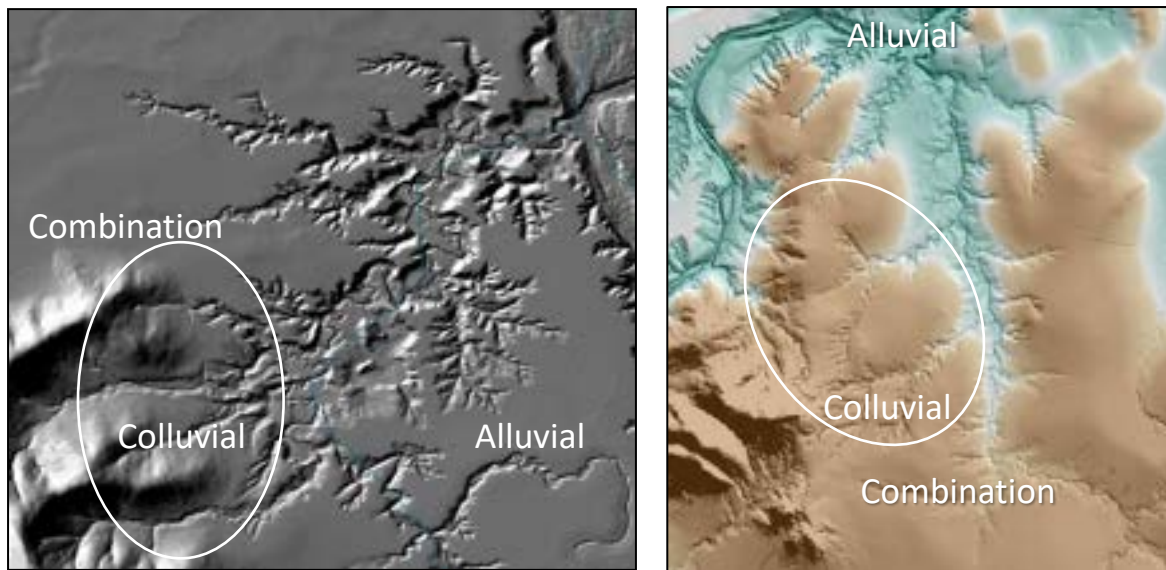


Figure 23: Examples of Combination Alluvial-Hillslope Colluvial Domain gullies.

Alluvium to Colluvium

An intergrading form where gullies or gully systems originate in Alluvial Domains and have migrated into a more colluvial landform context, e.g. footslopes of hills and rises associated with bedrock forms. Gullies may have developed by headward erosion from alluvial plains or terraces into the Hillslope Colluvial Domain, or channel erosion from hillslopes has been accelerated in the alluvial materials, with a change in material resistance and flow energy. Usually Linear or Dendritic Forms.

Alluvium slopes

Some older alluvial landforms may have been deeply dissected by prior phases of gully erosion, and have then been stable for many thousands of years. Such alluvial landscapes often contain valley fills comprised on material redeposited during the prior erosional phase and/or in association with backwatering from adjoining mainstem channels. Such landscape can exhibit some of the characteristics of hillslope gully forms. However, the fact that they are eroding into deep alluvial sediment deposits places such gullies firmly within the Alluvial Domain. These alluvial fills can host gully development in dispersive soils and the gully forms can migrate to adjoining colluvial and residual Domains. The re-incision into the fills is often characterised by Linear and Dendritic Forms in the younger fill, which then progress into Amphitheatre or Open Forms once the gully erodes into older alluvium.

3.1.5 Gully Form

The overall plan-form of a gully or gully system at the broadest spatial scale relevant to the feature, to encapsulate the whole feature or group of features. These Forms are distinguished by defining, assessing, measuring the following attributes, which serve as the criteria for rules to classify each type. Common variation to the Forms that are discerned from the metrics assessment are identified as Variant Forms or just **Variants**.

Attributes used to characterise gullies so far are:

Plan-form or gully margin and head(s); Profile-form of cross-profile and long profile of the system

Outlet form

Head shape; Head - dominant erosion processes

Sidewall shape; Sidewall - dominant erosion processes

Within gully architecture

Possible drainage network shape/form of the system and within the system

Basic morphometric analysis of:

Length

Width

Depth

Plan area

Surface area

Perimeter

Catchment area

Ratios of

Width/depth

Length of overland flow

Contributing catchment area / erosional gully area

Longitudinal axis / lateral axis

Circularity

Elongation

Texture

Indices of:

Plan shape

Cross-sectional shape

Compactness

In-gully hypsometry

In-gully stream power (derived from catchment area/slope metrics)

In-gully sediment transport capacity (derived from catchment area/slope metrics + channel dimensions).

Soil material characteristics

Stratified, uniform, or solum horizons

Cracking Clays or not.

Soil material unstable because of dispersivity/slaking

Indurated layers or not

The classes of Gully System Form are not dependent on each of these factors but will contain dominant factors and distinguishing factors that will specifically characterise the individual classes. The five Gully System Form classes outlined here are described in terms of the dominating and distinguishing factors.

Work is still in progress to use terrain morphometry, based on gully and catchment shape factors and ratios, to help categorise gully systems, subsystems, and gullies. This digital approach is more to characterise individual gully systems rather than to classify them. However, certain criteria are relevant to the classification process, and they are outlined below.

Five types of **Gully Forms** have been defined: **Linear**, **Dendritic**, **Open**, **Amphitheatre**, and **Scarp Front**.

3.1.6 Soil Material Layers

The concept of layers of materials is used in this gully appraisal context rather than soil horizons and geological strata because:

- Not all the material found in alluvial and colluvial environments can be termed soils and therefore do not possess horizons;
- Individual soil horizons are often difficult to determine and interpret with any confidence by non-specialists in soils and soil science;
- Not all horizons, once determined, are relevant to either the classification of gullies or to the management, control, and rehabilitation of erosion gullies;
- The A horizon or topsoil' is often not present in many gully wall profiles or gully surrounds, having been largely or completely eroded in or around gully systems. This makes standard soil classification difficult.
- Similarly, not all the materials in which alluvial and gullies form in are sedimentary strata, with geological interpretation and nomenclature. Strictly all the gully materials, except hard bedrock are part of a soft regolith' which also has particular nomenclature and interpretation by specialists;
- Following the precept that you should classify what you can observe, it is easier to observe and record the obvious layers that may be observed within the gullies, by differences either in colour or fabric' structured or cracking clays earth sands clays sandy loams, etc.), or by inclusions of gravels or nodules, or a combination of these;
- A simple determination of different layers can be made from systematically observing from the top-most to the base of the gully (preferably at the outlet, to get the deeper layers too), and giving them a sequential number.

This has been the system followed by the Griffith University PrESM research group for gully description, mapping and classification purposes, and has been incorporated in the gully database so far. This is the subject of a NESP Tropical Water Quality Hub project that is still in the reporting stage.

As far as the classification goes, it is necessary to observe layers as distinct from soil horizons (although horizons can be distinct layers), to determine the overall Soil Material Group that is the first criterion of the Soil Materials section of the classification (see Section 5.3.1). This criterion is based on the observation of:

- whether the layers represent strata in any way (in alluvial and colluvial environments i.e. transported materials therefore it is called 'stratified'
- whether the layers represent simple soil horizons weathering in situ from bedrock, and is therefore a soil profile only i.e. a solum' it is therefore called 'Profile'
- whether there are any layers at all can be observed and the eroded material is largely all the same in everything except colour, which may be a topsoil horizon change only (i.e. fabric, hardness/firmness/erosion resistance, inclusions like gravels). If it cannot be seen to be a soil profile on bedrock, it can then be identified as 'uniform'

Fabric

Although soil materials may be described by their structure (pedality), or lack of it (apedality), geomorphic and geologic materials are also described by their fabric, which can be defined as similar to both the soil structure and texture together. The soil texture can be determined

in the field by experienced personnel, and may not be the same as the particle size distribution (e.g. in estimating clay percentage or silt percentage).

The particle size distribution of the gully materials can be determined by laboratory analysis. The field structure and texture can be observed as a material fabric. Different fabric types have been identified for the descriptions in the gully database. For the classification, only fabric of the true cracking clays (with the shrink-swell properties evident) and a distinct contrast in fabrics in the upper two or three layers – often a weakly structured or structureless hardened sandy loam top layer over a structured clay (can be sandy or silty). The third fabric type is not necessarily so clear, but it relates to very old and weathered materials that have either become eroded and earthy or caliche without an structure as in a laterite or may have become indurated (see Glossary Appendix 4).

3.1.7 Erosion Activity

The need to determine the current status of erosion activity is to assess the general class of sediment yield potential and general instability of the gully or gully system and its future trajectory in this regard. This is an attribute (or set of attributes) of a gully that relates more to the management requirements and prioritisation for action than to describing its form and context. In this sense it is a primary component of the Gully Typology that will eventuate from this classification.

Franklin et al. (2004) devised a simple scheme to help prioritise gullies for some form of control management and rehabilitation by erosion status for hillslope and valley bottom gullies in NSW. For this they classified the erosion status of the gully head (singular), the gully walls, and the gully floor. Eight classes were defined from whether the gully head was active or inactive, then similarly for the gully floor, and ending with a similar binary allocation for the gully walls.

For all the gullies under consideration in Queensland this sort of system would prove too simplistic by itself – as it is constrained to erosion control and management on relatively small systems on hillslopes and valley bottoms found in NSW, and not covering the wider array of types found particularly in Queensland in the subtropical and tropical climatic zones. However, an adaptation of this idea can be tentatively incorporated into the Erosion Activity attribute Level in this scheme, with the intention of developing it further for the Gully Typology.

This is outlined in Section 5.3.2 below.

PART 2

4.0 THE GULLY CLASSIFICATION

4.1 The Gully Classification rationale

As outlined in the background, the classification described here is a beta version which is expected to evolve through time. It has been designed on the basis that the classification:

- 1) is only an initial approximation and will develop with use and feedback from users to develop a more robust and comprehensive, practicable framework;
- 2) is a 'technical' classification for scientific integrity and further technical and scientific research and development applications. Explanations and actions for using this classification have, however, been expressed so that it can be employed also by non-specialists or field technical users;
- 3) needs to be comprehensive as far as possible to include all forms of gully systems found in Queensland and the materials and landscape locations in which they occur. However, this should not compromise the practicability of both understanding the classification and applying it;
- 4) needs to have a limited number of groupings to each tier of the framework so that is easily understood and manageable in its use, Complicated groupings and class entities compromise its practicality and practicability;
- 5) allows for flexibility in application and use in the field as well as being also based on detailed desktop analysis and assessment. Although the classification is designed to be followed from the 'remote' desktop analysis first then verified and augmented field visit, it can be legitimately employed primarily in the field from the outset, using the Field Manual, and then completed with the desktop analysis. Both components are necessary to satisfactorily complete the characterisation and classification process;
- 6) focuses the main geomorphological tenets of *erosional form*, *environmental context*, and *soil material*. Although it is not process-based *per se*, erosional and depositional processes are included in the morpho-genetic concept;
- 7) has, at its basis, the ability to be applied easily to environmental management and planning requirements;
- 8) is designed to work, initially, from the most detailed spatial data available for desktop analysis: that is, lidar data of at least 1 m resolution, aerial and satellite imagery of sub-metre and sub-10 m resolution respectively, if possible;
- 9) directly compatible with the database and all data that is collected for gully assessment and classification purposes using the Field Manual and Handbook is compatible with the

database. However, the database has been developed to accept and manage other gully-related data that is not directly associated with the classification.

- 10) must employ clear definitions of attributes/criteria as far as possible, but these will need to be defined during the process of implementation. The attribute must also be independent of each other. Each attribute or criterion should have a clear rule-set to allow clear allocation of entities to groups or classes. These rule-sets will develop with the classification and with the development of automation in the process;
- 11) will have to be scale dependent owing to the nature of the entities being classified. Gullies and gully systems vary widely in their form and sediment transporting process and operate at different environmental scales. Gully systems also have to be perceived at different scales for environmental planning and management purposes. Clear definitions of scale and involving scaling in the classification are extremely important; and
- 12) allows for the development of one or more 'typologies' for specific purposes which are essentially modified and simplified derivations of the overall framework. These typologies will be more of a hierarchical process to focus on the specific management requirements and the associated attributes and criteria.

4.2 Structure of the Gully Classification

The classification is not based on a 'step' process – the subject matter does not yet lend itself to that, but future iterations of the classification, especially with automated processes will possibly develop a key approach. The classification is 'tiered' rather than hierarchical, and the major or tiered elements are termed **Levels** and correspond to the major **attributes** that are used to describe gullies. The treatment of spatial scale is a hierarchical process. The classification allows for entry at different 'levels' or 'tiers' and it relies on weight-of-evidence to some degree for grouping, and both intergrades and variations can exist.

In summary, the Classification is:

- **Attribute-based**;
- **Morpho-genetic** in concept, i.e. relates to forms, materials, and processes;
- **Scale dependent**, both by extent of data, and by resolution of data, in a hierarchical fashion;
- Composed of three integrated **Components** relating to the remotely- or field-based activities. Currently, the Classification is organised in such a way that it presupposes (although does not necessitate) that the desktop analysis will be done prior to going into the field, either using datasets that cover large areas (lidar or high resolution satellite imagery), or at an individual site. Field visitation is then necessary to collect data on parameters that cannot be gleaned from remotely-sensed information. The Components are: Remote / Remote-Field / Field, reflecting the type of data collection and assessment required.
- Within these three Components are eight (8) groups of gully environment **attributes** that are selected as being the most relevant to both a natural and functional classification, serving both natural sciences and land management respectively. Five (5) of these are

termed Primary Classifiers, which are attributes that contribute to the main Class or type of gully:

- **Gully system scale:** see Section 3.1.2
 - **Landscape Domain:** the geomorphic and materials setting.
 - **Gully Form:** the plan-form shape and geometry of the gullies.
 - **Gully catchment dimensions:** expressed by contributing catchment area (CCA), or distance to the divide, or watershed (DtD).
 - **Soil Materials:** the type of geomorphic materials in which the gullies are forming that vary in characteristics and erodibility. A particularly important attribute of the materials is their **dispersion** ability (dispersivity).
- Five (5) other attributes are then applied as Levels, being qualifications to those Classes only and are not part of the Class description, but they do have relevance to the assessment of gullies as to their management and control. These are termed the Key **Qualifiers**:
 - Climate/Rainfall zone: based on the Australian Köppen climate classification;
 - Gully system complexity: a subordinate Qualifier to the Gully Scale Classifier. See Section 3.1.3;
 - Multi-form Development: a subordinate Qualifier to the Gully Form Classifier;
 - Vegetation Cover: covering both inside and outside the gully;
 - Erosion Activity: evidence of active erosion to gauge overall activity levels. This will also be possible to assess remotely by DEM metrics in future.
 - Some of the attributes are measurable parameters in some way being both qualitative and quantitative in nature. Phases of measurement or calculation on the DEM morphology, and in the field are embedded within the classification both in the Remote Component and the Remote-Field Component. See Appendix 1.

An overview of the Primary Classifiers and the Key Qualifiers are shown in Table 1. A more detailed breakdown of each level of the conceptual model is shown in Table 2.

The attributes used as Classifiers and Qualifiers are also presented in Table 2 with respect to the way they need to be perceived and interpreted in terms of their scale of usage, whether they need to be quantified or not, and the need for field observation to characterise them.

The overall framework of the classification itself is presented in Figure 24 in the form of flow chart of the five stages of Classes with the five Qualifying attributes in the three activity Components mentioned previously.

Table 1: Summary of the primary classifiers and the key qualifiers, with indications of whether they are best defined in the office or field. Some can be derived from both remotely-sensed or field data, depending on gully scale, and scale of investigation.

		Mode of analysis	
Primary Classifiers:		Office (RS/GIS)	Field
I.	<i>Gully Scale</i>	●	○
II.	<i>Landscape Domain</i>	●	○
III.	<i>Gully Form</i>	●	n/a
IV.	<i>Gully Catchment Dimension</i>	●	○
V.	<i>Soil Materials</i>	○	●
Key Qualifiers:			
i.	<i>Climate/Rainfall zone</i>	●	n/a
ii.	<i>Gully System Complexity</i>	●	n/a
iii.	<i>Multi-form Development</i>	○	●
iv.	<i>Vegetation cover</i>	●	●
v.	<i>Erosion activity</i>	○	●

● - Dominant activity ○ - Supporting activity n/a activity not applicable

Table 2: Summary of the gully classification attribute criteria, with indications of the sources of information that are required to determine each attribute value.

Criterion	Scale	Qualitative	Quantitative	Field observation
1. Climate / Rainfall regime	Broad relates to coarse-scaled climate map	Defined from Köppen climate map of Queensland	No	No
2. Gully Scale	Broadest to define system of interest. Extent to cover gully system	Judgement from available spatial data: DEM, imagery, lidar; guidelines. Decision based on prioritisation, environment, access.	n/a	No
2.1 Gully system complexity	Finer extent and finer resolution than 1.2 and 2.1.	Defined by judgement from available spatial data: DEM, imagery, lidar; guidelines	n/a	Not initially, but preferable
3. Landscape Domain	Broad scoping outside gully environment. Extent beyond gully system	Defined from geology, soil, topographic maps and reports, DEM/imagery interpretation. Field visitation desirable	n/a	Not initially, but preferable
4. Gully Form	Extent as before, resolution finer than before	Delineation from DEMs / lidar; DEM / imagery; plan/profile shape definition	Axial ratios, geometry, drainage network, order, branching, and lengths. Topographic profile dimensions, slope morphometrics	Lengths, widths, depths
4.1 Multi-form development	As for 2.2	Interpretation from imagery/DEM (preferably lidar), criteria for evidence of rejuvenation/multi-sequel formation	Elevations and depths of floors/incisions from cross-/long-profiles	Not initially, but preferable
5. Gully catchment dimension	Fine resolution over fine to broad extent, dependent upon system of interest	n/a	CCA / DtD both measured from DEM (preferably lidar) and spatial hydrological analysis, slope gradients	No
6. Vegetation Cover	Extent as before, moderately fine resolution	Interpretation from imagery. Field observation of height class and density.	NDVI and similar from multispectral imagery. From lidar canopy height model (chm)	Not initially
7. Soil Materials	Extent beyond system of interest for contextual interpretation	Interpretation from available soil mapping/reporting (luck needed). Identification of soil material layers and erosion forms/types	Spatial (3-D) delineation of soil material layers (depths/spatial extent), soil material sampling and analysis to characterise soil material types and physico-chemical characteristics	Essential
8. Erosion Activity	Extent over gully system only, moderately fine resolution	Interpretation possibly from available soil mapping/reporting. Observation of evidence for different erosion types, and Identification of erosion forms/types	n/a	Essential

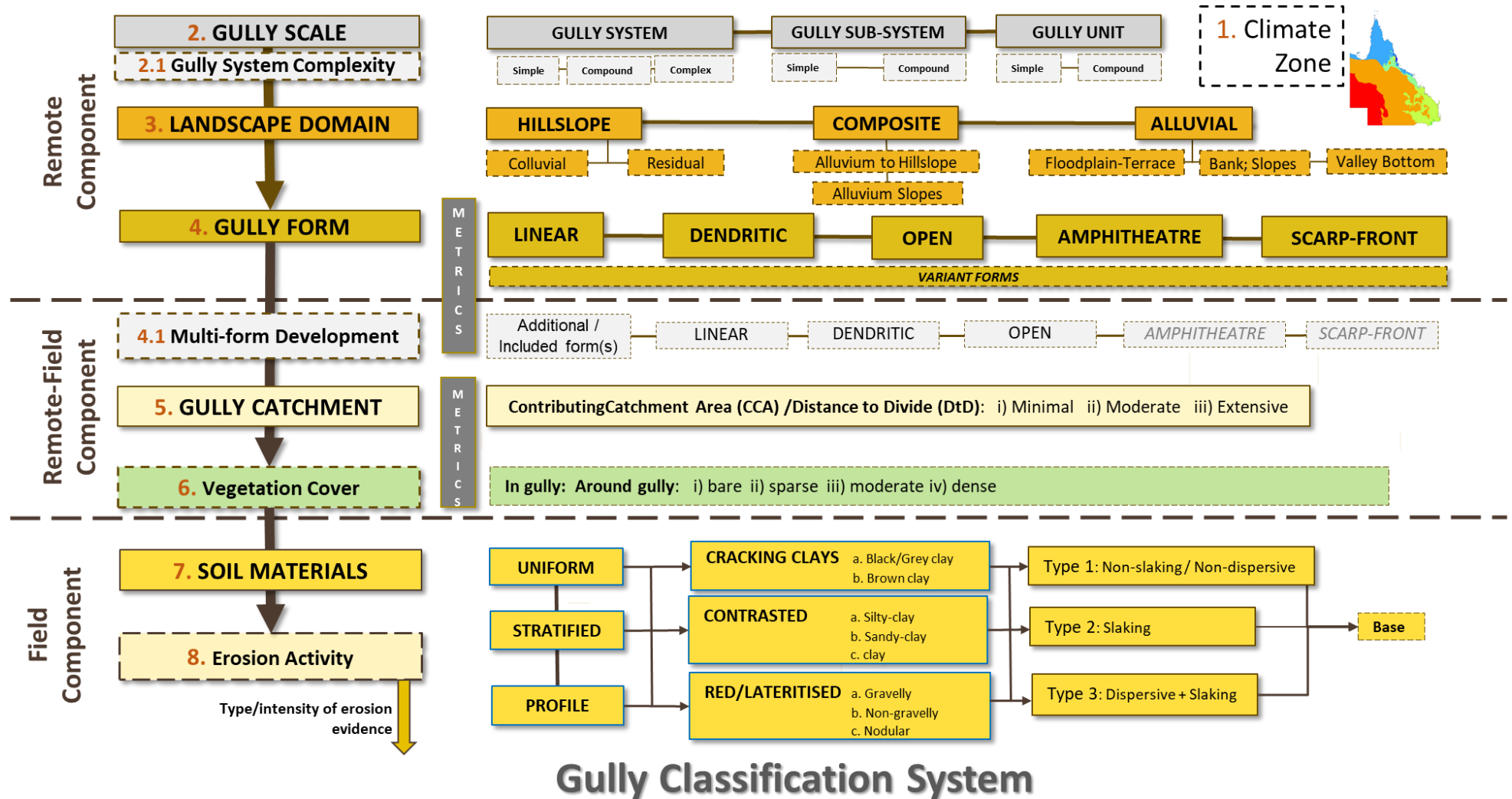


Figure 24: Schematic diagram of the Gully Classification System.

5.0 A GUIDE TO THE GULLY CLASSIFICATION

The following is the main component of the proposed *Gully Classification Handbook*, yet to be finalised.

This guide follows the Gully Classification System notation, i.e. each section heading is preceded by the notation 'e el' refers to that component of the Gully Classification System in Figure 24.

5.1 The Remote Component

5.1.1 Level 1 CLIMATE/RAINFALL REGION

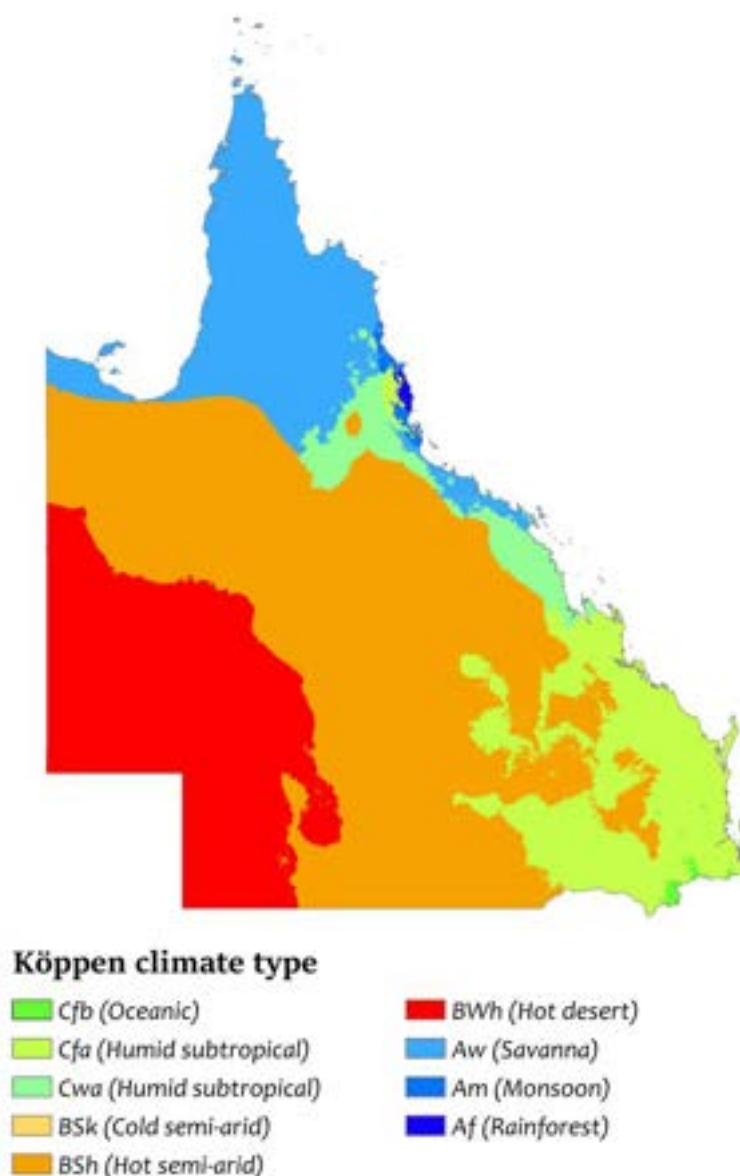


Figure 25. Köppen climate classification zones in Queensland

The general locality of gully systems under investigation can be located within the climatic zones displayed on the above map of Köppen climate types for Queensland. The Climate type and code should be recorded on the data sheet for the database along with subsequent gully data. The Köppen climate map and code explanations for Queensland are available from the Climate.org website <https://en.climate-data.org/oceania/australia/queensland-899/>. The Köppen climate map is also available as a shapefile for GIS use from the BOM (http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp?maptype=kpn#maps), or interactively from the Living Atlas of Australia (https://spatial.ala.org.au/?layers=koppen_all_classes).

5.1.2 Level 2 GULLY SCALE and Level 2.1 Gully Complexity

A critical aspect of classifying gully systems is to establish the scale (extent) and resolution (detail) at which a gully or gully system is being assessed at the initial stage of the process.

Gully systems develop different characteristics and different processes dominate as they expand in scale. Hence, an assessment and evaluation of gullies must be conducted and presented at the appropriate process-sensitive scale (See Section 3.1.2).



A Gully System

A group of gullies (including channels) with a common outlet or with outlets in close proximity to the drainage network or common depositional landform.

A distinct grouping of gullies, and possibly stream channel(s), that operate as an integrated hydrological and erosional system. The system can be of one main gully form or of a variety of forms.

A Gully Sub-system

A subset of the identified gully system that is an identifiable unit for assessment or management purposes (excluding channels). It can be a series of similar or disparate gullies in a connected network, that consist of more than one gully but constitutes only part of a gully system.

A Gully Unit

A simple unitary form that is not easily subdivided, that is identifiable as a single type in the field or on imagery and is not a stream channel. See full definition in Section 2.

Gully System complexity

Some gully systems and gully units exhibit multiple forms within their boundaries. These may be due to rejuvenation of erosion processes to create new floor levels, new levels by tunnelling, and creating secondary gully systems (or more). They can exhibit changed morphology within the system or subsystem because of differentially eroding materials or as a response to controls by vegetation or bedrock structure, or downstream base-level changes (See Section 3.1.2).

Identification of Simple, Compound or Complex systems, depending on scale and resolution of investigation.

- **Simple** a uniform type apparent based on shape of gully(-ies) and form of individual systems, even at finer scales of observation (Figure 26).

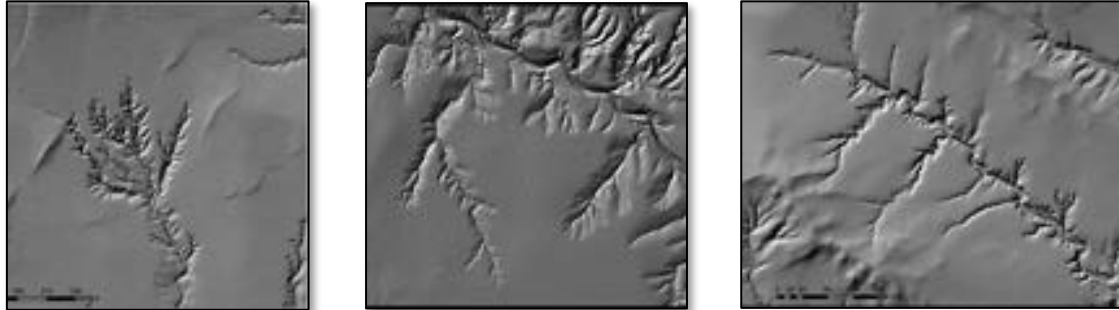


Figure 26: Examples of Simple Linear and Dendritic Forms of gully systems.

- **Compound** a multi-form gully system whereby the arrangement or form of different systems is **possible to ascertain at finer levels of observation** (Figure 27).

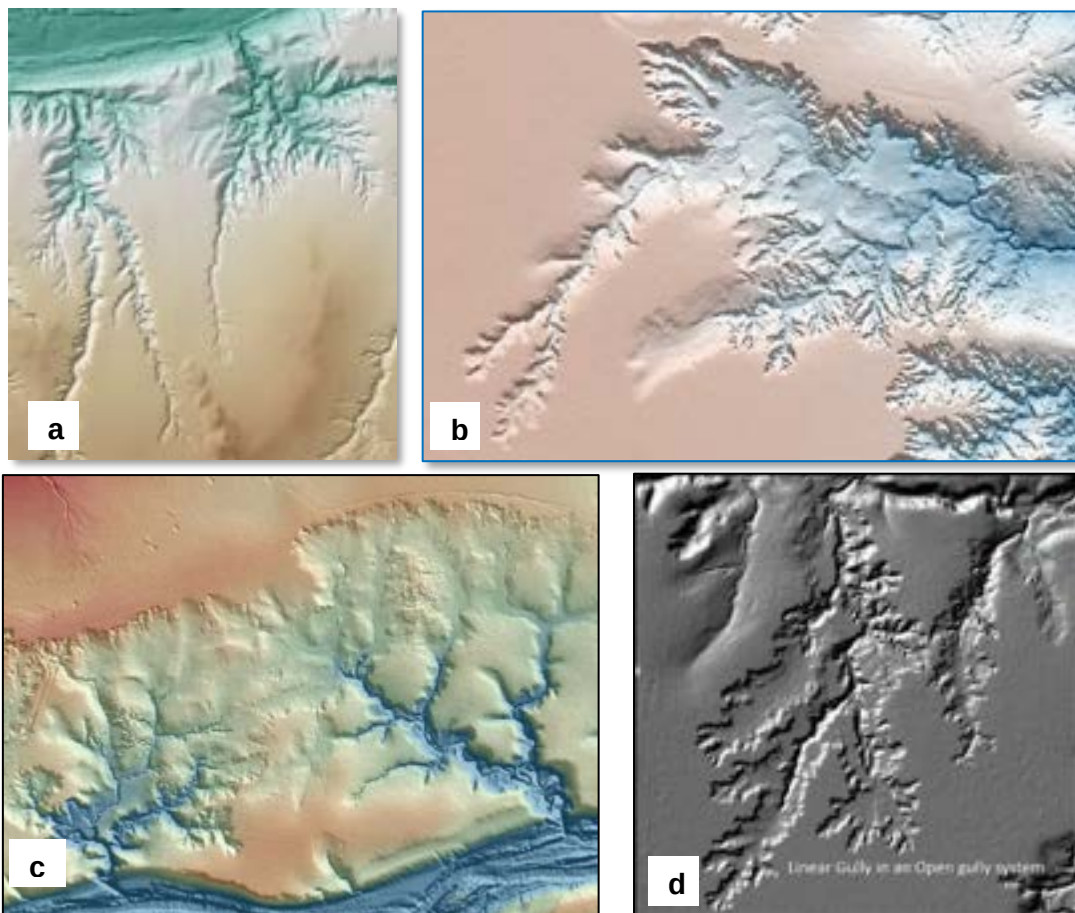


Figure 27: Lidar hillshade DEM images of examples of Compound gully systems. a) Linear gullies extending from Dendritic systems, b) Bifurcating Linear gillies extending from an Open system, c) Dendritic subsystems in a Scarp-Front gully system, d) a deep linear gully incising into a shallow open Dendritic gully Form.

- **Complex** a multi-form gully system whereby the arrangement or form of systems is not possible to ascertain at finer levels of observation. Usually on applicable to large alluvial systems.

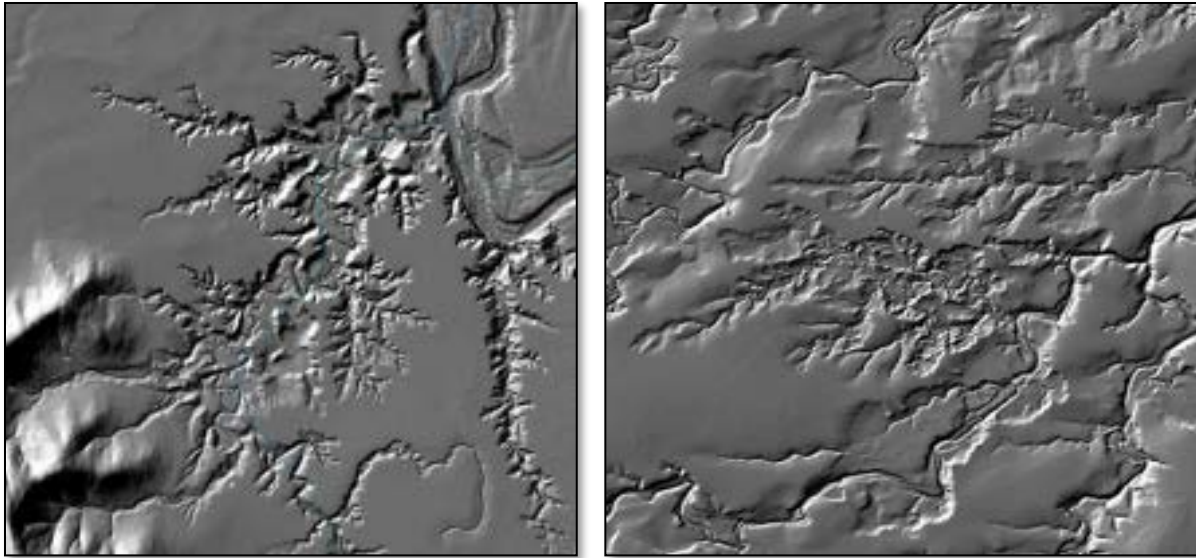


Figure 28: Lidar hillshade DEM images of examples of Complex gully systems, a) in a Floodplain Alluvial Landscape Domain, b) complicated by developing in both a Floodplain Alluvial and Composite Landscape Domain.

This can be established from DEMs, Imagery, Lidar DEM, morphometric analysis.

5.1.3 Level 3 LANDSCAPE DOMAIN



The **Landscape Domain** describes the context of the gully system by way of physiographic setting and geomorphological material and process. It includes the nature of the dominant erodible material in which the system has formed and the physiographic forms of hillslopes (**Hillslope Colluvial**) and alluvial plains and valleys (**Alluvial**). It includes an intergrade class (**Composite**) where the landscape position and type of host material is in question, or in complex association. The three main Domains have subordinate domains that act as modifiers, e.g. Colluvial Hillslope, Terrace Alluvial, Alluvium to Hillslope Composite Domains.

HILLSLOPE Domains

- **Colluvial**
- **Residual**

COMPOSITE Domains

- Alluvium to Hillslope
- Alluvium Slopes

ALLUVIAL Domains

- Floodplain; Terrace

- Bank; Slopes
- Valley Bottom

5.1.4 Level 4 GULLY FORM AND VARIANTS



LINEAR Form

Elongate plan-form morphology without a well-developed secondary drainage network, though often with some minimal branching with small linear gullies or minor dendritic form. Linear gullies are often associated with anthropogenic disturbances such as roads, stock tracks, or other linear surface features that tend to concentrate flow (Figure 29). Depth along profile can vary significantly depending on site-specific circumstances. This gully type is often an incipient phase of one or all the other gully types.

Key characteristics:

- Often exhibiting a distinct headscarp with an abrupt transition from the residual material upslope.
- Linear gully networks tend to have a distinct appearance of a micro-drainage network.
- Typically, not exhibiting piping or tunnel erosion sub-soils are far less dispersible/slaking than Amphitheatre, Open and Scarp-front forms. However, there are exceptions for linear secondary incisions into open or amphitheatre alluvial gullies.
- Usually exhibit V-, or U-shaped, or narrow trapezoidal cross-sectional profiles.
- The most common gully form, with Dendritic form, in Cracking Clays Soil Materials.
- Carbonate nodules are evident but not to the same extent as in the Amphitheatre or Open forms.
- 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 or buttresses
- The linear gully often appears to be inset within prior stable gully network
- May have a well-developed vegetation community within the more developed part of the gully network, owing to colonisation on non-sodic and collapsed soil materials.
- Relatively steep long profiles.

(Adapted from Brooks, Spencer & Knight, 2007)

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.
- Linear and curvilinear incision can also occur in association with prior streams or drainage valleys on hillslopes or on alluvial terraces or distal ends of floodplains (floodplain drainage).

- Subsequent form is then dictated by the dominance of processes driving head and sidewall retreat, which is in turn dictated by uniformity or otherwise of soil material.

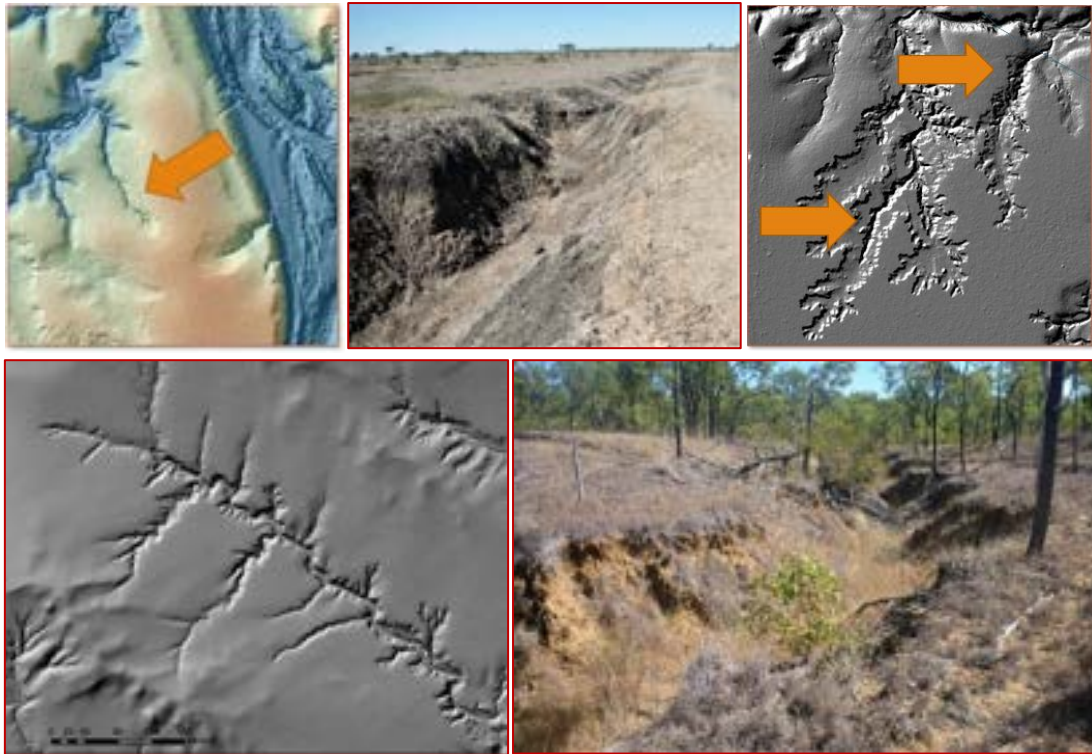
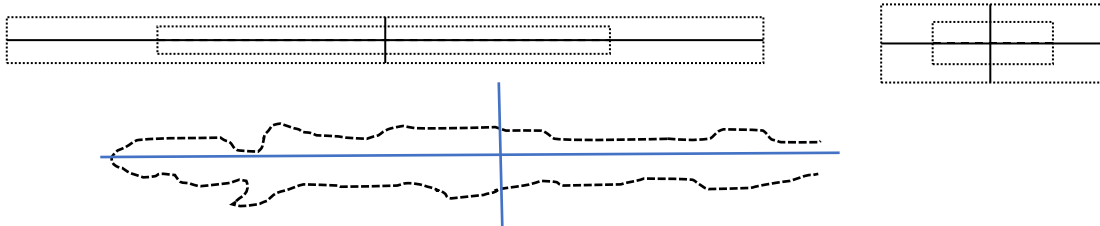


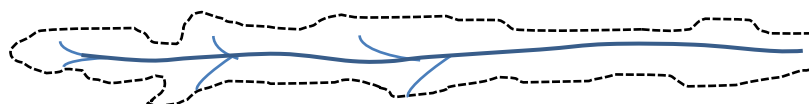
Figure 29: Examples of Linear Form gullies.

Geometry: (see Appendix 1)

Overall rectilinear in form, with minor curvature to gully wall plan form. Can be branched and can be broad but maintaining a clear long axis to short axis average ratio. See schematic representations of the geometric form and axial arrangement below.



Flow form within the system is linear with some minor tributary branching and a long, definitive trunk to the feature (see below).



Variants examples:

- Curvilinear
- Open Linear
- Multi-branched Linear

DENDRITIC Form

Tend to have a distinct elongate, moderate to strong dendritic (tree-branched) plan-form, with the hillslope gully complex forming a well-defined drainage network, separated by commonly wide interfluvies which often extend to the former floodplain or land surface level. Gully head is often indistinct, grading relatively gradually from the adjacent floodplain to the gully network. These gullies tend to have a distinct appearance of a micro-drainage network (Figure 30). Seldom exhibiting piping or tunnel erosion sub-soils are far less dispersible/slaking than Amphitheatre, Open and Scarp-front forms.

Key characteristics:

- Usually exhibit V-, or U-shaped, or narrow trapezoidal cross-sectional profiles.
- A common gully form in Cracking Clays Soil Materials.
- Carbonate nodules are evident but not to the same extent as in the Amphitheatre or Open forms
- 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 or buttresses
- Gully dendritic gulling often appears to be inset within prior stable gully network
- Often has a well-developed vegetation community within the more developed part of the gully drainage network, owing to colonisation of non-sodic and collapsed soil materials.
- Relatively steep long profiles

(adapted from Brooks, Spencer & Knight, 2007)

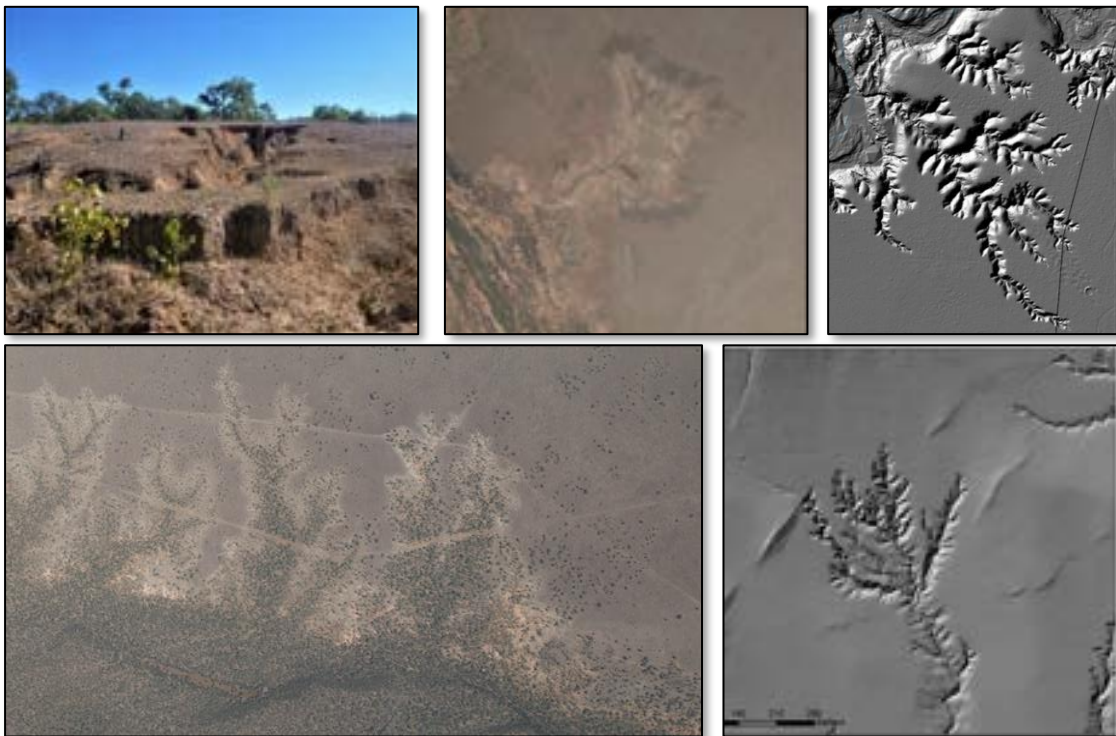


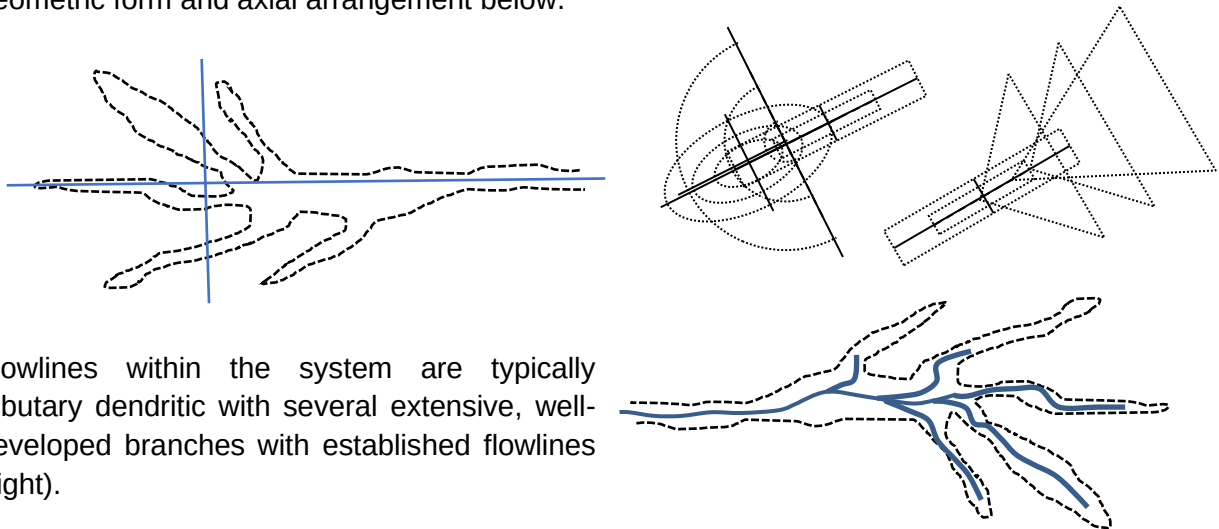
Figure 30: Examples of Dendritic Form gullies.

Key Processes:

- Gully system development in Hillslope Domains is dominated by overland flow and channelized flow over a hillslope converging within a valley feature. Structure of the branching can be controlled by bedrock jointing and lithological variation.
- Gully system development in Alluvial Domains 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.

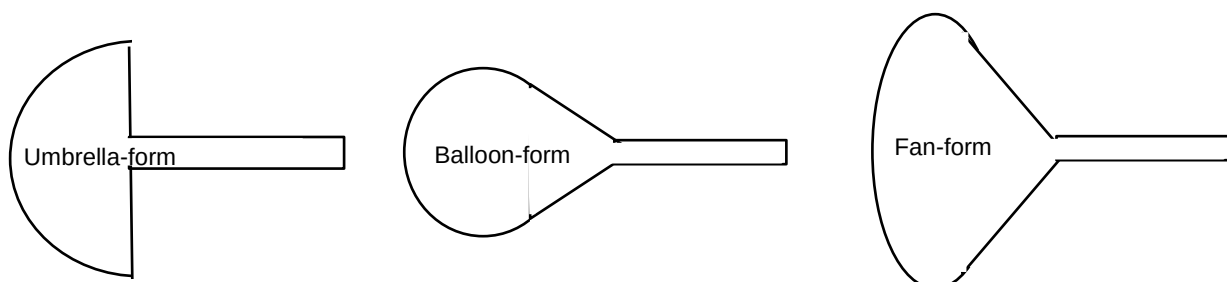
Geometry: (see Appendix 1)

Axial dimensions are asymmetric with the latitudinal axis nearer the distal end of the long axis. The latitudinal axis can vary considerably in length. See schematic representations of the geometric form and axial arrangement below.

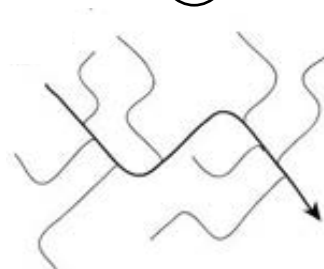


Flowlines within the system are typically tributary dendritic with several extensive, well-developed branches with established flowlines (right).

The overall erosion and flowline pattern can vary between Umbrella-, Balloon-, and Fan-shaped, depending upon the length of the trunk and the variability in erodibility of the soil materials (see below).



The drainage form can also be Trellised (right) if in a Hillslope Domain and bedrock structurally controlled.



Variants examples:

- Open Dendritic
- Dissected Dendritic
- Linear Dendritic
- Trellised Dendritic

OPEN Form

- Moderately broad to very broad, curvilinear, irregular, or angular plan-form taking on several forms, commonly teardrop, rectangular, rhomboid or elongate shaped with a relatively wide single outlet or more than one narrow outlet to the main-stem channel or distal floodplain creek.
- Flowlines from Open Form gully systems can be less coherent than those of Amphitheatre Form systems, which exhibit a more centripetal flow to the centroid of the system before egress through a broad outlet.
- Shallow longitudinal and cross-sectional profiles, often dissected, are characteristic and may distinguish these from the Amphitheatre Form. Open Form gully systems cover a wide variety of forms that cannot clearly be identified as Amphitheatre, Dendritic, or Linear.
- They are common in both Hillslope/Colluvial and Alluvial Landscape Domains and in all Soil Material forms.

Key characteristics:

- Usually possess multiple gully heads around the perimeter that are in the form of a distinct steep to near vertical or collapsed scarp face. Can exhibit many lobes with slot gullies at the distal margins.
- Often exhibit piping and tunnel erosion indicating the presence of dispersive / slaking, sodic soils and dominance of block collapse and mass failure, possibly aided by a basal sapping process.
- Often occurring on both the distal and proximal margins of an alluvial plain or rise adjacent to the main-stem channel. Also occurs on hillslopes associated with drainage catchment in colluvial or local alluvial soils or dispersive residual soils adjacent to the main-stem channel.
- Usually dependent on upslope catchment area to progress, as the processes are driven both by overland flow and subsurface flows (possibly by groundwater flow). Once initiated it will proceed until no susceptible material is left to erode.
- Can exhibit complex fluting on walls and head, with residuals and mounds in the broad floor and an extensive lag of carbonate nodules or ferruginous nodules in Red/Lateritised soil materials, or lag gravels in alluvial environments, on the eroded surface.
- Alternatively, this form can show usual block collapse and slumping from sapping without obvious dispersiveness. Can also exhibit slumping and crumbling headwall erosion forms.
- Vegetation in the gully can be well developed indicating variable rates of gully progression.
- Drainage network may be evident within the gully complex, but the interfluvies between drainage lines can be either clear or are subtle being lower, to significantly lower than the former land surface level, but still exhibiting much dissection.

Key Processes:

- Somewhat differing rates of erosion and headward retreat following drainage flowlines or zones of more susceptible materials prone to disintegration by overland flow, rainsplash, and tunnelling.
- Usually formed in dispersive soil materials

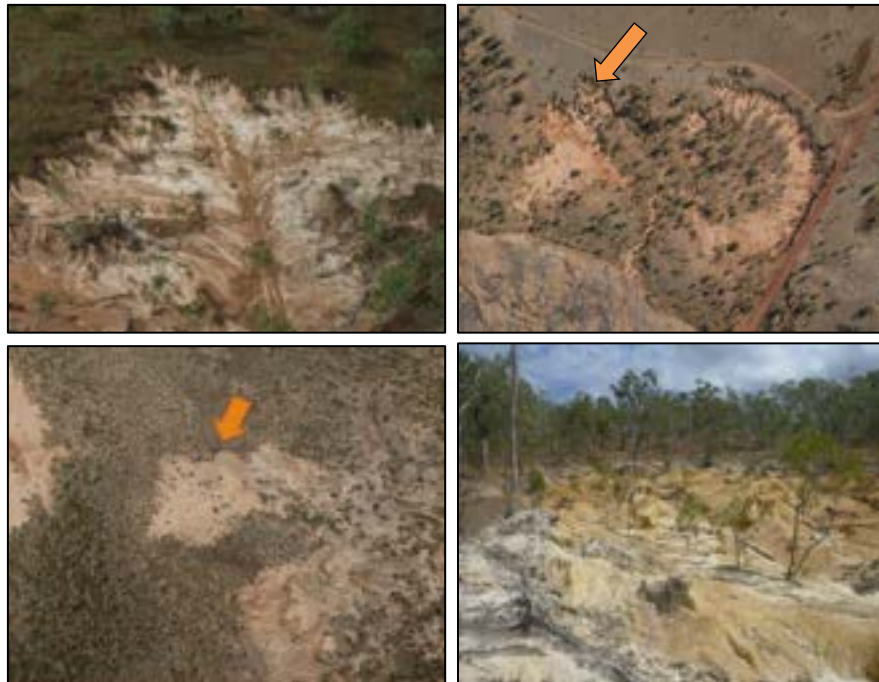
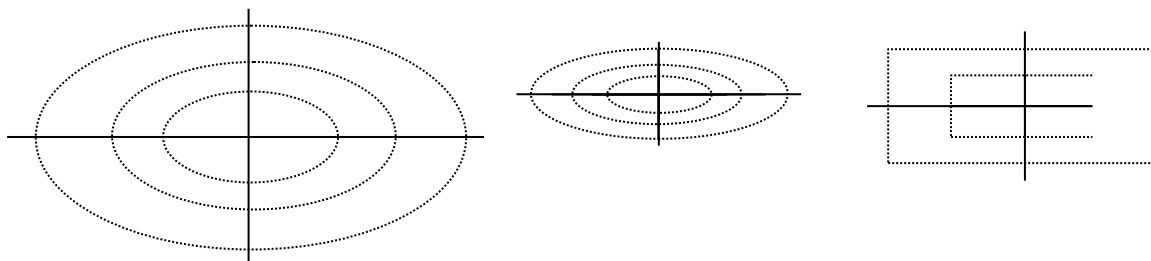


Figure 31: Examples of Open Form gullies

Geometry: (see Appendix 1)

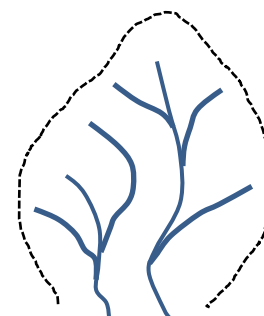
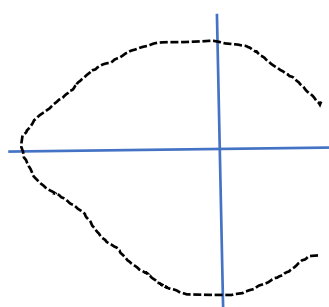
Both axes can be of variable lengths and offsets, but the latitudinal axis is often shorter and closer to the terminus or proximal end. See schematic representations of the geometric form and axial arrangement below.



Flowlines are convergent but may be segregated or centralised and may egress through one major outlet or more than one minor outlet (below).

Variants examples:

- Rejuvenated Open
- Shallow Open
- Dissected Open



AMPHITHEATRE Form

Broad circular to elliptical or teardrop plan-form with a deep headscarp, active around much or the whole of the perimeter. It has a graded or stepped appearance reflecting the plan-form as in amphitheatre-type structures. Amphitheatre Form gully systems usually have a relatively narrow, commonly single, or maybe dual, outlets to the main-stem channel or distal floodplain creek. More commonly occurring in Alluvial Landscape Domains, although they can occur in deeper colluvial hillslope environments or in residual lateritic soils/regolith.

Key characteristics:

- Usually possess many gully heads, or a continuous scarp, which are in the form of a distinct vertical or undercut scarp face.
- Often exhibit piping and tunnel erosion indicating the presence of dispersive / slaking, sodic soils and dominance of block collapse and mass failure.
- Often occurring on both the distal and proximal margins of an alluvial rise adjacent to the main-stem channel.
- Not dependent on upslope catchment area to progress. Erosion process associated with direct rainfall on the active gully surface area is sufficient to drive the gully expansion, however the rate of expansion will be greater with additional catchment upslope.
- Often exhibit highly complex fluting, also buttresses, and an extensive lag of carbonate nodules on the eroded surface, or ferruginous nodules if a 'Red/Lateritised' Soil Material class.
- Exhibit a dissected to a wide trapezoidal cross-section across the interior.
- Vegetation in the gully is generally not well established or developed commonly opportunist shrubs and isolated small trees - indicating high rates of gully progression.
- Drainage network may be evident within the gully complex, but the interfluvies between drainage lines are subdued to subtle being significantly lower than the former floodplain level. Interfluvies often well-dissected.

(adapted from Brooks, Spencer & Knight, 2007)

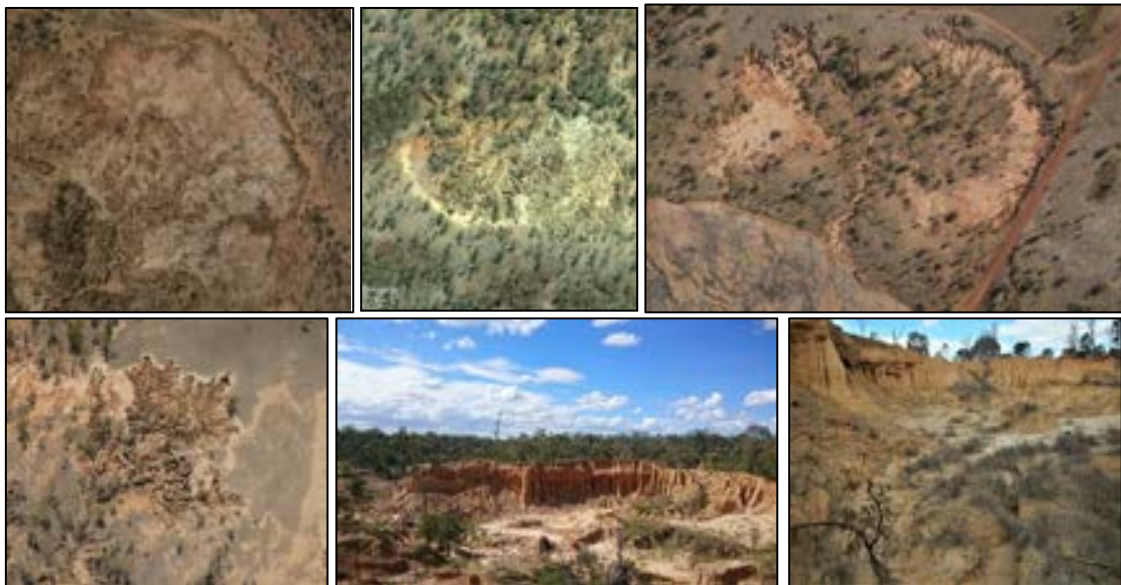


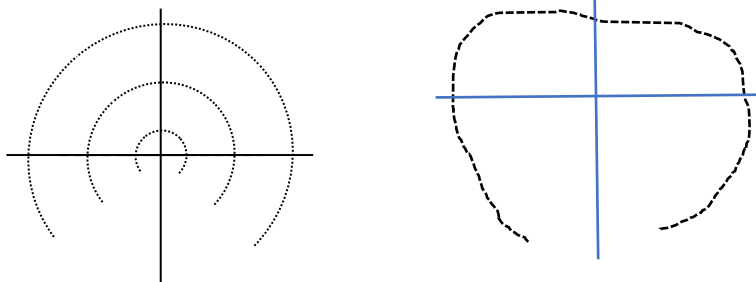
Figure 32: Examples of Amphitheatre Form gullies.

Key Processes:

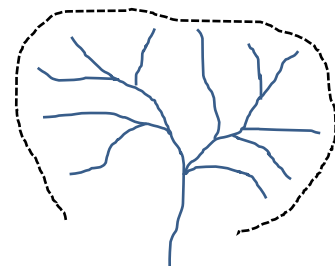
- Soils typically highly dispersive, so direct rainsplash erosion can be a dominant erosion process.
- Undercutting and mass failure due to plunge-pool splash-back and erosion of sodic sub-soils. Tunnel and pipe erosion can be a common process of headscarp erosion.
- Highest rates of headward erosion are where there is some overland flow as well, typically driving the undercutting through plunge pool splash back (which is often confused with basal sapping)
- Basal sapping is a rare process that 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 usually occurs on highly dispersible, deep, alluvial, sodic soil materials often with many calcium carbonate nodules or 'coral'.

Geometry: (see Appendix 1)

Both axes can be of variable lengths and offsets, but largely both the latitudinal and longitudinal axes have similar dimensions intersecting about the middle of each, as part of an arcuate form. Can be asymmetric variable difference in axes lengths. See schematic representations of the geometric form and axial arrangement below.



Flowlines can show more convergent and centripetal form owing to the existence of active erosion along sidewalls round towards the outlet or terminus (right).

**Variants examples:**

- Open Amphitheatre
- Dissected Amphitheatre
- Complex Amphitheatre

SCARP-FRONT Form

Relatively linear gully complex running parallel with the main stem channel of major rivers in the Alluvial Landscape Domain. This appears to be a well-developed variant, or late-phase of the Amphitheatre and Open gully Forms (or Dendritic Form in some cases), whereby a sequence of Open/Amphitheatre gullies coalesce to form a continuous gully scarp front (gully sidewall retreat is greater than headwall retreat). Can occur in Hillslope-Colluvial Landscape Domain in dispersive soil materials and in Red/Lateritised regolith. Unlikely to occur in Cracking Clays Soil Materials.

Key characteristics:

- Common in multi-channel rivers with extensive in-channel vegetation, and as coalescing gullies from single channels
- As with the Amphitheatre Form, the gully head tends to be in the form of a scarp face. However, variants exist where the scarp is relatively indistinct, possibly due to the role of fluvial scour/stripping during flood flows.
- As with the Amphitheatre form, piping and tunnel erosion is also common indicating the presence of dispersive/slaking sodic soils and potential 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 suitable material availability often driven almost entirely by direct rainsplash erosion but also flood scour.
- Relative rates of lateral gully expansion, by coalescence of contemporary gully subsystems, in this form of gully are much greater than headward retreat.
- Can be distinguished from stream bank erosion by distance from active stream channel and by multiple outlets from subsystem or gully unit flow lines. Some scarp-front gullies may develop lateral retreat and uniform headward retreat from relict or abandoned stream-bank sections.

(adapted from Brooks, Spencer & Knight, 2007)

Key processes:

- Soils typically highly dispersive, so direct rainsplash erosion can be a dominant erosion process.
- Undercutting and mass failure due to plunge-pool splash-back, and erosion of sodic sub-soils. Tunnel and pipe erosion can be a common process of headscarp erosion.
- 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.

- Flood flows play a key role in stripping and removing interfluves between adjacent gullies to aid transition of separate Amphitheatre or Open gullies into a continuous scarp.
- This process usually occurs on highly dispersible, deep, alluvial, sodic soil materials often with many calcium carbonate nodules or coral'.

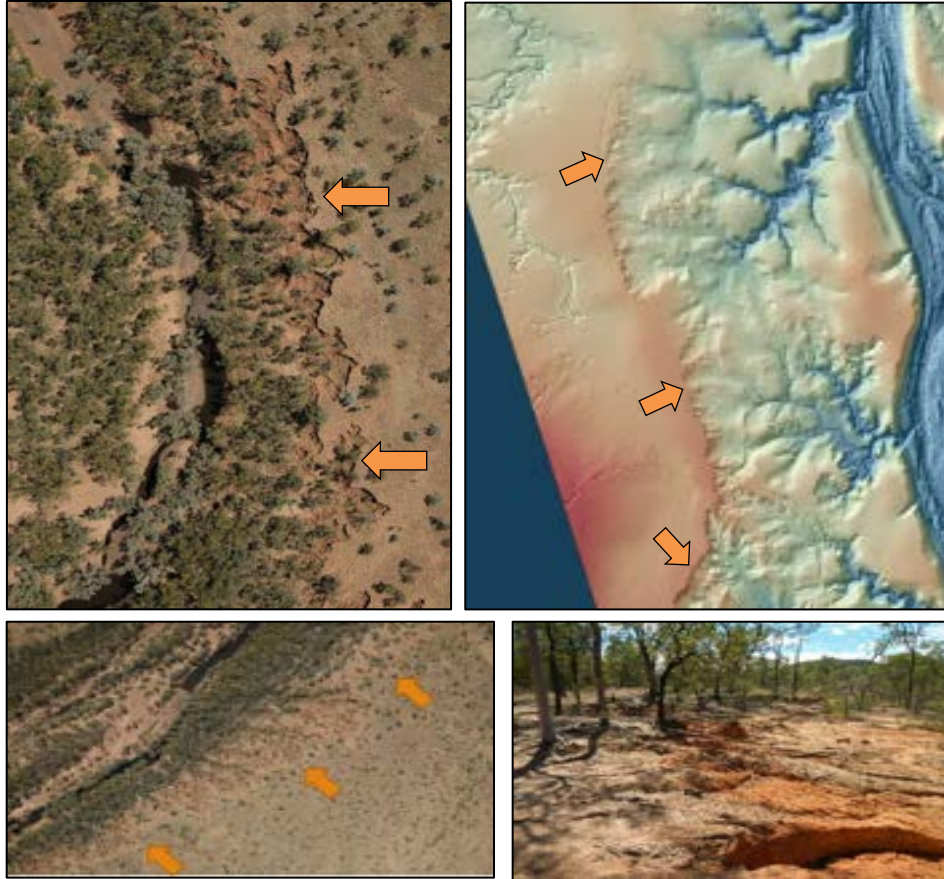
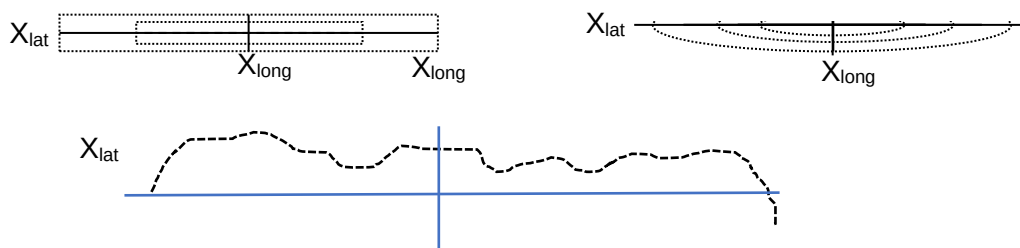


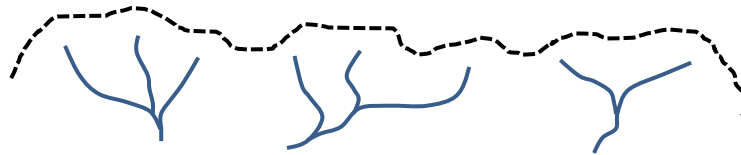
Figure 33: Examples of Scarp-front Form gullies

Geometry: (see Appendix 1)

Distinctly longer latitudinal axis with variable length longitudinal axis. Latitudinal axis can be very extensive. See schematic representations of the geometric form and axial arrangement below.



Flowlines can show more a variety of forms but often are coalescing Dendritic or Open, or even Amphitheatre Forms. Headwall retreat along the longitudinal axis is slower than the lateral wall retreat along the latitudinal axis, owing to the more active erosion along sidewalls and coalescing subsystems (below).

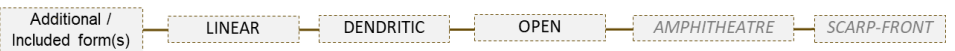


Variants examples:

- Dissected Scarp-Front
- Rejuvenated Scarp-Front
- Stepped Scarp-Front

5.2 Remote – Field Component

4.1 Multi-form Development



5.2.1 Level 4.1 MULTI-FORM DEVELOPMENT

This level of the classification deals with the occurrence of secondary incision creating a new, secondary gully system and perched gully floors on which modified processes occur. More than one level of incision and floor creation can be identified. These are then recorded in the same way as Gully Form and the number of observable floors, with the indication whether knick points have been observed or just gully wall extension (Figure 34 to Figure 36).

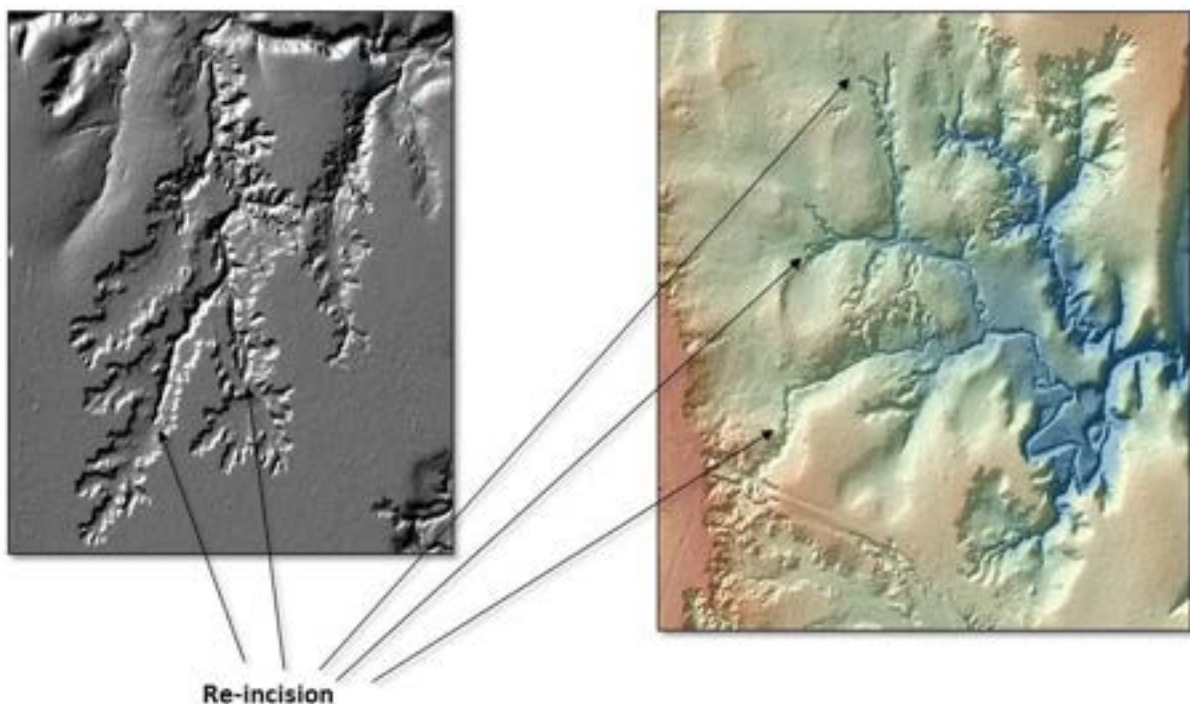


Figure 34: Lidar hillshade DEMs showing examples of gullies with secondary incision and multiple incisions into the gully floor (i.e. multi-phase incision).



Figure 35: Field examples of gullies with multiple floors from incisional phases.

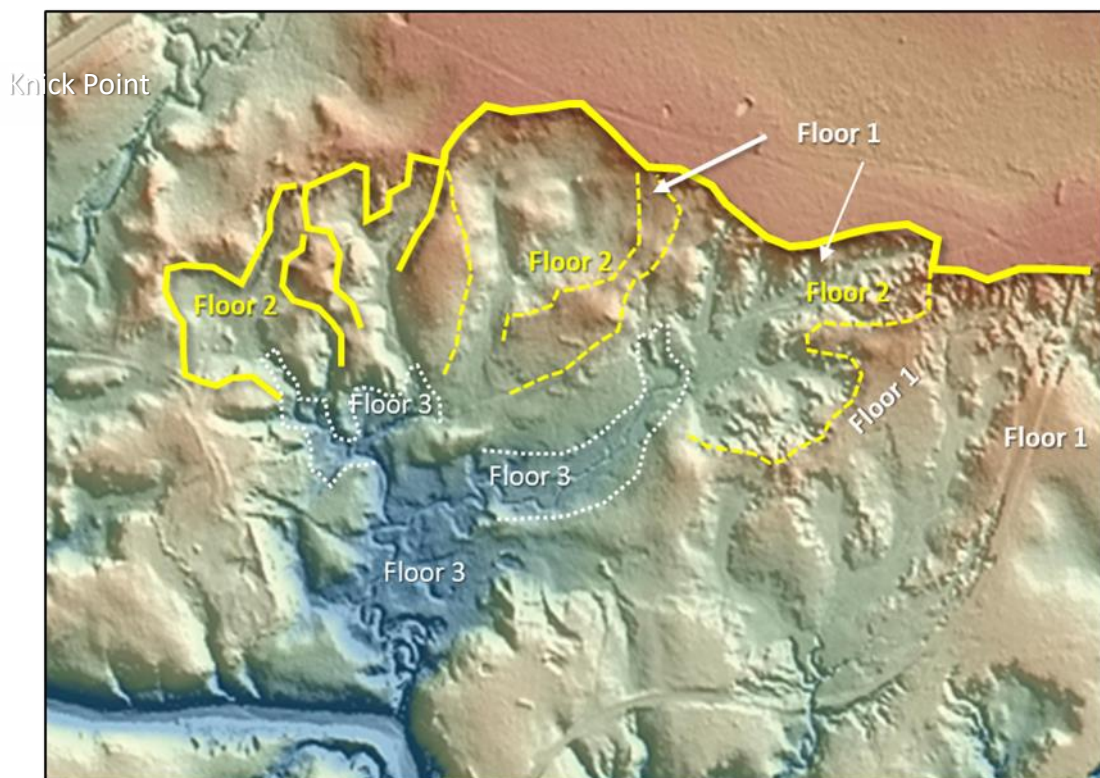


Figure 36: An example from a DEM of multiple incisional phases in a Compound System.

5.2.2 Level 5 GULLY CATCHMENT DIMENSION

5. GULLY CATCHMENT

Contributing Catchment Area (CCA) /Distance to Divide (DtD): i) Minimal ii) Moderate iii) Extensive

This component of the classification is to provide an indication of hydrological dynamics, and further erosion potential, and aids rehabilitation decision-making.

- **Distance to Divide (DtD)** can be measured on DEMs by geomorphometric analysis in GIS, or by measurement on aerial imagery, if the divide can be defined. It can also be estimated in the field. This is defined as the distance from the actively eroding part of the gully to the catchment divide watershed in an upstream' direction along the perceived flow line. It provides some measure of the minimum potential distance that the gully could still erode. However, many alluvial gullies will erode *through* the catchment divide as they are controlled more by the energy provided by internal gully excavation and lowering bed profile than the flow from the external catchment area.
- **Contributing Catchment Area (CCA)** can be measured on DEMs by geomorphometric analysis. The ratio between active gully area and gully catchment area is also a good indicator of minimum potential gully area. In many alluvial settings, with very subdued relief, the best way to accurately determine the catchment area with precision is through the analysis of lidar DEM data (as per Figure 37).



Figure 37: Schematic diagram showing the relationship between active gully area and gully catchment area in an alluvial gully.

5.2.3 Level 6 VEGETATION COVER

6. Vegetation Cover

In gully: Around gully: i) bare ii) sparse iii) moderate iv) dense

The vegetation community structure, percentage cover (per height class or cover type), and composition are important variables to help describe the relative erosion rates and behaviour of different types of gullies. Lidar data or other remote-sensing data can provide quantitative metrics on the vegetation characteristics within the gully itself and the gully catchment area (Figure 38). At this stage the relative density for the relevant gully units or subsystems can be estimated by eye, as well as the type if possible, to discern (otherwise a simple Tree; Shrub; Low categorisation will suffice).

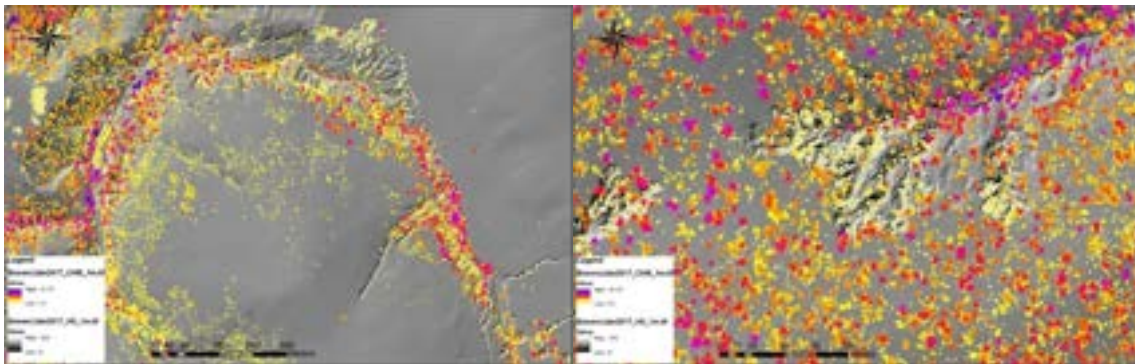
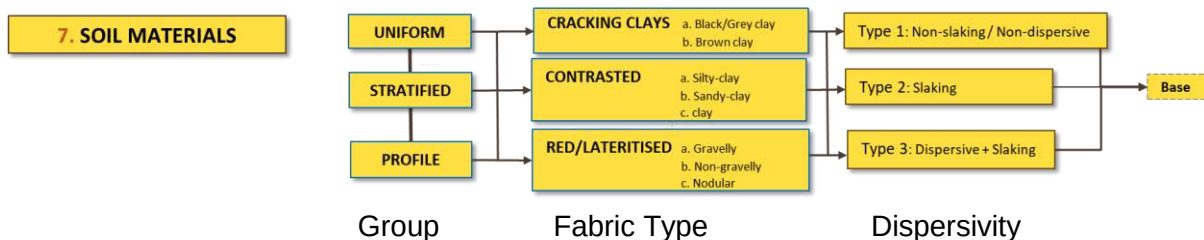


Figure 38: Examples of vegetation canopy height data derived from lidar data in different alluvial gully systems.

To complement the remotely-sensed vegetation community data, field surveys are also carried to characterise the extant vegetation within and surrounding the gully, using a rapid survey approach.

5.3 Field Component

5.3.1 Level 7 SOIL MATERIALS



The complex issue of soil material, i.e. residual soils, colluvial materials, and alluvial sediments and inter-relationships is dealt with as simply as is appropriate here from the perspective of both remote and field assessment with some understanding of soil and geomorphological interpretation.

Stratified materials (termed soil material layers here) will almost always need field observation and assessment. Distinct layers can possibly be identified from imagery of the land surface, in gully wall colours, and sequences of different coloured material along the length and across

the breadth of gully systems. Deployment of drone photography and videography in the field will aid the field observation of layer characteristics and boundaries.

In the defined rural land uses and natural environments to which the Classification applies, the presence of anthropic materials, or artificial layers is not included, as they are likely to be rare or isolated occurrences. Possible occurrences of such, e.g. road and track bedded materials are not included, but should be noted and commented in any recorded assessment.

Three sub-classes of soil materials are then also identified on the basis of colour and land surface / gully face morphology:

- the cracking clay lack soil' t pe Cracking Clays);
- the texture-contrast soil surface and deep clay substrates type (often highly dispersive) (Contrasted); and
- the red, often indurated, often lateritised, often residual material, forms in alluvium or colluvium in the lower-latitude tropical environments (Red/Lateritised).

Soil Material Group

Uniform

Soil materials in this category appear to be generally homogenous throughout the depth and extent of the gully or gully system. They are largely homogenous in the material Fabric and textures, overall colour, and mineral composition, besides the possibility of a more organic and texture-/fabric-variable topsoil (Figure 39). These materials do not exhibit clear layers in the depth profile although the materials may change gradually in lateral extent. The topsoil may be deemed to be a separate layer, in which case the gully material does not have to be considered as 'stratified' - unless the topsoil is considerably different in texture and fabric and is not related to the solum beneath. In that case a Stratified-Contrasted group may be considered. Eroded, hardsetting topsoils do not have to be considered as 'stratified'

Soil materials in this class include the a) cracking clays, with or without the shrink-swell, gilgai (vertic) properties, often deep, from clay alluvium, b) sandy earths of the red, weathered, lateritic/lateritised materials, which can be colluvial or alluvial in origin, c) homogenous colluvium can also come under this category.



Figure 39: Examples of a gully in a Uniform Soil Material Group

Stratified

Much of the soil material eroded by gullying is part of a suite of transported sediments of some form, i.e. colluvial or alluvial, or a combination of both. Consequently, this deposited material is represented in two or more layers that can be characterised as sedimentary strata or soil material layers (though not horizons). The strata usually can be distinguished by their changes in fabric, distinct changes in colour (and whole-coloured or mottled), and their exposed, eroded form (displaying erodibility variations). Strata can also be identified by distinct inclusions (e.g. layers of non-bedded nodules, and bedding of gravels and sands). Hardsetting topsoil, or 'surface layer', over an underlying material that appears not to be stratified, does not make the gully soil material in the Stratified group.



Figure 40: Examples of Stratified Soil Material Group

Profile

Some hillslope gullies have eroded the solum of a residual soil that has formed from weathering bedrock, and often have bedrock as a base. The soil material here can be identified as a soil profile (even if the topsoil/A horizon has been eroded or is absent altogether). The variable A and B horizons can be identified as Layers (although they are not strata for consistent recording purposes)

Soil Materials

Cracking Clays

These are the cracking clays or 'reactive clays' that exhibit shrink-swell properties upon wetting and drying. They are usually clay alluvia, but some may be derived from well weathered mudstones and coal shales in hillslopes. In the Australian Soil Classification (NCST, 2012) these types of soils are called Vertosols. Although the soil materials may not all be Vertosols, the familiarity of the name is sufficient to describe them. The cracking clay is obvious throughout the vertical profile and other features, such as gilgai, may be present

at and near the surface. They will nearly always be in the Uniform Differentiation category, though some may show stratification. Some of these soil materials may be saline and some may be sodic, sometimes throughout. They often exhibit obvious calcareous nodules and coral stick and ranch forms of calcium carbonate or calcium magnesium carbonates, sometimes copiously, in the lower part of the vertical profile. Gypsum can occur as crystals though it is less obvious.

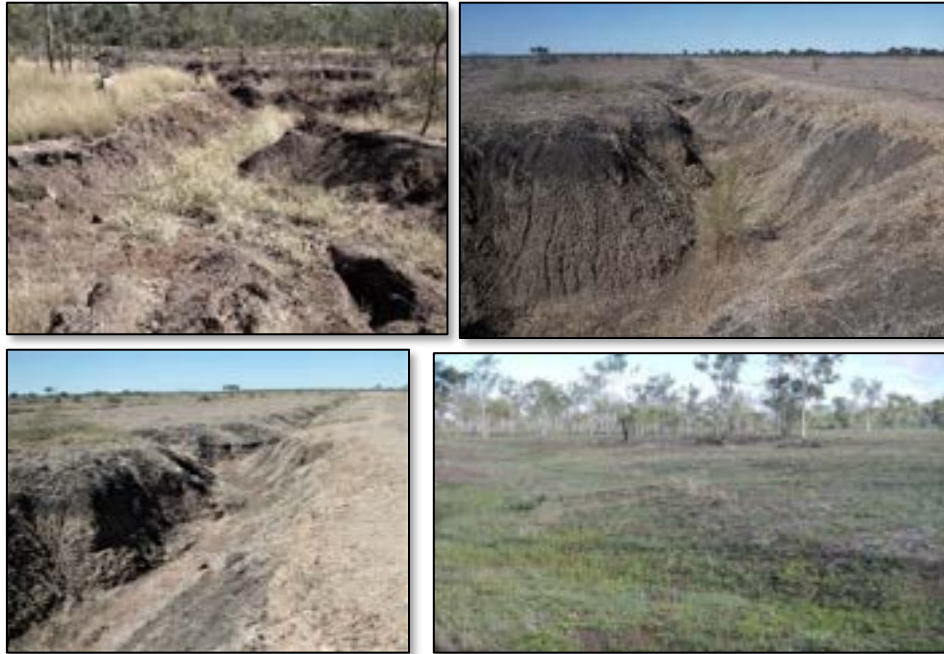


Figure 41: Examples of Cracking Clays Soil Material Group

Contrasted

These soil materials are characterized by a pale, usually hardsetting topsoil/surface layer in the residual soil or on stratified materials (Figure 42). The top layer may not be the topsoil/A horizon of the soil but can be the transported materials from upslope erosion, another colluvial layer, or a flood deposit. The surface layer(s) constitute(s) the contrasting nature of the materials as they almost always are of different texture, fabric, colour, composition and consistency to the underlying materials.

The topsoil or surface layers in these soil materials are important to identify and categorise for management and rehabilitation purposes. It may be considered as material for remediation as a growth medium or as a form of capping material.



Figure 42: Examples of Contrasted gully Soil Materials

Red/Lateritised

Deeply weathered, and transported weathered materials make up a distinct category of soil materials. These occur more in the humid to dry tropics and inland semi-arid to arid regions. They are often accompanied by products of deep weathering and groundwater interaction, such as lateritic earthy clays, ferricrete, silcrete, or alcrete (bauxite) layers, ironstone or ferro-manganiferous nodules, and red sands (Figure 43). They can be part of a deep soil profile, or solum, weathering from bedrock (i.e. as horizons), or more likely, from prior lateritic soil development in transported sediments, particularly old alluvium, but lateritised colluvial materials also occur (i.e. as strata). Some environments will have more recent soil development in newer materials burying the older lateritised profiles. In these cases it is best to treat these as Stratified Differentiation rather than Horizons.



Figure 43: Examples of Red/Lateritised gully soil materials

Dispersivity

Dispersive / Slaking

A critical factor in the erodibility of the soil materials in gullies is its propensity or otherwise to disintegrate or disperse when wetted or when exposed to water in any way. Slaking (disintegration see Glossary) and dispersion (going into fine particle or colloidal suspension see Glossary) of the soil clay aggregates is a key factor in the susceptibility of soil materials to water erosion. Together these two processes make great quantities of otherwise consolidated material available for detachment and transport by water. Dispersion and slaking are common to many gully materials and are responsible for their rapid and relentless erosion by water wherever they are present. The effects of both these processes explain the development of soil piping and tunnel erosion activity as well as the highly active erosion on exposed faces, and the mass movement of gully walls and headwalls.

Dispersion, and slaking (to a lesser extent) are usually associated with high sodicity (usually measured by the exchangeable sodium percentage - ESP), and high exchangeable magnesium percentage, amongst other compounding factors. A simple field test can be undertaken to give a practical indication of the materials likelihood of dispersion and slaking under natural circumstances.

The field test based on the 'Emerson test' (Emerson, 1967) involves immersing selected aggregates of the soil material in water then observing and recording their reaction both immediately and after 10 minutes (Figure 44). Aggregates may neither slake nor disperse (**Type 1**), or may slake only and not disperse (**Type 2**), or they may do both (**Type 3**). This should be done for each identified layer in the gully wall/head section.

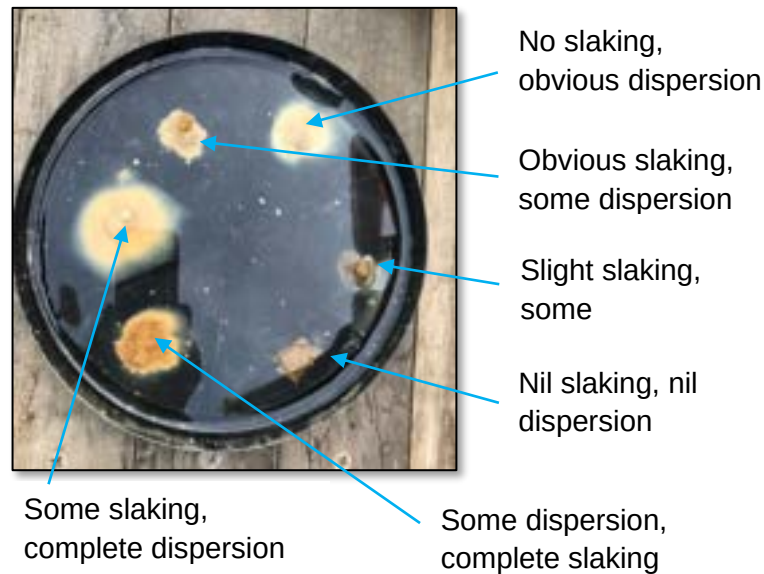


Figure 44: A demonstration of various dispersion and slaking classes in a field test.

Materials that show either *obvious* or *complete* dispersion/slaking immediately or have increased to these levels after 10 minutes are called **dispersed/slaked** for these purposes.

Gully Base Controls

It is useful to know what may be limiting the vertical development of a gully system. Hillslope gullies may erode vertically to bedrock and probably may not erode vertically any further, unless it is soft, weathered bedrock (saprolite), but may induce more lateral erosion instead.

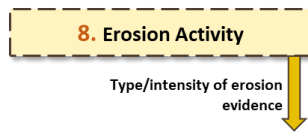
In colluvial and alluvial materials there may be a commonly occurring layer over a wide extent that restricts continued vertical development.

Lateritised materials commonly may have an indurated (hardened or cemented) and or gravel layer as the base or floor to shallow gully systems. In many dry to humid tropical gully systems a hardened, blue-grey and orange mottled layer is commonly found underlying the older alluvial sediments and extensive gully systems (Figure 45). It is not fully understood how extensive this feature is a base to gullies, as yet, or what it actually represents, although a prior and or fluctuating groundwater level over millennia is a probable cause (*sensu* Nanson et al., 2005). The hardened nature of this material (technically a plinthite) means that it can be more resistant to erosion and can form the effective base to many of these extensive alluvial gullies, and therefore should be recorded. It is likely that the indurated layer hardens and further develops as a result of oxidisation that occurs with erosion induced exposure.



Figure 45: Examples of different basal layers: a) indurated mottled layer, b) blue-grey, orange mottled layer, and c) bedrock.

5.3.2 Level 8 EROSION ACTIVITY



The history of erosion activity can be traced if sequences of historical imagery are available. The change in gully perimeter locations can be documented and visualised, and if superimposed on 3-D lidar data volumetric changes can be estimated (Figure 46).

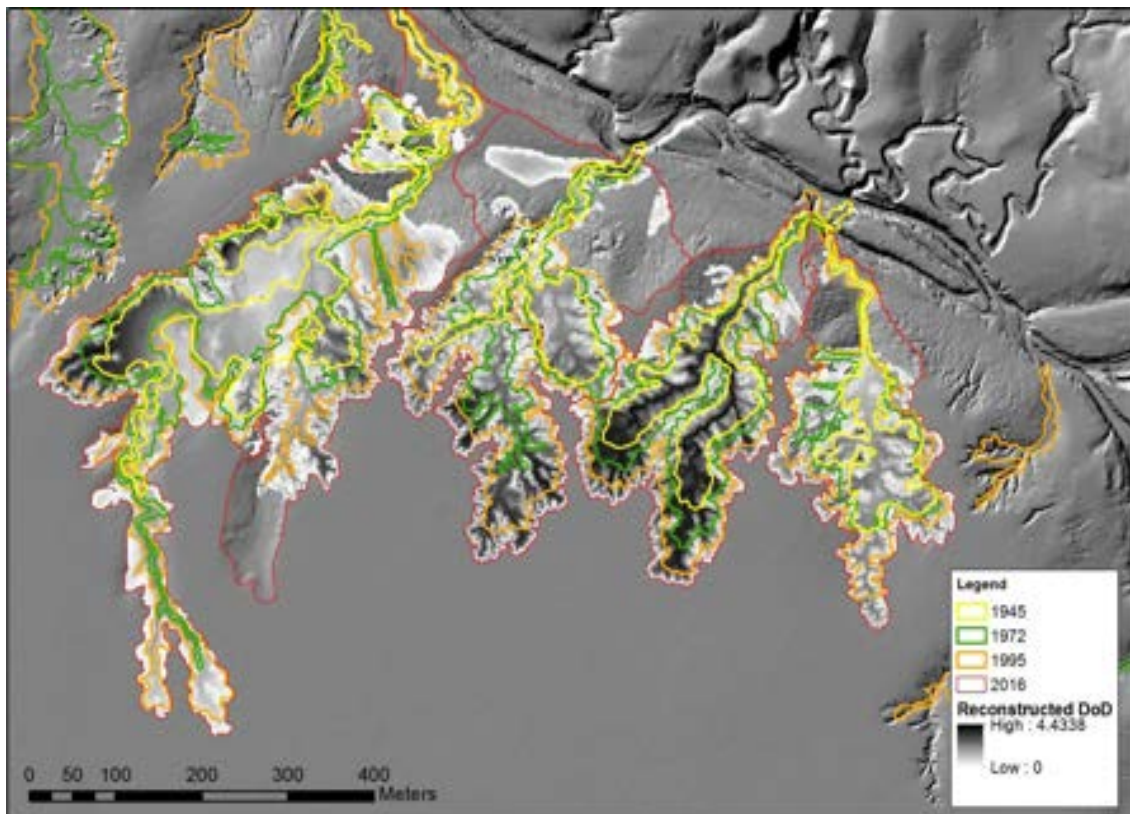


Figure 46: Example of a gully system for which growth rates have been reconstructed from an historical airphoto sequence.

In the field, there is often much evidence of erosion activity within the gully and peripheral to the gully system. Some of this has been described already, but some features and condition of the materials may give indications as to how recent and how intense this activity might be. This section of the database is to record available evidence that can provide insights into gully erosion rates, and aid simple classification of the erosion activity status as a basis to deciding priority for intervention.

Also recordable are evidence of possible causes for the erosion or causes for erosion to proliferate and/or allow predictions as to in what direction it may spread in the future. The future trajectory of the gully erosion both spatially and in intensity is directly relevant to the hazard status of the gully and its place in the prioritisation for intervention.

Erosion activity can be recorded at the active head walls of the gullies, as well as the walls, pediments, and particularly the floors of the gullies themselves, e.g. whether the flow channel is eroding or depositing more recently and what bedload materials are evident.

Lag deposits of carbonate nodules or iron / iron-manganese nodules covering the pediments and floors may act as protection to the underlying material thereby slowing the rate of erosion.

The type and prevalence of mass movement debris may indicate the rate of head and wall retreat, as does root exposure and fallen trees at the sites of active erosion, particularly if the plants are still alive, or at least moribund.

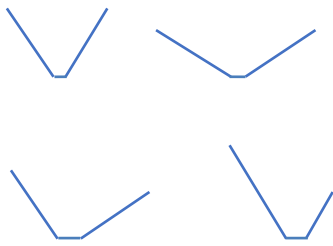
A basic classification of erosion activity in the gully for hazard rating and prioritisation has been developed here following the concept presented by Franklin et al. (2004) for NSW gullies. The hazard rating of erosion and sediment supply can be gained by observing the gully attributes below and rating their activity.

Internal Gully Architecture

The Variant Forms of each of the Gully System Forms can also be defined by the in-gully architecture and their distinctive cross-sectional shape as qualifiers to the classes.

Cross-sectional Shape

- a) *V-shaped*: Often in hard clay or coherent soil materials. Overall geometry is that of relatively straight slopes of gully walls from the land surface meeting at a narrow gully floor at similar or possibly asymmetric angles or lengths. Floor can be flat but narrow. Generally having a high depth/width ratio.



- b) *U-shaped*: Similar to V-shaped gullies but with a more concave slope near the base, usually of accumulated fall debris or protected footwalls by debris. Gully base may have a narrow, flat depositional floor. Often occurs in cracking clay / Cracking Clays' Soil Materials. Floor can be flat but narrow. Usually lower depth/width ratios than V-shaped.



- c) **Trapezoidal (flat-bottomed):** Essentially V-shaped gully forms with flat floors that are wider than those above. The flat floor is formed by sequences of deposition and erosion during and after rain and flow events. Asymmetry is more common in alluvial environments. Lower depth/width ratios than both the above.



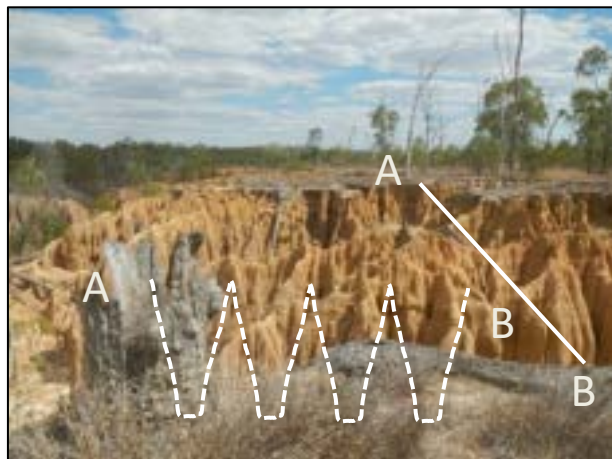
Vertical walls of this form can be called *Box-form*, but usually the walls have angles off the vertical in most gullies.



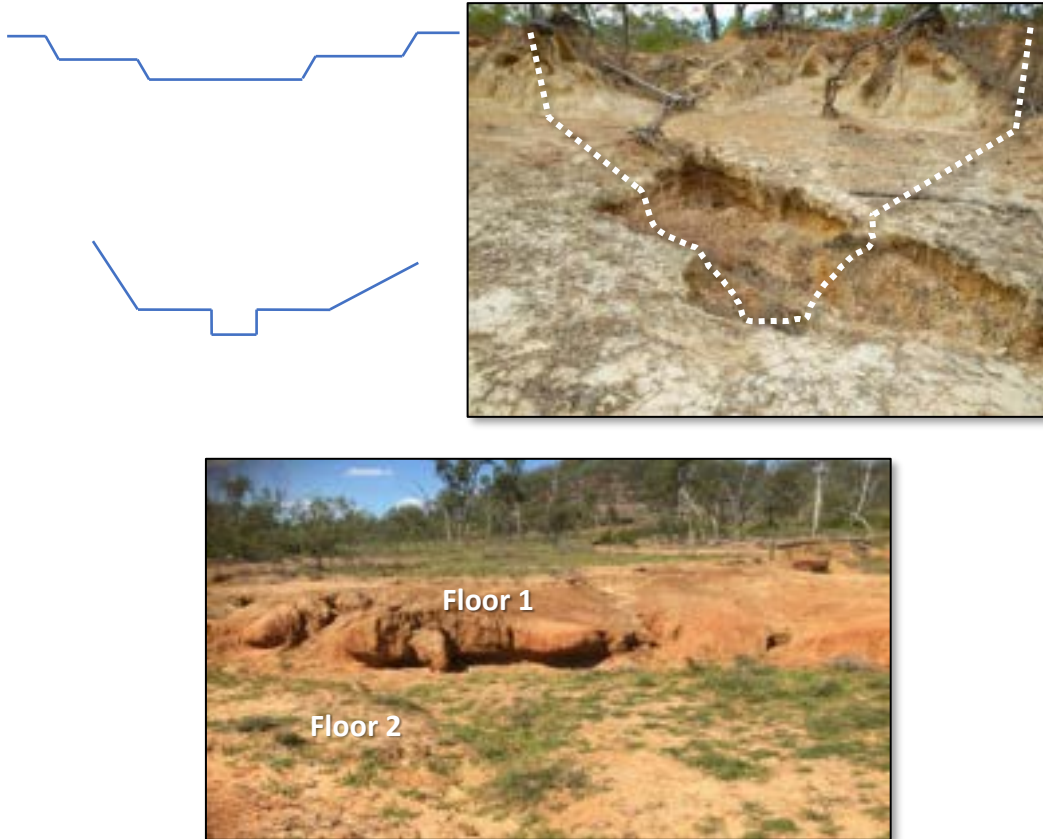
Commonly the soil profile of consolidated clay and/or hardsetting silty clay loams sit on these angled walls in a near-vertical step to the land surface. These can be termed *Step-trapezoidal* or *Stepped* if the soil 'step' is less than a third of the depth of the gully wall.



- d) **Dissected:** Complex internal head/wall/floor structure that is formed by varying degrees of erosional and depositional forms within the outer gully walls. Internal structures include pedestals, residual of landscape surface, domes, arches, and tunnel trenches.



- e) **Multiple floors (or 'tiered')**: Multi-form or multi-sequel development is evidenced by re-incision and renewed erosion leaving two or more bases or floors to the compound gully's stem. Floors may appear as eroded terraces or tiers' in large Open, Scarp-front and Amphitheatre gullies, usually in Alluvial Landscape Domains, or can be floors with recent incision and rejuvenation.



Within-gully features

Within the erosional gully void there are several features that can characterise both the gully type and morphogenetic nature (for Variants description) as well as provide insight to gully erosion processes at play, the types of materials, and the potential management methods that may need to be employed. They are part of the erosion hazard rating for the gully. Several types of features are presented here and need to be recorded in the field or from imagery.

a) *Open floor or tunnel eroded floor*

An open floor is one that is much wider than the gully is deep, largely devoid of residuals/islands, pillars, and large pedestals, and undulating pediments. It is largely clear of substantial uneroded elements.

A tunnel eroded floor is where rejuvenation or continued erosion of pediments makes the dispersive gully soil materials prone to subsurface water transport and collapses of pipes and tunnels (Figure 47). This continues the down-wearing of the gully floor surface.



Figure 47: Examples of open gully floors, and a tunnelled floor/low pediment.

b) Tunnel Erosion

Tunnel erosion is the process of creation of subsurface voids by subsurface water flow in small pipes or larger voids as tunnels, by dispersion and/or slaking of subsoil materials while the land surface remains intact (Figure 48). There is usually a detectable outlet from tunnel erosion which displays fans of deposited soil material. Tunnelling can lead to tunnel collapse, forming clefts or slots at gully heads and walls.



Figure 48: Examples of tunnel erosion in gully walls.

d) Residual pedestals (islands) and pediment surfaces

Residual pedestals are islands of eroded remnant of the original land surface that may or may not have the surface material intact and are subject to continual erosion by the same processes as the gully walls.

Gully walls and Residual Pedestals may display Pediments, which are the sloping, resistant surfaces extending between the gully flow channel or flat floor and the laterally back-wearing gully walls, or residual walls. Pediments can be the denser clay-B horizon of a soil profile or colluvial hillslope gully soil material, or a more resistant clay sediment in alluvial gully material. They are eroding by down-wearing as well as back-wearing. It can be viewed as a raised part of the gully floor, or a lower angle part of the gully wall, depending on material, process, and contextual factors.

An indurated base to gullies can often form a pediment to less-resistant materials above forming the walls. Some gullies will have just pediments and no apparent walls, and the interfluvial junction of pediments, which erodes to become part of the gully floor proper. Where bedrock is present, the bare rock sloping surface of an eroded bedrock floor is the pediment supporting the gully walls.



Figure 49: Examples of Residual Pedestals.



Figure 50: Examples of Pediments (residual slopes).

See also descriptions of additional remnant features in the glossary, including; Pillars, Buttresses and Domes.

e) *Dissection*

Some alluvial gullies can be highly dissected with myriad internal remnant features, which are best described as highly dissected landforms.



Figure 51: Examples of highly dissected internal gully structure on larger and smaller scales.

Evidence of recent erosion activity

Root exposure and excavation / tree fall

Exposed roots are indications of active erosion, as old tree roots eventually dry and become brittle and disintegrate over a period of a few years. If the trees are still standing, then the root exposure is comparatively recent. Fallen trees that have the finer roots still intact are also evidence of recent activity. Fallen trees that are still alive indicated very recent activity.



Figure 52: Examples of root exposure with very recent erosion activity and head retreat evident.

Block collapse

Significant blocks of headwall or wall material broken away from the gully margin that still have topsoil attached and/or live plants/trees are a good indicator of very recent activity on gully walls and the head.

Scour, incision, tunnelling, new deposition

When it comes to the gully floor, fresh scour of flow channels, and undercutting of walls leading to wall collapse, are evidence of fresh erosion activity. Incision by channels and creation of tunnels from upper levels in the floor or pediments are another indicator.

Gully Erosion Activity Class and Rating

A Gully Erosion Rating can be calculated by using the following flow chart to get an initial Erosion Activity Class (Figure 53). A final overall score is the sum of the scores for each of the five sections of the chart from observation of the erosion activity and intensity in the gully.

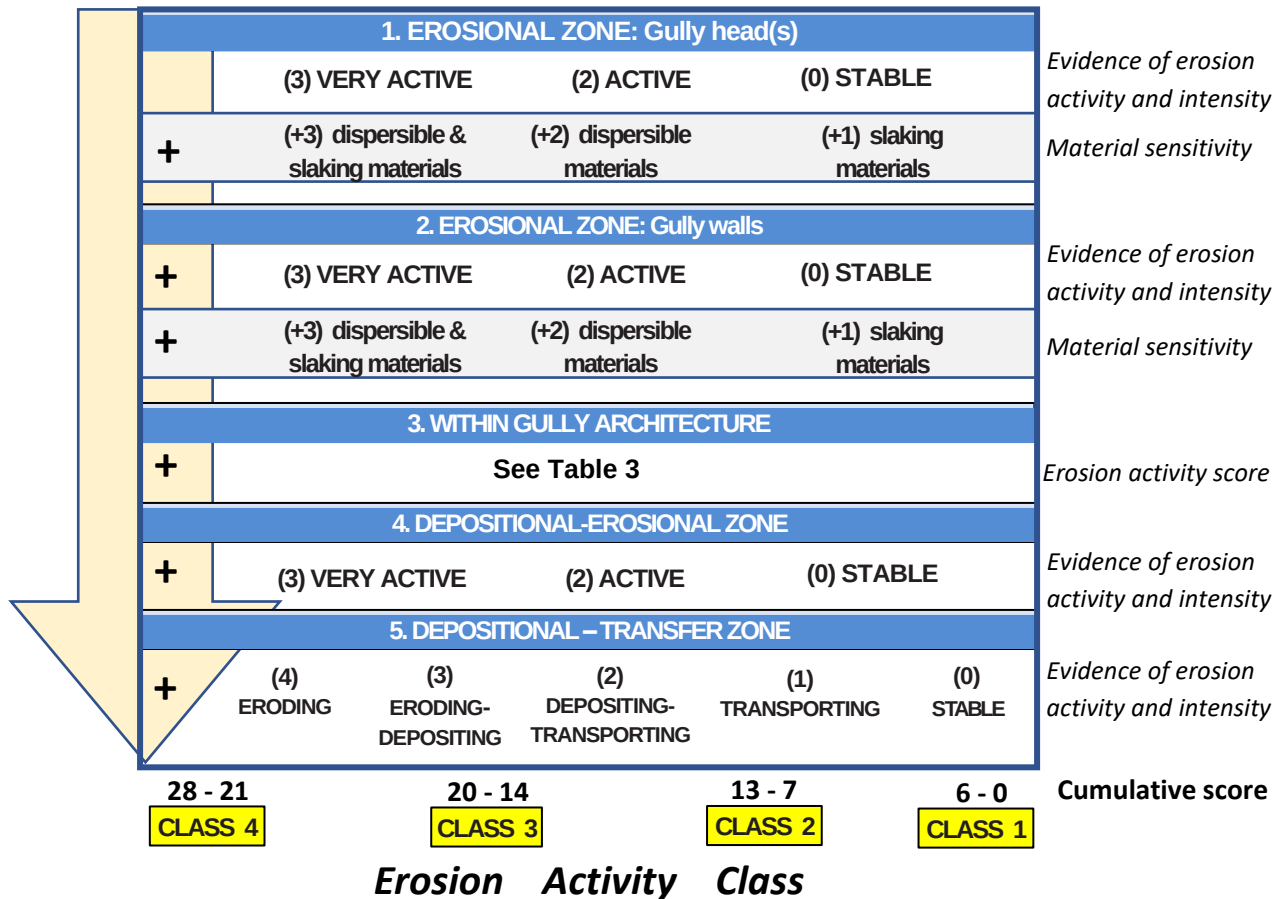


Figure 53: Erosion activity classes, (x) = score.

Table 3: Within-Gully Architecture erosion activity score.

Component		Score	0	1	2	3
Minimal - Open Floor			stable	active	very active	-
Cross-sectional shape	Trapezoidal / U-shaped		stable	active	very active	-
	V-shaped		stable	active	-	very active
	Dissected		stable	active	-	very active
Multiple floors	Rejuvenated / multiple floors		all stable	lowest active / very active	all active	all very active
Pediments (or multiple low walls), Residual Pedestals (Islands) present						+ 1
Dispersible eroding materials/Tunnelling eroding floor and/or pediments						+ 2

Table 4: Gully Erosion Activity Rating table.

HIGH		Erosion Activity Class			
MODERATE					
LOW		4	3	2	1
Gully Depth	> 5 m				
	2.5 - 5.0 m				
	1.0 – 2.5 m				
	< 1.0 m				

PART 3

6.0 THE FIELD MANUAL BASIS

This section provides a working draft of a generic field manual for use by non-specialists but have some understanding of the land sciences.

6.1 Background

A separate manual for using the classification operationally in the field and in the office will be produced upon receiving feedback on the proposed system and database components.

The procedure to use the Gully Classification relies on following the stages in the classification framework presented above and summarised below (Figure 54).

The procedure is stepwise and self-explanatory, and it is best to follow the sequence as presented although some steps can be left out and returned to at a later stage.

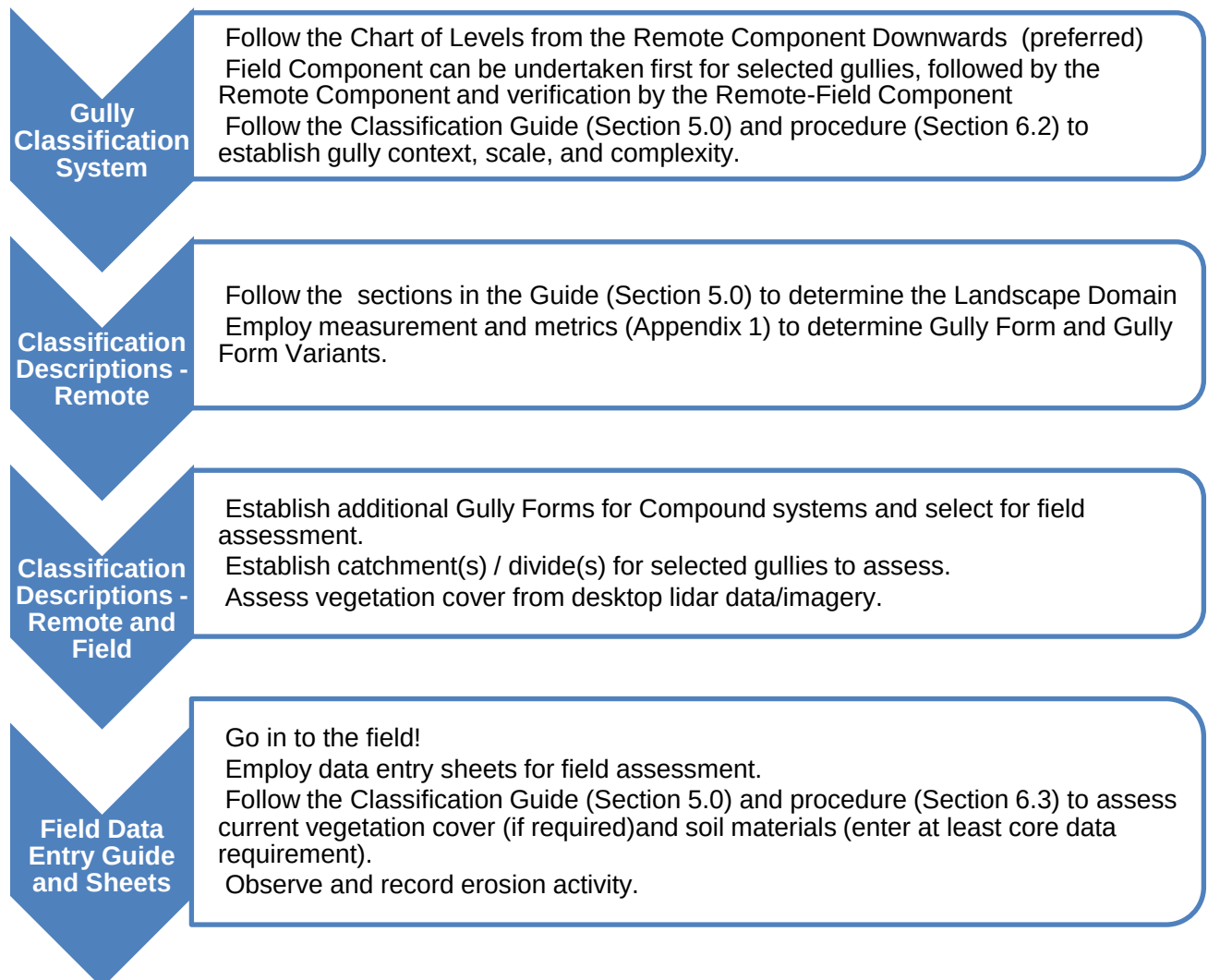


Figure 54: The basic procedure for classification and data entry.

It may be the case that some gullies have presented themselves to be assessed for other reasons than by external prioritisation. Field assessment can be undertaken initially for observation and measurement as well as vegetation and soil material assessment if appropriate at the time. However, the Remote Component of the Classification will subsequently have to be followed.

6.2 The Gully Classification procedure

The following is the 10 x 10 step procedural Manual for using the classification. Ten steps for the Remote Component and 10 steps for the Field Component. Currently it serves as the protocols that are expected to be followed when assessing gullies for management and intervention as well as for classifying them.

6.2.1 The Remote Component procedure

1. Climate-Rainfall Region

Refer to online maps or GIS maps to establish Köppen climate region

2. Identify and define Gully System / Gully Subsystem / Gully Unit

Use DEM data (preferably lidar) , imagery/ aerial photography, Google Earth to establish System hierarchy.

3. Establish Gully System complexity

Further investigation using available digital data and imagery

4. Identify Landscape Domain - initially

Using available geological, soil mapping from national and State databases or hardcopy maps

5. Undertake morphometric analysis

Digitally or manually
Can be verified in the field

6. Classify your gullies

Refer to the Guide
Make a short report on how gullies were classified and the reasons used and problems encountered

7. Decide on any additional forms if in Compound or Complex Systems

8. Determine catchment dimensions

Use digital DEM data and analysis to delineate catchments for each gully system (defined by their outlet points)
Use GIS tools to calculate catchment metrics (refer to the Guide)
Delineation and calculations can be done manually on maps, imagery, DEM prints, etc. and can be verified in the field.
If catchments cannot be satisfactorily delineated, then Distance to Divide can be substituted from map/imagery interpretation and verification in the field

9. Estimate Vegetation Cover - refer to the Guide

Use lidar vegetation classification to estimate vegetation cover and vegetation classes outside and inside the gully system
Use aerial photography, imagery, Google Earth to estimate vegetation cover outside and inside the gully system

10. Time for a field visit...

6.2.2 The Field Component procedure

1. Initial walk of gullies

Take waypoints, photographs, and notes at strategic points and sites of active erosion
 Take note of vegetation cover, densities and types around and inside the gullies
 Take note of distinct soil material layers, their location, depths, and association

2. Record vegetation cover

Outside the gully - record on data sheet
 Within the gully - record on data sheet
 Verify or revise previous remote/desktop assessment where necessary
 Estimate densities by eye
 Attempt to identify vegetation types or species, particularly grasses
 Take samples for identifying later if necessary

3. Observe and record gully characteristics

Complete the Gully System data sheet as far as possible
 Take photographs, record any comments, like uncertainties, and items out of the usual.
 Use UAV drone video or photography if available.

4. Determine soil material continuity

Does the nature of the soil material change through the extent of the gullies?
 If so, identify boundaries where the changes in fundamental soil materials change

5. Determine Soil Material Group

Refer to the Guide. Determine whether the gully soil materials are Uniform overall, Stratified, or Horizons (comprising largely a soil profile on bedrock)
 Determine the different System classes for identified changes in soil material type through the system
 Stratified materials will need further investigation to establish the number and type of layers.

6. Determine Soil Material Type - Refer to the Guide

Establish if the materials are Cracking Clays, Contrasted, or Red/Lateritised in nature
 Do this for each zone of different Soil Material Groups identified

7. Develop a simple sampling plan

At least two sites for observing , recording and sampling will be required
 Multiple Soil Material Groups and Stratified systems may need further sites
 Choose further sites if soil material complexity demands it.

The Field Component procedure continued

8. Sample and record soil materials at sites

see Field Protocols for sampling scheme and intensity
At each site record all details possible that appear on the Soil Materials data sheet
Location data is essential
Gully landscape data
Gully site conditions and characteristics
Record soil material data for each identified layer
Photograph the exposure
Use a pH kit, if available
Use a flat dish and water for soil aggregate dispersion test

9. Sample soil materials for analysis

Soil material samples are necessary for analysis of sodicity, salinity (electroconductivity, chloride), cation exchange capacity, particle size, pH, phosphorus, total carbon, and other analytes if required
Take a sample of each layer at each site if necessary with a trowel or pick
Samples for analysis can be chosen back in the office - rather take samples and discard them than not take them then needing them
Record if a sample of the layer has been taken and record the depths of the samples from the surface
Use zip-lock plastic bags and take at least 250 g of soil material for each bag
Label each bag with date, time, site ID, sample number, depth of sample
Record samples on the Data Sheet
Photograph the exposure and sample bags at the site

10. Make a sketch map of soil material boundaries

Record the location of any surface soil material boundaries and where layer boundaries occur at the surface, if they can be identified.
Use an aerial photograph, image print, or DEM print of the gully as a base map to record sites and boundaries.

APPENDIX 1: METRICS FOR DESCRIBING AND CLASSIFYING GULLIES

Certain parameters that can be measured both at the desktop level and in the field are useful to characterise and classify each gully or gully system for research and development purposes, database inventory, erosion activity prediction (for prioritisation), sediment yield modelling, and for management/rehabilitation planning.

1.1 Some requirements

For the following parameter calculations, it is assumed that certain data types and facilities are available for the Remote Component of this Classification process. For non-specialists undertaking any of this work, who may not have the more advanced facilities and data available, some basic metrics are still important at the Remote Component stage. These and the field-recorded parameters (within the other Components) are identified and outlined as such in this section.

1.1.1 Advanced requirements

- Lidar 1 m surface resolution. DEM and hillshade derivative.
- High-resolution satellite imagery, or large-scale aerial photography.
- GIS capability (e.g. QGIS or ArcGIS).
- Field measurement with distance-measuring equipment (DME) and GPS
- *All database entries for any gully (system / subsystem) need to be accompanied by a DEM/hillshade screen shot and an aerial/satellite/Google Earth image.*

1.1.2 Minimal requirements

- SRTM radar resolution DEM and hillshade derivative.
- Satellite imagery or aerial photography, otherwise *Google Earth* imagery.
- Some GIS capability (QGIS recommended).
- Field measurement with tape measure (or DME from hardware store) and GPS
- *All database entries for any gully (system / subsystem) need to be accompanied by a DEM/hillshade screen shot and an aerial/satellite/Google Earth image*

1.2 Preliminaries and measurement

1.2.1 Drainage form (hydrological connectivity) to identify streamlines and drainage catchment.

- Identify streamlines through gullies to the outlet and confluence with the drainage network: connectivity
- Identify single outlet to identify gully system subsystem(s) gully(-ies)
- Identify catchment: calculating and defining area of contributing area to catchment (CCA) through GIS or by measuring distance to drainage divide (via major stream line; DtD).

1.2.2 Endpoints and boundaries (see Glossary – Appendix 1):

- **Distal end:** where the gully starts (usually a headscarp or knick-point).
- **Terminus:** where the gully ends. This is a problematic concept (see earlier discussion on definitions of a stream channel and a gully). Usually it is the outlet to a stream, unless the outlet to the stream or drainage network is definitively a stream in itself. Often, gully drainage transitions to a stream channel before it joins the greater drainage network. This transition zone can be deemed to be the terminus of the gully, although judgement must be applied. In some cases, it is not clear if there is a transition, so it may be best to consider the 'drainage' flowline to the confluence as the outlet of the system and, therefore, the terminus also. *Defining the terminus of the gully system will also then determine the length of the gully, whether by length of flowline from the furthest head or the length of the longitudinal axis.*
- **Proximal end:** The outlet of the gully drainage system to the local drainage network. In the case of discontinuous, or disconnected gullies then the proximal end is where the gully feature loses its defining criteria, and presumably it is where the eroded sediment is depositing.
- **Gully system boundaries, or Perimeter:** All measurement related to the actively eroding/eroded 'old rounded hard edges' the outer 'soft edge' boundaries of gully systems and individual gullies vary considerably in their shape, character, and relationship to the erosion processes of the gully. In many cases this outer perimeter of these gully systems, where they occur, are not the location of active erosion, and can often be deemed to be at least semi-stabilised, although they have eroded in the past. *For a functional classification of gully systems for erosion management the inner, 'hard edge' perimeter, is used for the boundary of the gully system as the zone of active erosion and sediment supply, and/or the feature that needs to be considered for rehabilitation and management.* Reasons for using soft edges/hard edges where relevant needs to be stated.
- **Gully trunk:** the main body of the gully system, subsystem, or gully void (primarily, Linear and Dendritic systems). This is where the main drainage flows and may be connected by Branches and Lobes as tributary systems. This concept is scale dependent.

1.2.3 Length of streamline through gully and gully branches.

- GIS streamline measurement, or
- Map measurement following drawn average thalweg, or
- Length of longitudinal / main axis (for gully, or branch)

1.2.4 Gully width

- Measured at widest point, near head(s) at distal end, near outlet at proximal end or terminus (as far as possible). Uniform reaches of the gully main void (trunk)
- Width between scarp walls / break of slope between land surface and eroding walls of the gully/system perimeter (previously defined as hard or soft edge where applicable)
- Width and depths measured at same locations for cross-section calculation.

1.2.5 Gully area

- The 'gully area' is considered here to be the 'eroded gully void'. This can be calculated as either 'plan area' (within a simple 2-D boundary) and 'surface area' (taking the 3-D surface of walls and floor into account) or both.

1.2.6 Gully depth from differences between DEM points

- Measured as scarp depth at main head(s) from land surface to local floor.
- No scarp: from nearest head at land surface at gully perimeter to flat gully floor.
- Use long-profile / cross-profile tool in GIS on the DEM to identify slope breaks at measuring points.
- Note where elevation points for depth were taken and reasons.
- Gully depth can be determined by creating a topographically conforming 'lid' on the gully void from the perimeter polygon cell elevation values. The depth is then calculated as the difference between the elevation values of the lid cells and those of the gully floor.

1.3 The parameters (metrics)

1.3.1 Basic parameters:

- **Length (L_g)** = Length of gully void (m).
This is best taken as the distance from the furthest head to the gully terminus (along the path of drainage without sinuosity).
- **Representative Width (W_r)** = measured width of the gully void (m) from opposite gully perimeters. Across the gully trunk or open floor (W_r) or across branches in a dendritic system (W_{rs}).
- **Average Width (W_a)** = width measurements taken at three points at uniform reaches of the main gully void (trunk): proximal (near the head), central, distal (near the gully terminus) selected point along the gully void, then averaged (mean).
- **Average Depth (D_a)** = calculated mean from gully depth values from the gully lid, or from differential elevation values taken at selected points in the gully.
Otherwise, $W_a = (D_{rt} + D_{rm} + D_{rh})/3$ = where D_{rx} is the representative depth measurement taken at three points selected at uniform reaches of the main gully void (trunk): near the head (D_{rh}), central (D_{rm}), near the gully terminus (D_{rt}).
- **Representative Depth (D_r)** = average of the maximum depth of the gully measured from the perimeter, and depth at the active gully head(s) or wall(s).
- **Total long profile gradient (G_t)** = $L_g / (E_{\max} - E_{\min})$ where $E_{\min}$ is the elevation at the gully (system) terminus and $E_{\max}$ is the elevation at the gully (system) head.

- **Axial dimensions (X_{long} , X_{lat})** = maximum length and direction (longitudinal axis) and the maximum perpendicular width (latitudinal axis) of the 'minimum bounding geometric polygon' around the gully (system) unit. Otherwise the axes of a fitted regular geometric shape, i.e. circle, ellipse, rectangle, triangle, rhomboid, pentagon (for dendritic systems).

Areas and perimeters:

- **Area (A_g)** = plan area of gully system eroded void bounded by the perimeter, or actively eroded margin (m). Can be calculated by closing the perimeter polygon at the identified terminus point in GIS, or from advanced DEM analysis using GIS.
- **Surface area (A_{gs})** = actual areas of the gully land surface the surface of the basin compared to that of the lid' can be calculated from the surface area ratio tool in advanced DEM analysis.
- **Perimeter (P_g)** = perimeter of the gully system eroded void (m)
Can be approximated by simple digitising for basic analysis or created by automated DEM analysis.

1.3.2 Complex parameters:

- **Length of overland flow ratio (L_o)**

$$L_o = DtD / L_g$$

Where DtD is the distance to divide (the distance from a head, or selected multiple heads, to the catchment divide as far as can be ascertained), and L_g is the length of gully drainage.

> 1 = High; < 1 = Low; < 0.3 = Very low

In non-dispersive materials on hillslopes:

- High values = potentially active headward erosion and high runoff supply
- Low values = reduced headward erosion and runoff supply
- Very low values = little headward erosion and runoff supply

In non-dispersive materials on alluvial landforms:

- High values = potentially active headward erosion and moderate runoff supply
- Low values = reduced headward erosion and greatly reduced runoff supply
- Very low values = little headward erosion and little to no runoff supply

- **Catchment area ratio (A_{ca})**

$$A_{ca} = A_{tc} / A_g$$

where A_{tc} is the total catchment area of gully system and A_g is the gully system (eroded void) area (m^2)

> 1 = High; < 1 = Low; < 0.3 = Very Low

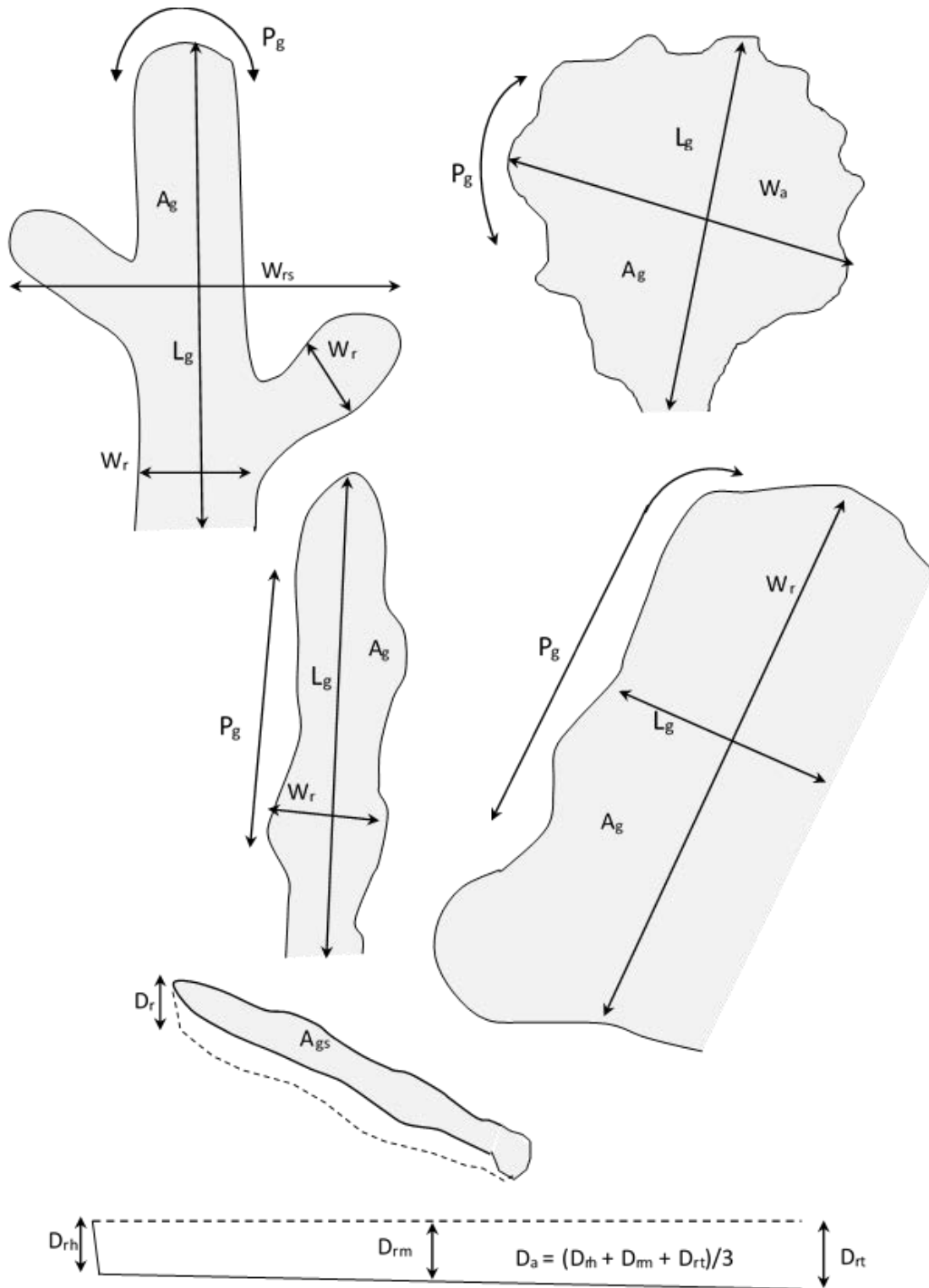


Figure 55: Schematic diagram showing the measurements for the basic gully dimensional parameters.

- **Width/Depth ratio (R_{wd})**

$$R_{wd} = W_a / D_a$$

where W_a is the average (mean) width of the gully void (m), and D_a is the average depth of the gully void.

< 0.5 = deep/narrow (Slot gully); > 3 = wide (for Linear, Dendritic); > 10 = broad (for Linear, Dendritic); wide (for Open, Amphitheatre, Scarp-front); >30 broad (for Open, Amphitheatre, Scarp-front).

For gully shape

- **Axial ratio (R_a)**

$$R_a = X_l / X_w$$

Where X_l is the longitudinal (long) axis of the gully (system) and X_w is the lateral (wide) axis of the gully (system).

- **Compactness constant (C_c)** (Horton, 1945)

$$C_c = 0.2821 P_g / A_g^{0.5}$$

where P_g is the perimeter of the gully system eroded void (m), and A_g area of gully system eroded void (m).

For dendritic systems and subsystems (and highly irregular perimeters to other systems) the minimum bounding geometric polygon should be used for this calculation.

- **Elongation ratio (R_e)** (Schumm, 1956)

$$R_e = L_g / A_g$$

Where L_g is length of gully drainage to furthest head from the outlet, and A_g is gully void area (m).

- **Texture ratio (R_t)** (Horton, 1945) for Dendritic systems (and within Scarp-front / Amphitheatre systems)

$$R_t = N_b / P_g$$

where N_b total number of branches in the gully system, P_g perimeter (m).

The following are yet untested but are promising for gully characterisation.

- **Cross-sectional Shape index (S_c)** (Gabet & Bookter, 2008)

$$S_c = W_{25} / W_{Top}$$

where W_{25} is the width of the gully at a distance (m) from the bottom that is 25 % of the maximum depth and W_{Top} is the gully width (m) at the top of the gully.

Valid only for individual gullies or branches, but can be applied conditionally to simple, flat floored systems and subsystems, with W_g being wide to broad.

- **Plan Shape index (S_p)** (Nooka Ratnam et al., 2005)

$$S_p = L_g^2 / A_g$$

where A_g is the gully system (eroded void) area (m²), and L_g is the length of the gully drainage (m).

- **Circularity ratio (S_{cir})** (Miller, 1953)

$$S_{cir} = A_g / P_g^2$$

A_g area of the gully void (basin) (m^2), P_g perimeter (m)

For Dendritic Systems and Subsystems, the minimum bounding geometric polygon should be used for this calculation.

- **Hypsometric index (H_i)** (Strahler, 1957)

$$H_i = E_m - E_{min} / E_{max} - E_{min}$$

where E_m is the mean elevation between the head and the terminus of the gully (system) and E_{min} is the elevation at the gully (system) terminus and E_{max} is the elevation at the gully (system) head. This is best achieved through simple GIS terrain analysis.

For Erosion and sediment transport potential

- **Stream Power Index (SPI)** (Wilson & Gallant, 2000)

$$SPI = A_s \cdot \tan\beta$$

Where A_s is the specific catchment area and $\tan\beta$ is the slope gradient

The following are, as yet, untested but are promising for gully characterisation.

- **Sediment Transport Capacity index (LS)** (Wilson & Gallant, 2000)

$$LS = (m+1) \cdot (A_s / 22.13)^m \cdot (\sin\beta / 0.0896)^n$$

Where A_s is the specific catchment area $\tan\beta$ is the slope gradient and $m = 0.4$ and $n = 1.3$ (for slope lengths < 100 m and slope gradients < 14°).

- **Sediment Transport Capacity Index (ΔT)** (Wilson & Gallant, 2000)

QGIS/GRASS GIS algorithm

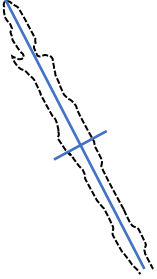
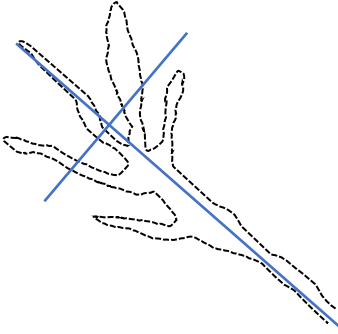
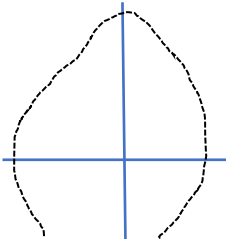
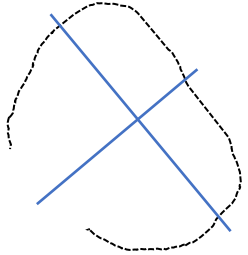
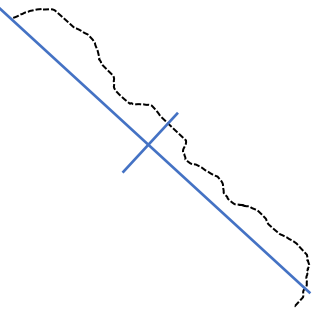
$$\Delta T_{cj} = \Phi \cdot A_{sj}^{-m} (\sin\beta_{j-})^n - A_{sj}^{-m} (\sin\beta_j)^n$$

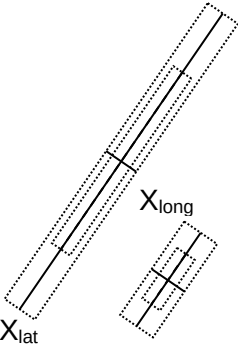
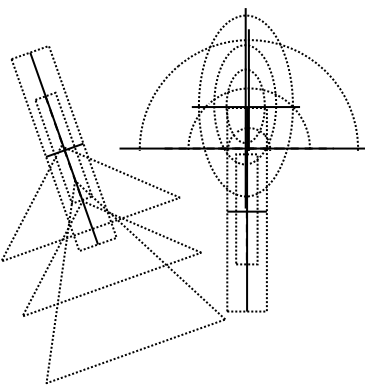
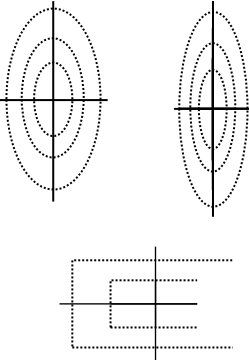
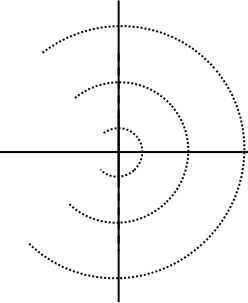
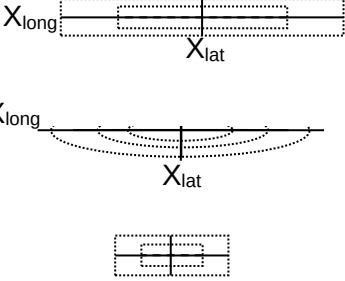
Table A1: List of all potential parameters for describing gully morphometry.

Parameter	Definition	Parameter	Definition
A_{ca}	Catchment area ratio: $A_{ca} = A_{tc} / A_g$	R_{wd}	Width/Depth ratio: W_a / D_a
A_g	Gully area (m ²)	R_a	Axial ratio: $R_a = X_l / X_w$
A_{gs}	Gully surface area (m ²)	R_e	Elongation ratio: $R_e = L_g / A_g$
A_{tc}	Area of total contributing catchment (m ²)	R_t	Texture ratio: $R_t = N_b / P_g$ (for Dendritic systems).
C_c	Compactness constant: $C_c = 0.2821 P_g / A_g^{0.5}$	S_c	Cross-sectional Shape index (S _c): $S_c = W_{25} / W_{Top}$
D_a	Average Depth of the gully void (m)	S_{cir}	Circularity ratio: $S_{cir} = A_g / P_g^2$
D_r	Representative Depth of the gully void (m)	S_p	Plan shape index: $S_p = L_g^2 / A_g$
E_m	Mean elevation between the head and the terminus of the gully (system)	SPI	Stream Power Index $SPI = A_s \tan$
E_{min}	Elevation at the gully (system) terminus	W_a	Average Width of the gully void (m)
E_{max}	Elevation at the gully (system) head	W_r	Representative Width of the gully void (m)
G_t	Total long profile gradient $L_g / (E_{max} - E_{min})$	W_{rs}	Representative Width (m) (dendritic system)
H_i	Hypsometric index (H _i): $H_i = (E_m - E_{min}) / (E_{max} - E_{min})$	W_{top}	Gully width (m) at the top of the gully
L_g	Length of the gully void (m)	W₂₅	Width of the gully at a distance (m) from the terminus that is 25 % of the maximum depth
L_o	Length of overland flow ratio: $L_o = DtD / L_g$	X_{long}	Longitudinal axis of the gully (system) (m)
LS	Sediment Transport Capacity index: $LS = (m+1) \cdot (A_s / 22.13)^m \cdot \sin^n$	X_{lat}	Lateral (width) axis of the gully (system) (m)
N_b	Number of branches in gully system	ΔT	Sediment Transport Capacity $T_{cj} = (A_{sj}^m \sin \theta_j)^n$
P_g	Gully perimeter (m)		

Table A2: Gully parameters relationships.

Factor	Gully Form				
	Linear	Dendritic	Open	Amphitheatre	Scarp-front
Length (L_g)	Relatively easily determined once terminus identified.	Usually measured from the head-cut furthest from the terminus once identified. Usually has a well-defined trunk.	Potentially problematic to define, as outlet(s) and terminus may be difficult to define. Furthest head on perimeter producing the longest flowline.	Potentially problematic to define, but outlet and terminus may be able to be defined satisfactorily. Furthest head on perimeter producing the longest flowline to the outlet.	Problematic to define, as outlet(s) and terminus may be difficult to define, and system may have several subsystems or phases of development. Furthest head on perimeter producing the longest flowline. Or length of longitudinal axis.
Width (W_a) (W_r)	See above				
Depth (D_a) (D_r)	See above				
Perimeter (P_g)	Long sidewall perimeter compared to very short headwall perimeter.	Very long sidewall perimeter that includes branches and lobes. Relatively short headwalls perimeter.	Variable perimeter for both sidewalls and headwalls.	Essentially curved perimeter so that lateral walls close in on the outlet /terminus part of the void.	Long head wall perimeter, compared to side walls.
Area (A_g)	See above				
Surface Area (A_{gs})	See above				
Catchment area ratio (A_{ca})	High values	High values for Hillslope gullies.	Low to high values	Low values to negative values.	Low values to negative values.
Width/Depth ratio (R_{wd})	< 0.5 = deep/narrow (Slot gully); > 3 = wide; > 10 = broad	< 0.5 = deep/narrow (Slot gully); > 3 = wide; > 10 = broad	> 10 = wide; > 30 = broad	> 10 = wide; >30 = broad	> 10 = wide; >30 = broad
Surface Area (A_{gs})/Area (A_g) ratio	Relatively high values dependent upon gully depth.	Relatively high values dependent upon gully depth, and openness of branches (lower values) and amount of dissection (higher values).	Relatively low values dependent upon amount of dissection (higher values).	Low values dependent upon amount of dissection (higher values).	Low values dependent upon amount of dissection (higher values).

Axial ratio (R_a)	 Distinctly longer longitudinal axis .	 Shorter latitudinal axis closer to the distal end.	 Both axes can be of variable lengths and offsets, but latitudinal axis is often shorter and closer to the terminus.	 Both axes can be of variable lengths and offsets, but latitudinal axis is either equal or longer and is often further from the terminus.	 Distinctly longer latitudinal axis .
Compactness constant (C_c)	Usually high values , slightly lower for broad gullies.	Usually very high values . Lower for open and broad gullies.	Medium to low values depending on crenulation of the perimeter.	Usually lower values , depending on the crenulation of the perimeter.	Highly variable depending on the X_{long} value and crenulation
Plan Shape index (S_p)	As for Elongation Ratio but values are logarithmically smoothed to higher index values, accentuating the elongated shapes.				
Cross-sectional Shape index (S_c)	Low values are associated with V-shaped cross-sections and high values are associated with U-shaped cross-sections for simple systems and compound subsystems.	Low values are associated with V-shaped cross-sections and high values are associated with U-shaped cross-sections for simple systems and compound subsystems.	Very high values for open, undissected floors. N/a for dissected and complex within-gully architecture systems.	Very high values for open, undissected floors. N/a for dissected and complex within-gully architecture systems.	Very high values for open, undissected floors. N/a for dissected and complex within-gully architecture systems.
Circularity ratio (S_c)	Usually very high values (non-circular)	High values (approximating balloon shapes)	Medium to low values .	Low values .	Usually high to very high values .
Elongation ratio (R_e)	High to very high values generally. Lower values for Open Linear systems.	High values generally . Lower values for open dendritic and dissected Dendritic systems.	Low values generally.	Very low to extremely low values .	Low to very low values .

Texture ratio (R_t)	Usually low values (lobes not counted as branches). Potentially high values depending how small branches are defined or identified.	Usually high values for systems . Lower for sub-systems. Nested Linear systems or rejuvenated dendritic would be lower values .	N/a. Nested Dendritic compound subsystems: see under Dendritic.	N/a. Nested Dendritic compound subsystems: see under Dendritic.	N/a. Nested Dendritic compound subsystems: see under Dendritic.
Geometric form and axes (range of variation also shown)					
Soil material uniformity	Commonly occur in Uniform and Horizon types.	Common in all types but compound systems vary according to heterogeneity in Stratified type.	Common in Stratified and Horizon types.	Usually in Stratified types (alluvial) or Contrasted-Horizon types.	Usually in Stratified types (alluvial) or Uniform Red/Lateritised soil materials.
Soil material type	Common in Cracking Clays soil materials.	Common in all types, dependent upon slope gradient and surface topography.	Usually not in Cracking Clays types.	Usually not in Cracking Clays types.	Usually not in Cracking Clays types.
Soil material dispersivity	If present, commonly forms open gully systems, dependent upon slope gradient.	Initially can occur in dispersive materials but can rapidly develop into open and dissected forms, and nested subsystems within Amphitheatre and Scarp-front systems.	Commonly occurring to form this type.	Usually dispersive soil materials	Usually dispersive soil materials.

APPENDIX 2: THE DATABASE AND DATA SHEETS

2.1 A Queensland Gully Database

2.1.1 Data collection and analysis

Data collection sheets have been designed to guide the collection of the appropriate gully parameters at the desktop level and field sites. The data sheets are intended to be flexible to accommodate varying skills and abilities of the recorder, accommodate for limits of resource availability, and accommodate future refinements to the data sheet design. A component of the flexibility is that the sheets differentiate between core data requirements and more specialised sections of data entries. The core data is a series of questions of gully shape and size, surrounding landscape, vegetation character, and basic soil observations. The specialised component is a comprehensive soil layers and properties data sheet. The Guide and the manual are intended to accompany the data sheets and be referred to during data collection.

A data structure has been created that incorporates and follows the design of the groupings and hierarchical relationships of parameters seen in the data sheets. The database at this stage is stored in an XML format. The code necessary to give the database some functionality has also been developed. The functionality at this stage is the extraction of entries from the data sheets and the translation of those entries to the database structure and format. The code will be augmented as needed to add functionality. Foreseeable additions will be data manipulation and organization for analysis and the reconfiguring of the data to output in formats suitable for other analytical software.

The central tenet of research involving the development of a classification with the goal of knowledge discovery is the circular feedback between the classification design, the analysis of the underlying object property values, and the refinement of the classification design. The critical steps to uncovering a better understanding of the gullies throughout Queensland are the cycles of classification design, data collection, analysis of the gully database contents, and refinements to the classification design (Figure 56).

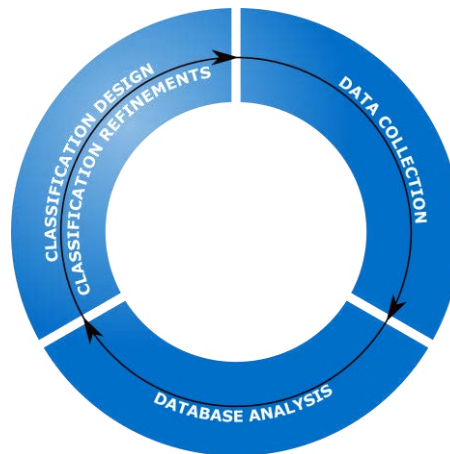


Figure 56: Feedback process to use classification development as knowledge discovery mechanism.

Examples from this initial data collection system are given in Figure 57. As the number of gullies visited, evaluated, and entered into the database increases, refinements to the classification are to be expected, driven by the insights gained through the analysis of the gully data collected. This analysis may show evidence that some metrics in the database are strongly correlated, or conversely, that some key attributes are missing. The efficiency of data collection and the effectiveness of the classification will likely increase by removing or combining correlated metrics and the addition of new metrics within the datasheets. The amount of data collection required is the threshold at which a judicious placement of a gully into a class can be made. The right gully classes and the right data collection are the basis for judicious decisions regarding, for example, prioritisation and selection of gullies for on ground rehabilitation works. The gully database will also be an important component in the analysis of the success of rehabilitation works, their efficiency, and the assessment of which rehabilitation techniques are most successful for which class of gully.

2.1.2 Database structure

The data structure, associated code, and choice of xml format are appropriate for this stage of development of the gully database. Currently, the datasheets are Excel spreadsheets (data either entered directly or entered from paper datasheets) which are sent to Griffith University to be added to the central database. Future development of the Queensland gully data could be a database held on a server with online functionality. This functionality could be a website where gully datasheet entries are transcribed, or the datasheets are uploaded and/or some sort of phone/tablet application containing the datasheets and loading directly to the database server in real time or when next in mobile network range. It is expected that the Queensland government's soils and information system will eventually host the gully database. An important requirement of the current database is that it has a strict structure so that, following future developments, the amassed gully data can be translated to another system with minimal resources and effort. The xml format can be used flexibly to change, rearrange, and add metrics and can implement the required strict structure.

Currently the database structure accommodates gully metrics recorded using the datasheets plus supplementary on-site photographs, satellite imagery, lidar imagery, or lidar data that have been submitted with the datasheets. Future experience and evolving necessity may

suggest that other information should be added to the database, such as, results of soil test, assessments of rehabilitation techniques, etc. The intent is that the Queensland Gully Database is as comprehensive a gully data repository as can be achieved and is not solely for the purpose of this classification. Other typologies and generic classification could be derived from the data within the gully database that relate to and serve yet unknown purposes.

2.1.3 Detailed data and core data

It should be stressed that we do not envisage that all gullies will need to be characterised to this level of detail. Similarly, it is not essential that every data field in the data sheets is populated for every gully, although the core data may be required. In particular, we would not envisage that the soil materials are characterised to the level of detail we have provided for most gullies. However, we have attempted to set up protocols for characterising gullies in a systematic and standardised manner so that the data collected can be compiled and analysed to inform management and planning and improve our collective understanding of the key controlling drivers of gully erosion.

We envisage that as the database grows that we will be able to highlight the metrics that are diagnostic of the major gully types. Hence, we anticipate that we will have a core set of metrics that are required fields, and another set that are optional.

The Queensland Gully Database will be made available through the NESP Tropical Water Quality Hub website www.nesptropical.edu.au and the eAtlas www.eatlas.org.au.

GULLY SYSTEM									
1	Project/Descriptive gully								
2	Site	Class	Flow	Gully box	Photo box				
3	Elevation	200m	in Contour map	in	GPS	in			
4	Location	Wpt No.	UTM Zone	Long. / Lat	24 00000	Lat/Long	10 00000		
5	Map	Gridline	N	Aspect	N.E. 200m	(Oblique Angle (Meters) code)			
Gully Unit									
6	System	Gully system	Yes	Sub-system	Gully	Single	Compound	Examples	Yes
7	Gully / Sub-system / System	Gully system is discontinuous			Yes	Gully system is continuous to larger channel, creek, river, etc.			
8	Gully system dissects to	Yes / No							
Landscape Context									
9	Gully is a primary feature cutting into flat or gently undulating / sloped alluvial material								
10	Landscape approach of gully head may consist of small surface and meanders within alluvial material. Erosion is limited to the alluvial floor of the valley / meander								
11	Gully is a primary feature eroding into alluvial and material / vegetation								
12	Gully is within an older and larger gully, no longer into the original gully flow								
13	Other								
Landscape Domain									
14	Hillslope	Yes	Soil or bedrock	Colluvial					
15	Alluvial	Yes	Fluvial / Terrace	Yes					
16	Combination	Yes	Fluvial / Terrace / Alluvial	Yes					
17	Planform Shape								
18	Single	Yes	Linear	Yes	Amphitheatre				
19	Compound	Yes	Linear	Yes	Amphitheatre				
20	Compound	Yes	Linear	Yes	Amphitheatre				
21	Compound	Yes	Linear	Yes	Amphitheatre				
22	Compound	Yes	Linear	Yes	Amphitheatre				
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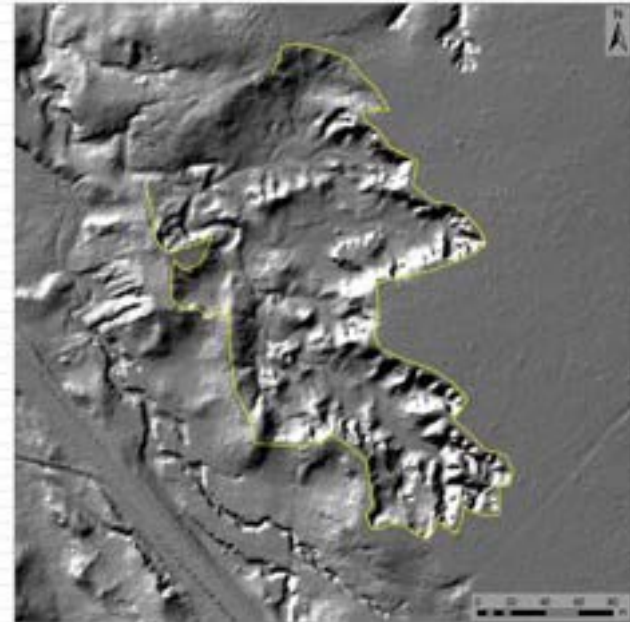


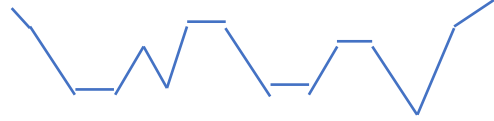
Figure 57: Worked example of the gully database.

APPENDIX 3: DATA SHEET GUIDE

3.1 GULLY SYSTEM

ENTRY	DEFINITIONS and EXPLANATIONS
Site Project	Name of project area or gully location
ID number	Gully or site code or project code/number, e.g. AMBR 01
Photo numbers	Sequential image numbers from camera
UAV no.	ID number of UAV and/or SD card number and/or photo numbers from UAV photography
Waypoint Number	GPS waypoint number on current GPS track from hand-held GPS or other GPS unit.
Elevation	Height in metres above AHD. Preferably from DEM, otherwise estimated from topographic map or GPS unit.
Location	UTM Zone and grid reference in metres (Easting; Northing) from GPS. Otherwise Longitude; Latitude in decimal degrees. GDA94 datum.
Slope	gradient: angle of slope down from a high point, up from a low point, or both up and down from a midslope point. In per cent (%) by clinometer (or mobile device surveying app). aspect: The direction toward which a slope faces with respect to the compass or map grid (degrees from North). From compass (or mobile device app).
R E Code	Regional Ecosystem (RE) code for units covered by the gully unit under assessment. From RE map.
Climate region	From Köppen climate map of Queensland.
GULLY UNIT	
System	Unit under assessment is determined to be a Gully System, Gully Sub-system, or Gully.
Complexity	Unit under assessment is determined to be a Simple, Compound, or Complex feature.
Continuity	Unit under assessment is continuous with the drainage system or is separated from it by a depositional feature at its mouth (egress): an alluvial/colluvial fan, or a marshland/pond.
LANDSCAPE CONTEXT	
Landscape Context	Choose one of the main contexts of gully feature development. If the context is none of these, enter text to describe context.
Landscape Domain See 2.1 Landscape Domain above	
	Select the relevant Domain and sub-Domain as far as can be determined from field, map and imagery evidence as specified in Section 2.1
Plan-form Shape	Select the G S Form that is the closest match to the unit under assessment. If a Compound system, select the Form of the major system first then subsequent system forms. Comment on complexities or irregularities or part-systems.

Gully and Catchment	Metrics should be calculated on available imagery, DEM, and/or lidar if available. Otherwise some of these can be estimated in the field by tape measure (width; depth) and pacing (DtD), otherwise estimate as accurately as possible.
Evidence of Active Erosion	Select all relevant options of observed evidence of active erosion. See examples.
Observable Processes	Select all relevant option that relate to observed evidence for causes of erosion and related geomorphic processes. See examples.
Gully Cross-sectional Shape	V-shaped: Overall geometry is that of relatively straight slopes of gully walls from the land surface meeting at a narrow gully floor at similar or possibly asymmetric angles or lengths, e.g.  Often in hard clay or coherent soil materials.
	U-shaped: Similar to V-shaped gullies but with a more concave slope near the base, usually of accumulated fall debris or protected footwalls by debris. Gully base may have a narrow flat depositional floor. Often occurs in cracking clay / Cracking Clays materials. 
	Trapezoidal (flat-bottomed): Essentially V-shaped gully forms with flat floors that are more than narrow in width. The flat floor is formed by sequences of deposition and erosion during and after rain and flow events. Asymmetry is more common in alluvial environments.  Vertical walls of this form can be called <i>Box-form</i>, but usually the walls have angles off the vertical in most gullies.  Commonly the soil profile of consolidated clay and/or hardsetting silty clay loams sit on these angled walls in a near-vertical step to the land surface. These can be termed Step-trapezoidal if the soil 'step' is less than a third of the depth of the gully wall. 
	Funnel: The main walls are steep and close together forming a gorge or slot gully with the walls widening out near the top and original land surface, Uncommon in simple / single form, but more common in active heads in very dispersible soil materials. 

	Dissected: Complex internal head/wall/floor structure that is formed by varying degrees of erosional and depositional forms within the outer gully walls. Internal structures include pedestals, residual of landscape surface, domes, arches, and tunnel trenches. 
	Multiple floors (or 'tiered'): Multi-form or multi-sequel development is evidenced by re-incision and renewed erosion leaving two or more bases or floors to the compound gully system. Floors may appear as eroded terraces or tiers' in large open scarp-front and amphitheatre systems usually in alluvial systems, or can be floors with recent incision and rejuvenation. 
Internal Gully Architecture	See examples for : Open floor; Tunnelled/sinkhole floor; Isolated residuals (islands of land surface); Complex / multiple heads of high and low relative relief; Fans; Pediments; Domes; Pedestals. Record presence of any of these features in the main gully system feature.

3.2 SOIL MATERIALS

* eference to the ellow ook' is recommended	
ENTRY	DEFINITIONS and EXPLANATIONS
Surface Erosion	Status: the current condition at the time of observation Type: Evidence of surface flow to erode the surface by sheet wash and running water to form rills, otherwise dominantly by raindrop impact. Scalds are usually completely bare of vegetation and may also be subjected to wind erosion. Degree: Either minor (some evidence) or severe (obvious, extensive evidence)
Basal layer	If visible, record the nature of the material at the base of the gully (at the base of the walls, and/or under the depositional floor, or through which the gully is also eroding). The base is of completely different material to that of the main gully material above. Indurated means hardened and possible cemented (like a ferricrete) that is rock-like but is not rock (see Glossary).
Material derivation	If identifiable or inferable in the field, otherwise from geology, soils, RE, etc. maps.
Material form	Simple classes from the Gully Classification. See the Gully Classification (above).
LAYERS	
ID	lphanumeric code of pro ect and suffi of ' for a er ' for a er ' etc
Layer depth	Measured depth of layer from the land surface to the bottom boundary of the layer.

Layer colour	Select one of the colours provided for the overall matrix colour of the layer material.
Mottles	Record the presence of any mottles of different colours to the matrix.
Nodules	Record the presence of any carbonate nodules of any form and iron/ironstone nodules that appear to have been formed in the soil material.
Fabric	The appearance of the soil material associated with the presence or absence of natural soil material aggregates, the appearance of the aggregate surfaces, and the presence and arrangement of macro- and meso-pores (cracks) in the soil material mass (adapted from Northcote, 1979) Distinguish incoherent materials with little, or without any coherent aggregation (either loose, single-grained sands or weakly held together earthy loams or sandy clays) from more coherent materials showing aggregation as dense or cracking or structured clays.
Gravel / Rock inclusions	Inclusions > 2 mm in size in the soil material such as rock fragments, deposited gravels, transported nodules, charcoal that have not developed or formed <i>in situ</i>, in the soil, i.e. they are allocthonous materials. Includes large cobbles and boulders, as well as bedrock outcrops.
Permeability of layer	An estimate the potential permeability of the layer material based simply on observation of porosity
Slaking	Slaking is the breakdown of a lump of soil into smaller fragments on wetting. It is caused when clay swells and the trapped air bursts out.
Dispersion	Dispersion (the separation of soil into single particles) is governed by soil texture, clay type, soil organic matter, soil salinity and exchangeable cations especially sodium (Na^+) and magnesium (Mg^{++}).
Field Dispersion test The dispersion test that is outlined here requires dispersion on wetting (immersing an air-dry aggregate in water) and observing its behaviour immediately after wetting and 10 minutes after wetting. Record both.	 No slaking, obvious dispersion Obvious slaking, some dispersion Slight slaking, some Nil slaking, nil dispersion Some slaking, complete dispersion Some dispersion, complete slaking

3.3 EROSION PROCESSES

ENTRY	DEFINITIONS and EXPLANATIONS
Site	Project no.; ID no.; Photos nos. as before. Note additional phot numbers for erosion processes capture.
Head Scarp/Walls	Surface Erosion: Evidence of rainsplash/ wash on gully walls particularly showing drapes of dispersed silts/clays. See examples in the Handbook for Slaking/Dispersion: Fluting / pillars
	
	Slaking/Dispersion: Rainsplash / wash
	
	Mass Movement: Evidence of mass movement on and from the head and gully walls, particularly showing slumped material and collapse blocks and debris on the gully floor. See examples in the Handbook for Block Collapse and Slump
	Shape/type: Most headscarps are open vertical or near vertical walls of varying depth. Some deeper heads are formed from tunnelling, which collapses and is excavated in to narrow, almost vertical slots.
	Basal erosion. Sometimes there is erosion of the base of walls and maybe the headscarp. Undercutting by flowing water from up-gully or channelling down the wall. Sapping by water seepage and possible tunnelling at, or near, the base of the wall.

	Evidence of tunnelling: Soil piping and tunnelling from dispersion of subsurface materials, as evidenced by cracks around the land surface, tunnel exits in walls that show fans of deposited material, collapsed blocks into narrow voids, arches and small tunnels through existing soil material.
Head/Scarp/Walls	Evidence of run-on / waterfall: Run-on is runoff from the land surface onto and into the gully erosion feature. Channel to head: Evidence of water channelling to the gully head, through vegetation or by rilling. Sheet flow to head: No channelling evident, but surface erosion or vegetation flattening/displacement by general overland sheet flow. Plunge pool: If there is evidence of concentration of flow over the gully head there may also be an over-deepened floor or pool of water/clay sediment below the head, which is evidence of a waterfall plunge pool. Note if evidence on run-on is unclear.
	Nodules. carbonate or ironstone iron nodules 'coral' or other forms of nodules formed in the soil material. Includes obvious soft, powder 'segregations' in the material Layer, or location either in the layers in the vicinity, on eroded blocks, slopes etc. Few Common Many
	Gravels. Inclusions > 2 mm in size in the soil material such as rock fragments, deposited gravels, transported nodules, charcoal that have not developed or formed <i>in situ</i>, in the soil. Either in some clear bedded arrangement or otherwise disordered. Layer or location either in the layers in the vicinity, on eroded blocks, slopes etc. Bedded Disordered
Floor	Dominantly Depositional – Flat. Active water flow, both depositing and transporting materials down-gully largely as sheets of water or unchanneled, laminar flow. Gravel Sand Silty Clay
	Dominantly Depositional – Channelled. Active water flow showing preferential channel pathways. May show some minor incision. Gravel Sand Silty Clay
	Dominantly Depositional – Nodules/Concretions. Nodules or concretions eroded out of the gully walls can remain as lag material on the pediments and floors of gullies, particularly where water flow is not common. It may appear as bedload lag gravels where there has been some recent flow. Few Common

	Many
	Dominantly Depositional – Gravels. Gravel and stony material eroded out of the gully walls can remain as lag material on the pediments and floors of gullies, even where water flow is common. It may appear as bedload lag gravels where there has been some recent flow. Bedded Disordered
	Dominantly Erosional. Where there is clear evidence of transport of eroded materials and erosion by water flow in the floor of the gully. On bedrock Channelled in residual materials (i.e. soils and colluvial/alluvial material) Bedload (obvious lag material in small channels)

3.4 VEGETATION

ENTRY	DEFINITIONS and EXPLANATIONS
In and around head(s), walls, and the gully floor	Exposed Roots, Fallen Trees: within the gully margins, tree stems, roots may be freshly exposed or fallen.
	Bare / V. sparse: record if vegetation cover is generally absent.
	Vegetation cover: estimated by eye into broad groupings of dominant types. Grasses / Herbs, Shrubs, Trees, of broad density groupings. Sparse Mid-dense Dense
	Species / type. Record species name or common names of dominant vegetation if known. In abbreviated form if necessary. Interpretations can be given in comments.

Detailed Soil Materials

<i>Reference to the 'Yellow Book' (NCST, 2009) is recommended</i>	
ENTRY	DEFINITIONS and EXPLANATIONS
Site	see Gully System above
ID number	see Gully System above
Exposure Depth	Depth of exposure in metres from tape measurement. Record width of exposure over which observations are taken if more than 1.0 m
Photo numbers	see Gully System above
Waypoint Number	see Gully System above
Location	see Gully System above
Elevation	see Gully System above
Slope	see Gully System above
Surface condition	Record condition of soil surface by observation and pushing forefinger into the soil surface. Any crust can be identified as either purely a soil mineral crust (may be with some organic matter) or being cemented with dark algae (where water has been sitting on the surface).
Other surface features	Record if there is obvious evidence of deposition on the soil surface (sand or clay drapes, or surface wash) and whether the top soil layer has 'set hard' like a cement when dried even though it may be powder on the surface.
Surface Gravels (rock fragments and nodules / concretions)	Type: multiple entries are possible record whether if cannot be identified as carbonate nodules/concretions or iron/ironstone nodules/concretions, or rock fragments. Abundance: estimate if gravels on the surface are greater than 10 % of an area or 2 m x 2 m, or not. Size: Record dominant size (greater than or less than 5 mm). Enter both if there is a mix of sizes. Shape: refer to the 'Yellow Book' for shape categories otherwise use good judgement.
Surface Erosion	Status: the current condition at the time of observation Type: Evidence of surface flow to erode the surface by sheet wash and running water to form rills, otherwise dominantly by raindrop impact. Scalds are usually completely bare of vegetation and may also be subjected to wind erosion. Degree: Either minor (some evidence) or severe (obvious, extensive evidence)
Runoff	Record if there is clear evidence of rapid runoff (erosion, debris dams) and contextual environment (slope gradients, amount of dense grass vegetation etc. to slow runoff)
Landform type	Text description of where the position of site and gully is as a general landscape description within 500 m of the site, e.g. with relation to the gully scarp, or multi-form features, to hillcrests, rock outcrops etc.
Gully position	Text description of where the position of site is within the gully system as a general morphological description within overall gully features, e.g. with relation to the gully head(s), outlet, branches, incision, etc.
Vegetation cover	Judgement on overall coverage of soil surface by all vegetation within 20 m of the gully system and eroded area. No measurement necessary.

Vegetation type	Multiple entry of commonly occurring types within 20 m of the gully system and eroded area.
Base / Floor	Materials: Multiple entry possible of the main types of materials present on or constituting the floor of the gully. Width: preferably measured with a tape, otherwise paced. The lateral extent of the flat, or near, flat gully floor that constitutes the depositional zone of eroded materials and the transport of eroded materials by water. The feature that is between the gully walls, collapsed debris, and / or pediments to the gully. Drainage overall: judgement of drainage potential of the gully materials overall based on the material, type, porosity and fabric structure (i.e. amount of small and large pores/voids).
Seepage at base	Record if there is evidence of water seepage from the base of the gully walls at or near the junction with the gully floor.
Basal layer	If visible, record the nature of the material at the base of the gully (at the base of the walls, and/or under the depositional floor, or through which the gully is also eroding). The base is of completely different material to that of the main gully material above. Indurated means hardened and possible cemented (like a ferricrete) that is rock-like but is not rock (see Glossary).
Material derivation	If identifiable or inferable in the field, otherwise from geology, soils, etc. maps.
Material form	Simple classes from the Gully Classification. See the Classification (above).
LAYERS	
ID	Alphanumeric code of project and suffix of ' for a er ' for a er ' etc
Horizon equivalent	If possible, identify soil horizons clearly, attribute the layer with the equivalent soil horizon label (e.g. A horizon, B horizon, A1, B2, D1, etc.)
Layer depth	Measured depth of layer from the land surface to the bottom boundary of the layer.
Layer thickness	The thickness of the layer calculated from the Layer Depth (above) minus the depth of the layer immediately above. For the first layer, the layer thickness is the layer depth.
Boundary	Refer to the 'Yellow Book' for definitions
Layer colour	If practicable, enter the Munsell colour chart code for the main matrix colour of the layer. Otherwise select one of the colours provided.
Mottles	Abundance: Estimate overall coverage of discernible, dominant mottles Size: Size of commonly occurring mottles (multiple entries possible) Contrast: Clarity of dominant mottles whether clearly discernible or not.
Mottles colour	Up to two colours of mottles can be recorded: either by reference to Munsell Colour Charts codes or by colours provided.
Segregations	Abundance: Estimate overall proportion of nodules or soft segregations in the layer material matrix. Size: Size of commonly occurring nodules/segregations (multiple entries possible) Shape: Shape of commonly occurring nodules (hard segregations) or whether crystalline or soft segregations. <i>[examples here]</i> Type: Refer to the Yellow Book to discern types.

Coarse Fragments	Inclusions > 2 mm in size in the soil material such as rock fragments, deposited gravels, transported nodules, charcoal that have not developed or formed <i>in situ</i>, in the soil, i.e. they are allocthonous materials. Abundance: Estimate by eye, using Fig. A below, overall proportion of fragments in the layer material matrix. Size: Size of commonly occurring fragments (multiple entries possible) Shape: Shape of commonly occurring fragments using Fig. B below. Type: Ironstone and nodules commonly occur as transported fragments, otherwise the most likely type is gravels of mixed form.
Fabric	The appearance of the soil material associated with the presence or absence of peds, or natural soil material aggregate units, the appearance of the ped surfaces, and the presence, size, and arrangement of macro- and meso-pores (voids) in the soil material mass (adapted from Northcote, 1979) Grade: Distinguish incoherent materials with little or without any coherent aggregation (either loose, single-grained sands or weakly held together loams or sandy clays) from more coherent materials showing aggregation either moderately or strongly. Massive type: Dominant feel and composition of the soil material. Size: commonly occurring aggregates, multiple entries possible. Aggregate Type: See Yellow Book for aggregate/ped types or use Table A and Fig. C. below.
Texture	See the Yellow Book for Texture groups and how to discern them.
Permeability of layer	Estimate the potential permeability of the layer material based on observation of porosity
Slaking	Slaking is the breakdown of a lump of soil into smaller fragments on wetting. It is caused when clay swells and the trapped air bursts out. Organic matter reduces slaking by binding mineral particles and by slowing the rate of wetting.
Dispersion	Dispersion (the separation of soil into single particles) is governed by soil texture, clay type, soil organic matter, soil salinity and exchangeable cations especially sodium (Na^+).
Field Dispersion test The dispersion test that is outlined here requires dispersion on wetting (immersing an air-dry aggregate in water) and observing its behaviour immediately after wetting and 10 minutes after wetting. Record both. Classes are: • Nil • Some • Obvious • Total	 No slaking, obvious dispersion Obvious slaking, some dispersion Slight slaking, some dispersion Nil slaking, nil dispersion Obvious dispersion, total slaking Some slaking, total dispersion

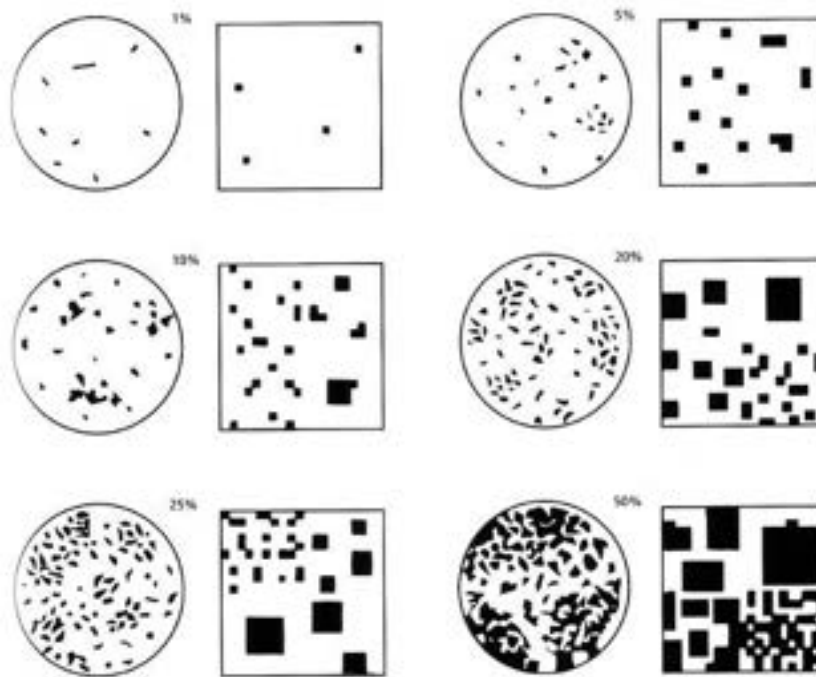


Figure A: Abundance chart (NSSH, 2008).

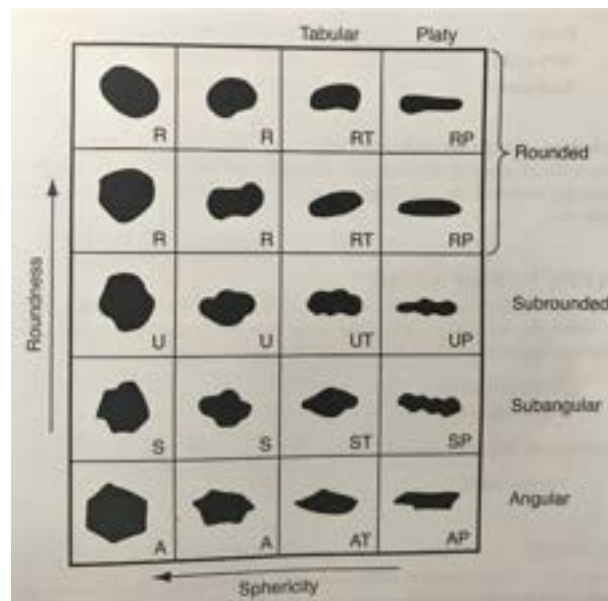


Figure B: Shape Chart (Fragments and Nodules) (NCST, 2009).

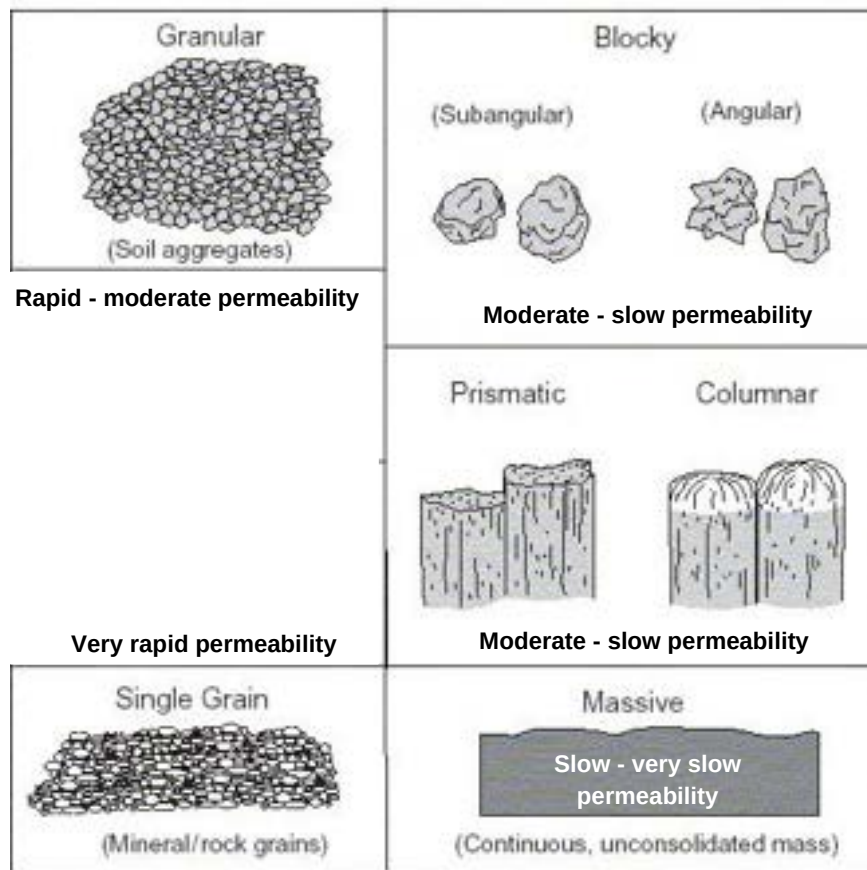


Figure C: Aggregate types chart with common permeability classes (adapted from NSSH, 2008).

APPENDIX 4: GULLY CLASSIFICATION GLOSSARY

A glossary is necessary for any classification process as some terms are used specifically in the context of the classification or of the concepts behind the classification. This glossary is provided with the aim to try and standardise terminology used in this document as well as in gully science in general. It contains both commonly used terms as well as terms unique to this classification. Some of the commonly used terms have had additional definition and explanation as they are used in a specific context in this document and for gully classification. Some common terms have also been revised to relate more closely to the gully classification environment.

Sources:

GoG: Jackson, J.A. (ed) (1997). Glossary of geology, 4th Ed. American Geological Institute, Alexandria, VA. 769pp.

GoL: NSSH (2008). Glossary of Landforms. Part 629. National Soil Survey Handbook. Natural Resources Conservation Service, USDA.

ODES; Oxford Dictionary of Earth Sciences: Allaby, A. & Allaby, M (1991) The Oxford Dictionary of Earth Sciences. Oxford. 410 pp.

Gully Classification Glossary

Aggradation The building-up of the Earth's surface by deposition; specifically, the accumulation of material by any process to establish or maintain uniformity of grade or slope; also called accretion. Compare degradation. (GoG)

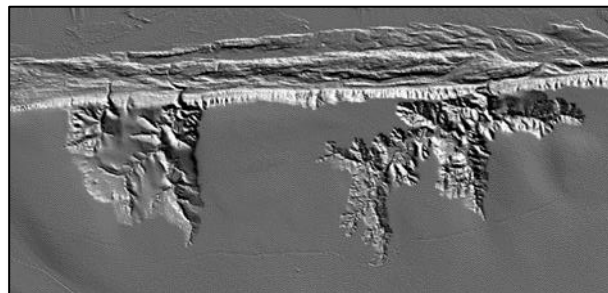
Alluvial The environments, action, and products of rivers or streams. See *Alluvium*.

Alluvium Unconsolidated sediment of sorted or unsorted silts, sands, gravels, and clays that are usually stratified but often in complex associations, that has been deposited by the action of rivers or streams, or predominantly by flowing water.

Badlands A term that is inappropriate for use in alluvial and colluvial gully development. Badlands are argued to be landscapes that develop on surfaces with little or no vegetative cover in unconsolidated or poorly cemented marine sediments. (Brooks et al., 2009).

Bank Gullies Erosional gully systems that have developed on the alluvial banks and levees of major stream and river channels. The gullies can be quite well-developed but remain comparatively small systems as they form on the coarser, more recent alluvium that is not usually composed of dispersive or other materials susceptible to rapid or intensive erosion. They do not extend longitudinally into the flood plain of the main stream, but they may extend laterally into other gully erosion and amalgamate into dendritic or open forms with multiple outlets.

They can be considered as part of the stream bank erosion zone.



Bank gullies in the extensive levee and stream bank deposits of the lower Burdekin River (top)

Branch A minor gully unit or gully subsystem that is part of a larger gully subsystem or gully system that can be identified as a distinct gully form void in its own right. Branch develops from the trunk or main gully void as a tributary to it. Usually part of a dendritic or linear gully system. A branch will usually have a linear form or uncommonly a dendritic or open form. Cf. *Lobe*

Buttresses Erosional features within gullies in dispersive soil materials. The intact wedge-shaped remnants of eroded and dispersed gully walls extending from the gully wall in degraded form usually tapering in width from the base to a narrow peak or ridge. Like Pillars they remain after block and tunnel collapse, and are now subject to rainsplash erosion (see Fluting; Pillars).

Channel The bed and banks that confine the surface flow of a stream.

Colluvial	The environments, action, and products of erosion and deposition on hillslopes, by the action of gravity (mass movement) with or without water. See Colluvium.
Colluvium	An unconsolidated mass of rock debris and weathered material that has accumulated at the base of a cliff or slope and deposited by surface wash and various mass movement processes
Complex Gully System	see <i>Gully Complexity</i>
Compound Gully System	see <i>Gully Complexity</i>
Dispersion	Dispersion is the chemical dissociation of the soil material aggregate surfaces with the intervention of water, which lowers the EC, leading to expansion of the exchange layer, and exchanges with sodium (Na^+), magnesium (Mg^{++}), and maybe potassium (K^+) ions. This process separates soil material aggregates into single particles that immediately go into suspension in the soil water. It is governed by soil texture, clay type, soil organic matter, soil salinity and the concentration of exchangeable cations especially sodium.
Distal	<i>For gullies:</i> Close to or at the point furthest from the origin of the gully erosional feature, i.e. the actively eroding head(s) or scarp walls, adjacent to the residual/uneroded land surface. <i>Sediment erosion/transport processes:</i> Close to or at the point furthest from the origin of the material erosional, i.e. end of the fluvial transporting system or point of measurement usually the catchment egress to the sea, lake, or impoundment.
Duricrust	A deep weathering product that is a hardened mass that may have gravels and nodules within, which are all cemented by a dominance of one of more iron, aluminium, silica, calcium carbonate, and other precipitates. Common duricrusts are ferricrete (iron), silcrete (silica), bauxite (aluminium, and calcrete (calcium carbonate).
Erosion	Types of erosion relevant to gullies and gully systems <i>Block Collapse</i> A mass-movement process, associated sediments (block collapse debris) characterised by a localised, very rapid type of fall in which large blocks of soil material fall over or structurally collapse, either rotating outward over a low pivot point, or collapsing vertically. Collapse can be caused by voiding material beneath the blocks by tunnel erosion, undercutting, or basal sapping. Portions of the original material may remain intact, although reoriented, within the resulting debris pile. <i>Slump</i> The mass-movement process, associated sediments (slump debris) characterized by a slow to moderately rapid type of slide, composed of moist to wet, largely unconsolidated soil material, portions of which remain largely intact and in which movement occurs along a defined, concave shear surface and resulting in a partial rotation of the displaced mass.

Tunnel erosion

The removal of subsoil material by subsurface water while the surface soil material remains relatively intact. There is usually a detectable outlet from tunnel erosion which displays fans of deposited soil material. See also Soil Piping.



Sapping (basal sapping)

The preferential erosion of the sub-soil or substrate by dissolution weathering and positive pore pressures, thereby weakening the structural integrity for support of the column of materials above (an uncommon process in Queensland gullies generally).

Undercutting

The erosion by flowing water at the base of a wall of sediment or rock material usually at a meander or bend in the flow channel. Also the erosion by backsplash at the base of a waterfall and rotational backflow within the plunge pool.

Fabric

The appearance of the soil material associated with the presence or absence of peds, or natural soil material aggregate units, the appearance of the ped surfaces, and the presence, size, and arrangement of macro- and meso-pores (voids) in the soil material mass (adapted from Northcote, 1979).

Fan

A low, outspread mass of loose, eroded materials, commonly with gentle slopes, shaped like an open fan or a segment of a cone, Deposited by a sediment flow from channelled gully walls, branches, lobes, or other tributaries. Commonly seen at the egress of tunnels or soil pipes in gully walls. The depositional feature at the proximal end of a disconnected gully of aggraded sediment eroded from the gully.

Fluting

Distinctive features of near-vertical gully walls, Pillars, and interfluves resembling deep vertical channels and grooves, created by rainsplash and surface flow erosion on highly dispersive soil material. Often in association with Pillars (see Pillars) and Buttresses (see Buttresses).

Gully

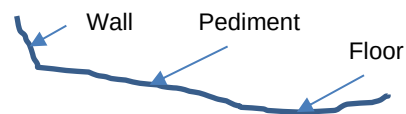
- A persistent erosional landscape feature > 0.3m deep that has multiple modes of expansion, but always including headward retreat into an otherwise un-dissected landscape since land use intensification (typically ~ 150 – 200 years in Australia).
- Has an active head (see Knick-point) or headscarp at the upslope limit of the gully, or sometimes a series of headscarps. A scalded area (i.e. an area stripped of its topsoil with degraded vegetative cover) may often fringe the upslope area of the headscarp.

Gully Complexity	Some gullies and gully systems exhibit multiple forms within their boundaries. These may be due to rejuvenation of erosion processes to create new floor levels, new levels by tunnelling, changed morphology because of differing eroding materials, or controls by vegetation or bedrock structure. Three forms of complexity are defined: Simple: where the gully or gully system appears to be of one form and shows no change in floor or base level or nick points. The gully can be described as one Gully System Form as a whole. Compound: where the gully system appears to be of more than one form and shows change(s) in floor or base level and/or nick points. The system may be nested, and/or each form and Gully System Form can be fairly simply identified and defined at a more detailed level of description and assessment. The gully can be described as one or more Forms as a whole. Complex: where the gully system appears to be of more than one form and shows changes in floor or base level and/or nick points. The system may be nested but each form and Gully System Form cannot be identified and defined at a more detailed level of description and assessment as the associations are too complex to describe simply or clearly. The gully can be described as more than one Form as a whole.
Gully Head	The actively eroding point at the Distal end of a gully or gully system into the soil material thereby enlarging the gully feature. It is the knick-point of the overland flow or drainage for any upslope flow, or it is the point of mass movement (by block-collapse or slumping of the soil material. Narrow, deep notch heads can form from the progressive collapse of tunnel erosion. Lobed head Series of active heads usually formed from wall collapse or sheet flow overflow that develop as lobes to a main gully that has a broad region of headward retreat.
Gully Headscarp	Where the Head of a gully has a distinctive vertical or steep drop from the land surface to the developing gully floor and may have a moderate to a considerable lateral extent. The free-face of the head.
Gully Network	A group of gullies or gully systems that are connected hydrologically and can be viewed as a drainage network. Another name for a Gully System.
Gully System	A group of gullies (including channels) with a common outlet or with related outlets (e.g. in coalesced gully systems) in close proximity to the drainage network or common depositional landform. A distinct grouping of gullies, and possibly stream channel, that operate as an integrated hydrological and erosional system. The system can be of one main gully form or of a variety of forms. Includes stream channels if they are part of the streamline to the outlet / egress.
Gully Type	see <i>Gully Form</i>

Gully Wall	The perimeter of a gully that may or may not be actively eroding, that is not the head or headscarp. Walls can be steep or shallow angle and can vary in height from a few centimetres to many metres. Some gullies do not exhibit walls, where the walls of interfluves have been eroded away. The interfluve is then just the junction of pediments (see Pediment).
Indurated	The result of a material undergoing a process of hardening or cementation to produce a hard and 'rattle hardpan' in soils or a <i>duricrust</i> , or indurated' layer in deeply-weathered soils and sediments.
Knick point	An abrupt change of gradient in a smooth, low long profile of a stream or gully floor. The zone of active vertical erosion owing to rejuvenation or the current eroding head of a catchment streamline. Nick points migrate upstream. A gully headcut is a knick point in the profile of the catchment flowlines. Also 'nick point'
Laterite	A deeply-weathered material that has been ferruginised (reddened by iron oxides) and kaolinized (clay minerals are almost completely kaolin). It may, or may not have a <i>duricrust</i> capping it or a pale kaolin clay 'pallid' one beneath it, depending on whether the material has been lateritised as in situ regolith, or as alluvium or colluvium with water table influences.
Lateritised	A material that has been subjected to deep weathering and has formed a laterite and may be associated with a duricrust or lateritised sediments.
Lobe	A gully unit component that cannot be called a gully at the finest scale. A Lobe is usually a collection of headscarps or heads as an open or dissected in-gully architecture that often is the initial stage of gully branching, Lobes generally are rounded in plan-form and occur as multiples in the distal ends of all gully system forms. Cf. <i>Branch</i>
Mass movement	The downward and outward movement of slope-forming material under the influence of gravity. The process does not require a transporting medium such as water, air or ice (GoG)
Mass wasting	The failure and movement by gravity of a volume of soil, alluvium, rock, etc. to a downslope site (GoG)
Mound	A remnant erosion feature of low relative height on the floor of gullies that are the remains of a pillar or pedestal. They may support, or be protected by a plant or collective vegetation.
Nick point	See <i>Knick point</i>
Outlet	The point at which a gully drainage exits the system (egress) to join the greater drainage network if hydrologically connected, or into a wetland or forms a depositional fan if not connected 'the mouth' of the gully or Proximal end of the system. In GIS the point of confluence with the exterior drainage.
Pedestal	Small feature within a gully where an object or area of vegetative cover has protected the subsoil material from direct erosion by rainsplash or surface flow. The feature may be a degraded form of Remnant Surface and may develop eventually into a Mound.

Pediment In alluvial or colluvial soil materials, the sloping, resistant surface extending between the gully flow channel or flat floor and the gully walls proper. It can be the denser clay-B horizon of a residual or colluvial hillslope gully soil material, or a more resistant clay sediment in alluvial gully material. It can be viewed as a raised part of the gully floor, or a lower angle part of the gully wall, depending on material, process, and contextual factors. An indurated base to gullies can often form a pediment to less resistant materials above forming the walls. Some gullies will have just pediments and no apparent walls and the interfluvium is the junction of pediments.

Where bedrock is present, the bare rock sloping surface of an eroded bedrock floor supporting the gully walls.



Pillars Erosional feature within gullies in dispersive soil materials. The intact remnants of eroded and dispersed gully walls after block and tunnel collapse and are now subject to rainsplash erosion. They may or may not be attached to the main wall or head (see fluting).

Plunge pool A depression formed at the base of a step, or knick-point, waterfall as a result of the hydraulic impact of the descending water and its sediment load (GoG).

Proximal or gullies lose to or at the point of origin of the gully erosional feature, this is generally assumed to be end near the outlet where the feature is assumed to have originated.
 ediment erosion transport processes lose to or at the point of origin of the material erosion (i.e. the gully head, walls, eroding in-gully features).

R-E-D Zones	For Soil material mapping of gullies: Residual zone (landsurface): Moderately dynamic to static processes; enduring features. Uneroded/intact land surface unaffected by gully erosion process. Exhibits a largely intact soil profile, except for eroded material by surface wash. Part of the landscape into which the gully is eroding and is currently only affected by hillslope and surface processes. Erosional zone: Dynamic processes; temporary features. Actively eroding gully head(s), walls and pediment(s), if present. The eroding zone is dominated by evidence of current or prior erosion processes, but it can also be subject to localised deposition and residual lag material development. Dominated by mass movement, surface wash, dispersion and slaking, tunnels. Small, localised areas of temporary deposition in eroded pockets can also occur in this zone Depositional-Erosional zone: Dynamic processes; temporary features. Actively depositional features (fans/cones) of coarser colluvial/alluvial wash load, i.e. temporary, unconsolidated materials. Rarely vegetated with grasses. Can show evidence of erosion (e.g. rilling, sheet wash) and tunnelling. Depositional-Transfer zone: Dynamic processes; temporary features. Dominantly flat, or gently sloping, planar features below Transitional/Eroding or Transitional/Depositional zones. The local gully floor. Characterised by accumulation of coarser materials with finer sediment layers and micro-fluvial features and evidence of flood flow or drainage flow. Rarely vegetated with grasses, sedges, reeds. Maybe divided into separate floors by rejuvenation knick-points but is continuous to the gully outlet/end-point.
Rejuvenation	A renewed period of vertical erosion in response to either a change in base level (e.g. scour at the outlet of the system, or changes in the drainage network itself) or an increase in erosive power of drainage flows in the gully system (e.g. higher rainfall, greater flow volumes). Results in creation of new knick points and excavation of existing gully floors.
Scald	A part of the land surface where the surface fine sandy loam soil has been eroded to expose sub-surface material that is unsuited to plant growth, usually because of high salt contents and particularly sodicity (high exchangeable sodium). The bare surface often seals over and is prone to further erosion by wind and sheet flow. Scalds may produce enough sheetflow runoff to create off-site erosion downslope.
Scalded margin	The periphery to gullies in duplex soil materials or highly saline or sodic materials that sets hard upon drying after wetting and dispersing fine clays and silts. It is where the surface fine sandy loam soil has been eroded to expose sub-surface material that is unsuited to plant growth and the surface material has dried out to an extent behind the gully wall because of exposure (evaporation) and drainage in the gully.

Scarp	The erosional steep edge of a gully or landform from a plain such as a floodplain or terrace. Also applies to the free-face of a gully head or headwall (see Headscarp).
Sediment	Material, both mineral and organic, that is in suspension, is being transported, or has been moved from its site of origin by water, wind, or gravitational processes (mass-wasting), and has deposited and accumulated (aggraded) for varied lengths of time. Some areas exhibit extensive sequences of transported materials, such as alluvial flood plains, and colluvial foot slopes (see Alluvium; Colluvium).
Sediment yield	The total sediment outflow from a gully system or a drainage area at a point of reference and in a specified time period.
Sheet erosion	The process by which thin layers of surface material are removed more or less evenly from gently sloping land by water (GoG).
Sheet flow, Sheet wash	A form of overland flow on gentle slopes, including pediments, where water is spread widely as a thin layer over the land surface (GoG).
Simple gully system	see <i>Gully Complexity</i>
Slaking	Slaking is the physical breakdown of small aggregates to microaggregates by the pressure of entrapped air upon the introduction of water, and from the swelling of clay particles. Organic matter reduces slaking by binding mineral particles and by slowing the rate of wetting.
Slot or Slot gully	A recently-formed narrow, deep branch or head of a gully formed by tunnel erosion collapse and may form the focus of channelised flow from a headcut or seepage from tunnel flow. Depth dimension is much more than the width and can be from around three to tens of metres long.
Soil	The natural dynamic system at the surface of the lithosphere composed of both mineral and organic materials developed <i>in situ</i> by physical, chemical and biological (pedogenic) processes into organised layers more or less parallel to the land surface. (Adapt. from Northcote, 1979).
Soil material	The natural materials in which, and from which, soil (see above) can form. It includes those geomorphic and geologic materials in which soil has not yet formed (pedogenesis) but has the potential to do so. The materials and processes are more geomorphic than pedogenic.
Soil piping	Linear or contorted voids in subsoil material where soil material has been evacuated through subsurface erosion (through slaking and/or dispersion and suspended load transport) by percolating flow of water. Piping can lead to tunnelling.

Stream	Small ephemeral low order channels are characterised by the fact that they have a defined bed and banks. This differentiates them from zero-order drainage basins which do not have a defined channel (Montgomery & Dietrich, 1989; Dietrich & Dunne, 1993). These small channels can have some similar characteristics to gullies, such as vertical banks, but they are differentiated from gullies in that - the main show signs of meandering, - they are dynamic and - are both erosional and depositional systems comprising autochthonous and allochthonous sediment sources) without an active upslope headscarp. Many complex gully networks will transition to a stream channel at some point, but the transition point may be difficult to identify precisely (i.e. they have a fuzzy, or transitional, boundary). Key features that indicate the gully may be viewed as transitioning to a channel, are: - the presence of a self-formed floodplain; - distinct assemblage of fluvial derived depositional geomorphic units, e.g. point bars, lateral bars, benches; - sediment material load that is distinctly different to the local available sediment source (i.e. from bank erosion); - width depth ratio > 1; - meander development (NB not all are required, nor is each characteristic in isolation a defining feature of a channel).
Stream Channel	see Stream
Swale	A low, shallow, usually broad, linear depression or vale in unconsolidated or semi-consolidated materials, between rises (or dunes) which can act as a drainage line for ephemeral surface water flow. Also can be called a Fluve.
Tunnelling	The process of creation of subsurface voids by subsurface water flow in pipes or other voids by dispersion and/or slaking of subsoil materials while the land surface remains intact. Can lead to tunnel collapse, forming clefts or slots at gully heads and walls. See Erosion > Tunnel Erosion

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