Three Dimensional Gully Mapping and Erosion Quantification within a Geoinformatics Framework

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This thesis is submitted to the Faculty of Engineering, Health, Science and the Environment, Charles Darwin University, Australia in partial fulfilment of the requirements for the degree of Doctor of Philosophy

July, 2011
Declaration

This is the original work and contains no material which has been accepted for the award of any other degree in any other institution or university. To the best of my knowledge, it contains no material previously published or written by any other person, except where due reference is made in the text.

Farha Sattar

20 July, 2011
Dedicated

To my Mom and Dad

Who raised and fed me spiritually and morally
Acknowledgments

I owe my deepest gratitude to the supervisory panel members: Prof. Bob Wasson, for providing me a chance to pursue this doctoral research, making opportunities for regular meetings, giving comprehensive advice on data analysis, provoking stimulating discussion, continuous encouragement, providing substantial support and research funding and being a major determining factor in the completion of this thesis; Dr. Diane Pearson for her role as principal supervisor, warm encouragement and thoughtful support; Dr. Guy Boggs for advice and discussion on gully erosion data and interpretation.

I am grateful to Dr. Waqar Ahmad for providing various kind of assistance. The field work for this study was conducted in the Fergusson River catchment. I am grateful to David Howe, Jayson Hill and Prof. Bob Wasson for providing support for field trips to the Fergusson River Catchment, their field experience was a great help to me for acquiring the field knowledge of gully types and erosion processes. I appreciate the help and support provided by Charles Darwin University. As a part of this study, secondary information was collected from various agencies: the Northern Territory Geological Survey (NTGS); Natural Resources, Environment, the Arts and Sport (NRETAS); the Bureau of Meteorology (BOM); and Geoscience Australia. I highly acknowledge their positive attitude towards sharing their valuable databases - free of charge for this research.

Punjab University (PU) and Higher Education Commission (HEC) funded part of the study. I acknowledge their contribution. Charles Darwin University (CDU) funded the field work, purchase of satellite images, and soil sample analysis through their Tropical Rivers and Coastal Knowledge (TRaCK) project. I am thankful to the team members of this project for their help and kind cooperation.

I extend my deepest gratitude to a number of CDU staff: where the administrative and financial arrangements are concerned, I want to express my gratitude to Shivaun MacCarthy, Sarah Hanks and Fiona Steele. I sincerely appreciate the help and positive attitude of the CDU Library staff for timely arranging research articles from other libraries, in particular Jayshree Mamtora for timely updating about online databases.
I express my deepest appreciation to my parents. This research would not have been possible without their prayers, encouragement and good wishes.

Lastly, I express my gratefulness to my husband Dr. Muhammad Nawaz and kids Ashaar Nawaz and Shahan Nawaz for their support, care and patience during the period of my studies.

Farha Sattar

20 July, 2011
Abstract

The contribution of gully erosion to total soil loss has been much debated amongst geomorphologists and hydrologists. However, there is growing evidence that gullies are a major contributing source of sediment in river systems. The study area for this thesis, the Fergusson River catchment; a sub-catchment of the Daly River, Northern Australia, is no exception.

This thesis presents and uses a Geoinformatics based framework for three dimensional (3D) gully mapping that focuses on the spatio-temporal analysis and quantification of gully erosion. The framework incorporates traditional and cutting edge spatial data and technology, namely Cartosat-1 stereo imagery, topographic maps, a 1_second Shuttle Radar Topographic Mission, Digital Elevation Model, historical stereo aerial photos, and Differential Global Positioning System measurements and thematic layers representing the physical and human environment.

The framework is used to create Digital Surface Models (DSM) from the 2008 Cartosat-1 stereo imagery and 1948 stereo aerial photographs. Gullies are identified based on 3D visualization of these images and their 3D properties mapped from the DSMs. Four classes of gullies were identified in the study area based upon their spatial distribution in the catchment, morphology and inferred underlying erosion processes; amphitheatre gullies, gullied slumps, bank gullies and ‘other gullies’. Sapping is the primary erosion process for gullying.

Volumetric changes in gully erosion between 2008 and 1948 have been measured and the specific yield of gully erosion is determined to be 6.1x10³ t km⁻² yr⁻¹. A regional and global comparison of the estimated specific sediment yield indicates that it is globally among the highest.

Gully control factors are examined and causes of gully initiation and development have been described. The results show that alluvial soils are most prone to gullying but heterogeneity in gully distribution and form indicates that other factors are likely to affect gully formation and development in the catchment.
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List of Acronyms and Abbreviations

2D Two Dimensional
3D Three Dimensional
ALOS Advanced Land Observation Satellite
ALUM Australian Land Use and Management
ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer
BOM Bureau of Meteorology
BRS Bureau of Rural Sciences
DEM Digital Elevation Model
DGPS Differential Global Positioning System
DSM Digital Surface Model
DTM Digital Terrain Model
ETM Enhanced Thematic Mapper
GCP Ground Control Point
GIS Geographic Information Systems
GPS Global Positioning Systems
HRV High Resolution Visible
HRVIR High Resolution Visible and Infrared
LiDAR Light Detection and Ranging
MLC Maximum Likelihood Classifier
NRETAS Department of Natural Resources, Environment and the Arts and Sport
OSL Optically Stimulated Luminescence
PRISM Panchromatic Remote-sensing Instrument for Stereo Mapping
RS Remote Sensing
SCOP Stuttgart Contour Program
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<tr>
<td>SPOT</td>
<td>Systeme Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topographic Mission</td>
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<tr>
<td>SSY</td>
<td>Specific Sediment Yield</td>
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<td>TM</td>
<td>Thematic Mapper</td>
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<td>TSY</td>
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Chapter 1: Introduction
Chapter 1: Introduction

In this chapter, the context for using a geoinformatics based framework for three dimensional (3D) mapping and quantification of gully erosion is presented. The research aims and need are described. The research problem, and approaches for the identification, classification and quantification of gully erosion are introduced.

1.1 Research Aims

The contribution of gully erosion to total soil loss and its quantification has been much debated amongst geomorphologists and hydrologists. This study looks at the gully erosion in the Fergusson River catchment that can contribute to the determination of the gully erosion component of the sediment budget of the Daly River catchment. In addition, the research aims to develop a geoinformatics framework for mapping and quantifying gully erosion and to further understanding of gully erosion in northern Australia. Therefore the aims are:

i) To develop a geoinformatics based method for identification and 3D mapping of gullies.
ii) To delineate and classify the mapped gullies and infer the underlying erosion processes.
iii) To quantify gully erosion in time and space and determine the gully volumes and the sediment yield of gullies.
iv) To describe the role of environmental factors (i.e. geology, soil, vegetation, climate, topography, landuse) in controlling gully erosion.

1.2 Need for Research

Gully erosion has adverse impacts including the loss of soil resources, destruction of natural habitat, and sedimentation of both water channels and reservoirs (Lal, 1990; Xu, 1996). Gully erosion contributes between 10 and 94 percent (%) of total sediment production within a catchment (Wasson, 1994; Poesen et al., 2003). Many studies suggest that gully erosion is one of the largest sediment sources in a catchment and is an important component of the sediment budget (Heusch, 1980; Oostwoud Wijdenes and Bryan, 1994; Bull and Kirkby, 1997; Poesen et al., 1998; Wasson et al., 2002). In the study area, the Fergusson River catchment in the Northern Territory of Australia (Figure 1.1), this important sediment source has been
neglected so far in the sediment budget construction of the area (Rustomji and Caitcheon, 2010) because of non-availability of data. Little work has been done on gully erosion in the Northern Territory of Australia (e.g. Brooks, 2009, McCloskey, 2009), but no work has been done to determine the gully erosion volume, particularly in the Daly River (of which the Fergusson River catchment is a component) catchment. The Daly River catchment is one of the largest catchments in northern Australia, and has been a focus of environmental, ecological and economic concern (Erskine et al., 2003). The catchment is unique in terms of the availability of reasonable agricultural soils and a large groundwater resource and as such has been a focus of many future development plans (Jolly, 2001; Blanch et al., 2005; Petheram et al., 2008). Another reason for previous research having neglected the gully erosion component of the sediment budget is the lack of suitable methods for gully erosion mapping and volume estimates.

Figure 1.1 Location of the Fergusson River catchment

Traditionally (Belyaev et al., 2004; Avni, 2005; Vanwalleghem et al., 2005a; Ionita, 2006a) gullies were mapped by tapes, benchmark pins, and theodolite surveys for the
quantification of gully erosion. These field based measurements are laborious and time consuming. Another problem with field based methods is the site coverage, as complex topography and accessibility issues make comprehensive surveys difficult.

However, aerial photographs provide a source of information for documenting the geometry of gullies, and facilitate their quantitative and qualitative analysis. The advantage of quantifying gully erosion by aerial photographs was realized in the 1990s (De Rose et al., 1998; Betts and DeRose, 1999; Martinez-Casasnovas et al., 2003; Daba et al., 2003) but is still confined to small catchments. However, the shortcoming of this technique is that it only provides a two dimensional (2D) representation, since gullies are 3D features, therefore, the creation of a 2D representation is not a true representation of the gullies. Stereo aerial photographs provide the possibility to identify gullies in 3D but a lack of digital tools for analyzing stereo aerial photographs have restricted their use, particularly for gully erosion applications. The shortcoming of this technique is the effort required in processing the imagery (e.g. scanning, georectification and stereo photogrammetric interpretation) which limits its application over large areas.

The geoinformatics approach proposed in this study integrates the spatial tools and techniques and incorporates the structure and characteristics of spatial data, its processing, analysis, storage, standardization and dissemination (Duckham et al., 2007; Ehlers, 2008; Ramachandra, 2010; Dubois et al., 2011). A geoinformatics approach for quantifying gully erosion has many advantages over field survey because it integrates the spatial technologies needed for gully mapping with those needed for erosion volume estimation, therefore providing a cost effective solution in terms of time and money. This approach is used in this research for 3D mapping and quantification of gully erosion in the Fergusson River catchment.

1.3 Research Problem

Gully erosion has been considered a major sediment source globally and across Australia. Gully erosion has been a focus of attention in southern Australia (Boucher and Powell, 1994; Prosser and Winchester, 1996; Prosser et al., 2001) and is receiving increased attention in northern Australia (Aldrick and Robinson, 1972; Riley and Williams, 1991; Bartley et al., 2006; Brooks et al., 2006; Hancock and Evans, 2006; McCloskey, 2009). In southern Australia, past studies have focused on
gully initiation and historical erosion events (Eyles, 1977; Prosser and Winchester, 1996), gully head migration, and influencing factors that determine the distribution of gullies (Prosser and Abernathy, 1996) and quantification of gully sediment yield (Wasson et al., 1998). However, erosion processes are less understood for northern Australia than for southern Australia (Bartley et al., 2006).

Other components of sediment budget in northern Australia have received some attention. Lu et al. (2001) have determined an annual hill slope erosion for the Daly catchment of 0.5-1 t/ha/y and suggested that erosion potential in northern Australia may not be realised due to a high percentage of rock cover. Accumulated mud and sand in the Daly River has reduced channel capacity and is believed to be adversely affecting aquatic habitats, degrading water quality and damaging recreation amenity (Cowan, 2004). A top soil tracer ($^{137}$Cs and $^{210}$Pb) based study conducted in the Daly River catchment shows that between 89 and 97% of the fine sediment in the Daly River during the last ~30 years has been derived by erosion of subsoils by gullying and channel erosion (Wasson et al., 2009), but the relative contribution of each source is still unknown and from a management perspective it is important that soil loss estimates from each source should be known.

The study site, located in the lower Fergusson River catchment (Figure 1.1), a sub catchment of the Daly River catchment, has been identified as a hot spot for gullying through field (Figure 1.2, 1.3 and 1.4) and aerial (Figure 1.5) reconnaissance surveys and conversations with experts in soils and soil erosion in the Daly River catchment. The current activity of gullying is clear in the catchment. Exposed tree roots (Figure 1.2) have been identified in the gully affected areas which indicate significant, recent soil loss. Tension cracks at gully head cuts (Figure 1.3) and freshly deposited material in the gully floors (Figure1.4) indicate that gully erosion processes are active and moving eroded material. Furthermore, these gullies are well connected to the main channel and therefore are a significant sediment source for the main channel (Figure 1.5). Therefore, the study area, 58 km$^2$ above the junction of Fergusson and Daly Rivers was selected to investigate gully erosion dynamics.

Quantification of gully erosion is helpful to calculate sediment budget of Daly River which is an important river catchment in Northern Territory.
Figure 1.2 Exposed tree roots due to gully erosion (Photo by author, dated: 06-07-2008)

Figure 1.3 Active gully headcut (Photo by author, dated: 06-07-2008)
Figure 1.4 Gravel lag deposits on gully floor (Photo by author, dated: 06-07-2008)

Figure 1.5 Sediments from gully erosion are being transported to the Fergusson River (Photo by author, dated: 12-09-2009)
1.4 Focus of the Research

The research presented in this thesis is focused on both the development of a technology oriented method for 3D gully mapping and quantification as well as classifying and analysing processes of gully erosion in the Fergusson River catchment. The research has four major components: the integration of geospatial data using geoinformatics tools and techniques; generation of a Digital Surface Model (DSM) from satellite imagery and use of DSMs in 3D gully mapping; quantification of gully erosion including spatial and temporal dynamics; and the analysis of potential drivers of gully erosion in the Fergusson catchment (Figure 1.6).

![Integration of Geospatial Data](image)

Figure 1.6 Research context

1.4.1 Integration of Geospatial Data

Spatial technologies can play a significant role in gully identification and developing gully erosion models. The use of remote sensing techniques provides a means for data collection, mapping, modelling and monitoring of gully erosion (Bocco, 1991; Nachtergaele and Poesen, 1999). Sequential aerial photographs and photogrammetric techniques can be used to examine gully erosion and its contribution to sediment production (Poesen et al., 1996). Volumetric changes in gullies and gully extension rates can also be computed using multitemporal aerial photographs (Thomas et al., 1986).
Satellite images with varying resolution offer a range of possibilities to investigate gully erosion. Multispectral images have been used to map the extent of gullies (Bocco, 1990) and erosion activity of gully walls from the mapping of vegetation cover (Martínez-Casasnovas, 1998).

Digital Elevation Models (DEMs), enable the computation of basin hydrology, soil erosion assessment, mapping of landslide hazard, and topographic visualization (Florinsky, 1998). Automated software packages are in use to accurately derive DEMs from conventional aerial photographs in a quick and efficient way (Chandler, 1999; Gertner et al., 2002; Kienzle, 2004; Smith et al., 2006).

Geographic Information Systems (GIS) offer an integrating platform for performing multidimensional and advanced analysis (e.g. proximity analysis, overlay analysis). GIS can compute maps of altitude, slope and aspect as primary input data for most erosion models. In situations where insufficient field measurements are available, geostatistical interpolation techniques, incorporated in the GIS, can be used to fill data gaps. Use of raster based GIS tools is ideal for relating soil, topography, vegetation, hydrology and landuse/land cover data with the distribution of gullies in a pixel based manner. Together, advancements in digital imaging technology, photogrammetry and GIS have contributed to the use of multitemporal DEMs to compute sediment production by gully erosion (Thomas et al., 1986).

Despite the fact that a range of technologies have been used for gully erosion research, few studies to date have integrated these tools and data sources to provide useful information on the distribution and management of gullies (Martinez-Casasnovas et al., 2003; Shepherd, 2010). There is a need to develop methods to understand both the distribution and underlying processes influencing gully erosion at a catchment scale so that resources can be used efficiently and effectively to manage existing and prevent further gully erosion (Smith et al., 2003). Therefore, this research presents a framework for the integration of a set of technologies to examine gully erosion.

1.4.2 DSM Generation and 3D Gully Mapping

Gullies are 3D features and therefore in order to develop an understanding of gully formation processes, gully growth patterns and volumetric measurements, 3D
modelling and mapping is a prime requirement. However, there is a scarcity of studies dealing with the generation and analysis of 3D information relating to gullies (Valentin et al., 2005). Many studies stress the need for more detailed monitoring, mapping and modelling of gullies (Poesen et al., 2002; Poesen et al., 2003; Marzolff and Poesen, 2009).

A number of studies have attempted to use remotely sensed information to address gully erosion phenomena (Bocco, 1991; Dwivedi et al., 1997; Kiusi and Meadows, 2006). Aerial surveys of gully sites have been carried out by blimp or kite for site specific gully monitoring (Marzolff et al., 2003; Ries and Marzolff, 2003). Large scale images obtained by blimp or kite were scanned and rectified using image processing software to provide multi-temporal datasets. Gully extent and morphology were digitized and change analysis was performed with GIS software. However, this method only allows the computation of areal extent and development of the gullies; neither gully volume nor volumetric changes can be measured directly.

Several studies have used DEMs and photogrammetric techniques to try to understand gully erosion in the last two decades (De Rose et al., 1998; Betts and DeRose, 1999; Martínez-Casanasovas, 2003). DEMs and Digital Terrain Models (DTMs) are used to represent height information. There are many definitions (Gertner et al., 2002; Kienzle, 2004; Lin and Oguchi, 2004; Martínez-Casanasovas et al., 2004; Tay et al., 2007) which equate and treat the DEMs and DTMs as same. These are interchangeable terms. A DEM refers to a continuous surface of elevations represented in a raster data model. A DTM also refers to a continuous surface of elevations, but generally represented by a very dense network of point elevations. Both DEMs and DTMs are represented as a grid of squares or as a Triangular Irregular Network (TIN). Throughout this study the term Digital Elevation Model (DEM) and Digital Terrain Model (DTM) are used to represent the height information without any further definition about the surface. In this study the term DSM is used to refer to a digital topographic representation of the Earth’s surface with a geometrically corrected reference frame including natural terrain features such as vegetation, buildings and roads.

The term DSM is in common use in the literature (Ullah and Dickinson, 1979; Priestnall et al., 2000; Zhao et al., 2005; Baltsavias et al., 2008; Waser et al., 2008;).
DSMs are currently being used to create 3D fly throughs, support location based services, and conduct line-of-sight analysis, and are a comparatively inexpensive means to produce cartographic products such as topographic line maps with a high degree of accuracy (Reinartz et al., 2006; Crespi et al., 2007; Emmanuel et al., 2008).

Previous studies emphasize the techniques for DEM extraction from stereo aerial photographs or describe total soil loss by calculating the volume from DEM differences. No study describes the 3D mapping of gullies by which gully dimensions could be measured directly. This research presents a technique for 3D gully mapping using a DSM by incorporating the appropriate landscape detail. Landscape and earth surface information cannot be accessed through a DEM which only provides generalization of a bare earth surface without surface detail.

1.4.3 Quantification of Gully Erosion

It has already been noted that gully erosion causes considerable soil loss and contributes large volumes of sediment to rivers. The contribution of gully erosion to total sediment yield has been reported globally. In more detail, in the USA, gully erosion was calculated to be from zero percent to 89% of catchment sediment yield (Glymph, 1957). In semiarid parts of Niger 80% of the annual sediment yield was from gully erosion (Heusch, 1980). Oostwoud Wijdenes & Bryan (1994) reported that, in Kenya, sediments produced from gully headcut retreat were 53% of the total sediment output. In the north western part of Australia, the contribution of gully and bank erosion to total sediment yield was 80% (Wasson et al., 2002). Data shows that the relative contribution of gully erosion to total soil loss varies between catchments. Variations of soil loss from gully erosion are often related to variations in environmental conditions such as soil type, land use and slope.

It is important to know the rate of gully development and sediment production rate in order to determine the economic feasibility of soil conservation measures to reduce damage (Seginer, 1966). The quantification of gully erosion offers valuable data for designing and implementing appropriate erosion control and soil and water conservation practices (Shi et al., 2004). Gully erosion is also an important component in some models of sediment transport, landscape evolution and sediment budgets (Walling, 2001; Bartley et al., 2007; Ramos-Scharron and MacDonald, 2007; Brooks et al., 2008). The quantitative assessment of gully erosion enables the
more realistic construction of land evolution and sediment budget models. This research quantifies gully erosion in the study site and determines the volumes from gully erosion for the time period 1948-2008 and is used to calculate the gully sediment yield for the Fergusson River catchment.

1.4.4 Gully Classification Dynamics, and Processes

Gully initiation and development is affected by a number of topographic and environmental factors. Gully development is usually linked to geology, soil, vegetation, climate and landuse (Medcalf, 1944; Aldrick and Robinson, 1972; Branch, 1981; Bartley et al., 2007). Overstocking and rainfall have been reported as the main factors contributing to gully erosion in the Fitzroy River, in north-western Australia (Medcalf, 1944; Blandford, 1979; Leys, 1980; Branch, 1981).

Gully morphology, describing the form and structure of gullies, reflects the underlying erosion processes. Understanding gully morphology and the spatial distribution of gullies forms the basis for classifying gullies. Leopold and Miller (1956) classified gullies based upon their appearance and described two classes of gullies: continuous and discontinuous. Gully head platform and catchment properties were used in semi-arid Kenya to classify gullies based on their driving forces as follows: base level controlled gullies, subsurface flow-controlled gullies, and catchment-controlled gullies (Oostwoud Wijdenes and Bryan, 2001).

Temporal changes in gully morphology provide a strong basis to understand gully behavior in space and time. Lane et al., (1998) point out that monitoring of changes in gully form may provide a more successful basis for understanding landform dynamics than monitoring the processes driving those dynamics, particularly when spatially distributed information on process rates cannot be acquired. Most gullies, once initiated, rapidly develop, then stabilize (Graf, 1977), and evidence from some Australian gullies shows that their lengths have not increased significantly since the 1940’s (Wasson et al., 1998; Rutherfurd, 2000) suggesting stability. The research presented in this thesis provides a spatio-temporal analysis of gully dynamics in the study area and classifies the gullies based upon their morphology, erosion processes and spatial distribution; an approach that has been used by Imeson and Kwaad (1980). Further, in order to understand the gully erosion processes and dynamics, gully control factor analysis has been performed to identify the causes of gully
erosion so that better management strategies can be developed to prevent future gully ing.

1.5 Thesis Structure

The research uses a geoinformatics based approach to explain and describe gully erosion phenomena. A brief summary of each chapter now follows.

In Chapter 1, a general introduction to the research and aims are given. The significance of gully erosion is presented. Important aspects of gully erosion research have been illustrated and the problem described in the study area. Finally this chapter describes the structure used in this thesis.

As a basis for providing a better understanding of gully erosion and sedimentation processes, Chapter 2 provides a review of the literature covering gully erosion quantification methods, both recent and past.

Chapter 3 describes the biophysical characteristics of the study area. It provides an insight into geology, physiography, soil, vegetation, climate, and landuse/landcover of the study area. The purpose of this chapter is to present the environmental conditions of the study area and provides a basis to discuss the relationship between these variables and gully erosion.

Chapter 4 presents the development of a framework integrating geoinformatics based tools and techniques to quantify gully erosion. The potentials of Cartosat-1 satellite imagery for mapping gullies is explored and the processing of these images described. A DSM created from the processed images is used as a source for 3D gully mapping. A Differential Global Positioning Survey (DGPS) is performed for accuracy assessment. The method for 3D gully mapping and calculation of gully dimensions and volumes is illustrated. In order to map historical gully erosion, stereo aerial photographs from 1948 are processed and a method for orthorectification without a camera calibration report is provided. Information on historical gullies is recorded in the form of 3D gully mapping and determination of gully dimensions.

Chapter 5 discusses gully erosion processes, classification and spatial distribution of gullies in the study area. An analysis of the dynamics of gully erosion is undertaken comparing gully mapping from 1948 aerial photography with 2008 Cartosat-1
satellite imagery to calculate volume and specific sediment yield, and these results are compared with regional and global datasets.

Chapter 6 describes the relationship of gullies to environmental factors in the region. Gully erosion processes and development aspects have been illustrated with respect to geology, soil, vegetation, landuse, climate and topographic characteristics of the study area. Important aspects of each of these factors are discussed and elaborated.

Chapter 7 presents a summary of the research. The methods developed in this research and the results are summarized and evaluated with respect to the aims of the research. Finally, some limitations and further research issues are presented.
Chapter 2: Literature Review
Chapter 2: Literature Review

2.1 Introduction

This chapter reviews gully erosion determination, various approaches for gully mapping and method for erosion quantification. The history and background of research on gully erosion in relation to Two Dimensional (2D) and Three Dimensional (3D) gully mapping and erosion quantification is given.

2.2 Gully Erosion Determination

Gully erosion rates vary in space and time under different environmental conditions. Variation in gully erosion rates has raised the issue of how to accurately map and assess soil loss at adequate spatial and temporal scales. Cassali et al. (2006) mentioned the methodological problem of accurately measuring rill and gully erosion, and indicated the problem of gully mis-identification leads to inaccurate gully mapping. From the work of Cassali et al. (2006) it can be inferred that accurate gully measurement is heavily dependent upon precise mapping. Further, meticulous erosion rate determination depends upon the accuracy of the method used. Studies (Thompson, 1964; Seginer, 1966; Piest and Spomer, 1968; Stocking, 1980; Sneddon et al., 1988; Burkard and Kostaschuk, 1995, 1997) show the use of several field and mapping based methods for erosion rate determination; including linear measures (Thompson, 1964; Seginer, 1966; Burkard and Kostaschuk, 1997), area measure (Burkard and Kostaschuk, 1995, 1997), volumetric measures (Stocking, 1980; Sneddon et al., 1988), and mass measures (Piest and Spomer, 1968). Stocking (1980) reviewed different methods for taking gully erosion measurements and concluded that volumetric measurements are the best way to determine gully erosion.

Gully erosion rates can be determined by incorporating various field and laboratory based techniques. Poesen et al., (2003) describe the techniques for measuring the rate of gully erosion at various temporal scales: short time scale (<1-10 years); medium time scale (10-70 years); and long time scale (> 70 years). Short time scale studies involve both field-based and laboratory-based techniques: measuring directly the volume of gullies (Vandaele and Poesen, 1995; Nachtergaele et al., 2001; Valca´rcel et al., 2003); monitoring gully head retreat rate (Vandekerckhove et al., 2001b); and
using photogrammetric techniques on sequential aerial photographs (Thomas et al., 1986; Ries and Marzolff, 2003).

Medium time scale techniques have used aerial photographs for measuring change in gully morphology (Burkard and Kostaschuk, 1995; De Rose et al., 1998; Daba et al., 2003; Ga`bris et al., 2003; Mart`inez-Casasnovas, 2003). Dendrochronology based on tree roots, exposed by gully erosion, root suckers, stems, and of trees within gully floors (Vandekerckhove et al., 2001b) has also been used. Historical documents, maps, and dating techniques have been used to chart the course of gully formation and development over long time scales (Prosser and Winchester, 1996; Trimble, 1998; Webb and Hereford, 2001; Dotterweich et al., 2003; Ga`bris et al., 2003).

2.3 Gully Mapping and Erosion Quantification Approaches

This section presents a review of gully measurement methods and techniques, and examines the use of various methods for gully mapping and quantification. Different approaches used for mapping gully erosion and its quantification are discussed.

2.3.1 Conventional Approaches

2.3.1.1 Field Based Methods and Erosion Pins

Field based gully erosion measurements include the use of tapes, benchmark (erosion) pins and theodolite surveys (Poesen et al., 1996; Hessel and van Asch, 2003; Belyaev et al., 2004; Avni, 2005). Using these methods surface level changes can be measured in one dimension at a given surface point, in two dimensions to give a profile or cross section, or in three dimensions for volumetric measurements. With these traditional measurement methods, changes of soil surface heights are determined where the rate of erosion is high. However, surface level changes are not suitable to assess the rate of soil loss in arable land because the surface level is affected by cultivation (Kiusi and Meadows, 2006).

Erosion pins are widely used to measure soil loss. Pins are driven into the soil and the top of the pin provides a reference level allowing changes in soil surface level to be measured. Horizontal and vertical measurements of gully morphology are required in order to study gully growth and to measure gully volume. Generally, a network of erosion pins in the form of a regular gird with appropriate intervals (normally 2 to 5 meters) is set out and grid line measurements plotted on a squared
paper to sketch the surface area (Figure 2.1). Gridlines also provide the location for transects to measure gully cross-sections. At each transect location, a cross section of the gully is surveyed and volume of soil loss calculated for each segment before being summed to estimate the total volume of soil loss from the gully (Figure 2.2) (Hudson, 1993). These surveys can be repeated over time to estimate gully expansion rates.

Figure 2.1 Setting out a network of erosion pins to measure gully erosion (Source: Hudson, 1993 [Figure 10])

Figure 2.2 Calculation of cross sections in a gully (Source: Hudson, 1993 [Figure 11])
Rates of gully development and volumes have been measured in several places using the erosion pin method (Crouch, 1987; Crouch and Blong, 1989; Ghimire and Higaki, 2003; Boardman and Foster, 2008). Near Wellington in central New South Wales, the measurement of gully development by survey and erosion pins showed that the vertical sides, subject to undercutting, had the highest erosion rate (75 mm year\(^{-1}\)) followed by the vertical fluted walls (37 mm year\(^{-1}\)) (Crouch, 1987). In the Bathurst Granite on the Central Tablelands of New South Wales, the soil movement rates from gully sides were measured with erosion pins and survey. The erosion rates varied considerably, over short distances, from 0 to 53 mm year\(^{-1}\), with an average removal rate of 19.8 mm year\(^{-1}\) (Crouch, 1990). Gully head retreat has been measured in the Siwalik Hills, Nepal, by measuring the change in distance between the edge of the gully head and benchmark pins around the gully head (Ghimire and Higaki, 2003).

Field based methods have been used to investigate the retreat of gully headcuts and gully cross section change (Poesen et al., 1996; Vandekerckhove et al., 2000; Rustomji, 2006). Some studies have used microprofilers (device for precise width and depth measurement) to monitor gully cross sections and subsequently computed gully volume (Archibold et al., 2003; De Santisteban et al., 2006).

The main advantage of field based methods is that they are simple, detailed measurements of gully dimensions are possible, and results are reliable and usable for erosion applications. Field based methods are usually easy to apply and done with a moderate level of skill. Instruments used for measurements may take little maintenance but field based measurements can be expensive in terms of time and effort. A major disadvantage of field based method is they are spatially limited in scope and cannot be easily employed at complex or at inaccessible areas.

### 2.3.1.2 Dendrochronology

Dendrochronology, also known as tree-ring dating, is a method based on analysis of the patterns of tree-rings. The fundamental principle of dendrochronology is that most trees produce new growth rings each year, in between their wood and the bark. The thickness of each of the tree rings varies depending on the environmental conditions from year to year. A thick ring may indicate a very wet year, whereas a thin ring may indicate a relatively dry year. The size of a tree’s rings varies
depending on environmental factors and generally leads to the assumption that trees in similar regions will have similar rings, and this allows cross-dating of the rings. Matching patterns in ring widths among several different trees allows for the identification of the exact year in which each tree ring was formed (Pilcher et al., 1984).

Dendrochronology has been applied to estimate gully erosion rates as an alternative to traditional methods for assessing medium-term gully retreat rates, such as field monitoring of headcuts or aerial-photo interpretation of gully retreat. The method uses trees, or parts of trees affected by gully erosion, reveals information on the history of the erosion process by datable deviations from the growth pattern (Vandekerckhove et al., 2001a).

However, several disadvantages have been mentioned (see Pilcher et al., 1984; Ionita, 2006b) for using this method to estimate gully erosion; it has a limited time span as compared to other methods; growth of tree rings begins in spring, and ends in summer or early autumn. When one or more factors are limiting, distinct growth rings are formed. It is possible therefore that no growth rings are formed under favourable conditions or, one or more growth rings can be formed during an unfavourable year. Therefore, there are many species in different geographic areas that are not suitable for applying dendrochronology. Tree-rings can estimate the minimum-limiting age of a tree. There are some difficulties in defining the age of the tree i.e., the estimation of the length of time between land surface stabilisation and seedling establishment, determination of the oldest tree in the area, false rings, and missing rings in the years of extreme environment.

2.3.2 Modern Approaches

2.3.2.1 Aerial Photographs

The use of aerial photographs to map soil pattern and erosion risk is not new (Goosen, 1967) and has been used in support of conventional geomorphological methods (Stromquist, 1990). Availability of digital analytical stereoscopes and the advancement of photogrammetric methods have offered new ways to use this historical source and facilitate the integration of information from aerial photographs with other data sets. As a result aerial photograph interpretation has also become a modern approach to mapping gully erosion.
Aerial photographs have proved to be a particularly effective source for mapping the extent of gully erosion (Ritchie, 2000) and are useful for tracing the history of gullies. Visual interpretation has been a common method for detecting individual gullies from aerial photographs (Martinez-Casasnovas et al., 2003; Nachtergaele and Poesen, 1999). In South Africa, gully boundaries were identified and digitized based on grey tones from aerial photographs at scales 1:10,000 and 1:20,000 (Thwaites, 1986). In Zimbabwe, gullies were measured using air photo interpretation by identifying the black spots, and gully severity was mapped at a scale of 1:25,000 (Jones and Keech, 1966).

Gully erosion has been mapped based upon the homogeneity and heterogeneity of the gully structure and gully erosion risk zone map was produced (Flugel et al., 2003; Zucca et al., 2006). Results of the study by Zucca et al., (2006) demonstrate six levels of erosion risk; slightly eroded (1) to severely eroded (6), at a scale of 1:50,000. The availability of large scale aerial photographs supports mapping of gully landforms even at sub catchment level, so this means that linear features are also visible and convenient to map (Sonneveld et al., 2005).

Historical aerial photographs and field monitoring data were used to estimate the sediment production from active gullies in small catchments of the Siwalik Hills in India (Ghimire and Higaki, 2003). Long-term change analysis by sequential aerial photo comparison indicated that the gullies expanded remarkably over the period between 1964 and 1992 by 34% to 58%. On the eastern shoreline of Lake Huron, Canada, gully erosion rates were measured by aerial photography (1930, 1955, 1966, 1978 and 1992) with scales ranging from 1:10000 to 1:16000 (Burkard and Kostaschuk, 1997). Keech (1992) showed the correlation of gully changes with land use and vegetation change over a period of forty years in Zimbabwe using aerial photographs.

Although, aerial photographs have been used widely to map gully extent and to find gully changes over time, aerial photograph interpretations are usually limited to 2D analysis of change and mapping. 2D photograph interpretations may not support the visualization of all gully types; narrow linear gullies might not be visible on aerial photographs. However, stereo aerial photographs allows stereoscopic viewing of the
3D structure of terrain and vegetation (Slama et al., 1980) and also the retrieval of object heights and depths.

2.3.2.1 Stereo Aerial Photographs

Stereo photography was invented in the mid 19th century. By the late 1800’s to early 1900’s the viewing of stereo photographs was popular entertainment (Daba et al., 2003). Stereo Aerial photographs are normally flown in runs with a pre-determined amount of forward and side overlap. The overlapping portions, usually 60 percent, of adjacent aerial photographs are called stereo pairs and can be visualized in 3D (Figure 2.3). The height, angle, relative and horizontal distance and dimensions of objects can be calculated using photogrammetric principles. The accurate geometry of the photographs also enables three dimensional coordinate data to be extracted; the same height distortions that affect the single photograph can now be used to determine the height of an object in a stereo pair (Ford and Ogleby, 1997).

Military Mapping in Australia began in 1907 as a part time activity of the Australian Intelligence Corps (AAMME, 2009). The first use of aerial photographs for mapping was during World War I (WWI). The Royal Australian Air Force (RAAF) started flying aerial photography in 1927 to support plane table mapping. Vertical aerial photographs were flown in September 1928 by the RAAF at a scale of 1:2400 and again in 1945 at a scale of 1:3000. Most of the aerial photographs and stereo aerial photographs covering Australia were taken between 1928 and 1987. Until 1930, aerial photographs were not used for mapping due to their low quality (AAMME, 2009).

Figure 2.3 Geometry of stereo aerial photographs (Source: Leica-Geosystems, 2006 [Figure 12])
Using stereo photographs stereoscopic views can be generated by applying photogrammetric techniques. Photogrammetry is the art, science and technology of obtaining reliable and quantitative information about physical objects and the environment through the process of recording, measuring and interpreting photographic images and patterns (Karara, 1989; Lillesand and Kiefer, 1994). Photogrammetry is used by engineers, spatial scientists, and spatial planners for various purposes including surveying and mapping. One of the great benefits of photogrammetry is the development of a detailed 3D model that can be used for the production of digital mapping products. Photogrammetric techniques eliminate the systematic and non systematic errors of raw aerial photography and satellite imagery, so geometrically correct images can be produced and used with reliability (Campbell, 1996). Photogrammetry involves image-forming geometry, utilizing information between overlapping images, and explicitly dealing with the third dimension: elevation. Accurate and precise information can be derived from aerial photographs and satellite imagery in an efficient and cost effective manner. Photogrammetric techniques allow for the generation of orthorectified images, Digital Elevation Models (DEMs), and Digital Terrain Models (DTMs), Digital Surface Models (DSMs), and 3D Geographic Information System (GIS) (Sidle et al., 2006) vector layers.

Stereoscopic viewing allows depth information to be determined with detail and accuracy. The human brain judges and perceives changes in depth and volume in a stereoscopic view. A stereo effect is created when two overlapping images (a stereo pair), or photographs of a common area captured from two different angles, area viewed simultaneously. The stereo effect, or ability to view with measurable depth perception, is provided by a parallax effect generated from the two different acquisition points. Parallax is a displacement of a ground point appearing in a stereo pair as a function of the position of the sensors at the time of image capture. (Leica-Geosystems, 2006).

3D visualization allows the identification of all types of gullies (Thwaites, 1986; Morgan et al., 1997; Watson, 1997). Stereo aerial photographs form a basis for volume estimation and rate of sediment production from gully erosion. The accuracy of estimating erosion rate is increased when using stereoscopic photos with high resolution (Nachtergaele and Poesen, 1999). Stereo photographs and
photogrammetric techniques have been adopted by various studies; to compute the amount of eroded material and rate of concentrated flow erosion (Thomas et al., 1986; Poesen et al., 1996; Nachtergaele and Poesen, 1999; Daba et al., 2003). The studies have derived DEM from stereo aerial photographs for gully volume calculations, but none of these studies described 3D gully mapping. However, overlaying 2D maps of gullies on a DEM to retrieve depth information (Daba et al., 2003) indicates that 3D gully representation has been recognized but so far no general solution regarding 3D gully mapping has been provided.

2.3.2.2 Remote Sensing

With the availability of a variety of space borne sensors, satellite remote sensing offers an important input for mapping erosion features at various spatial scales. Satellite images at a variety of spatial and spectral resolutions are readily available (Table 2.1), and some are even free which enables the use of spatial technology for a wide range of applications and have potential to be an important data source for these applications.

Spatial resolution is a measure of the linear separation between two objects that can be resolved by a remote sensing system (Jensen, 2005) which dictates the size of the smallest possible feature that can be detected in the satellite image (Wilkie and Finn, 1996). The spectral resolution (dimension and number of wavelength regions of a sensor system) usually expressed as bands allows for feature extraction methods for gully mapping. The temporal resolution of a satellite system refers to how frequently it records imagery of a particular area and radiometric resolution refers to the range of intensity levels used to quantify spectral responses assessed by the respective sensor system. Knowledge of spatial, spectral temporal and radiometric resolution helps to identify the suitable imagery for various applications.

High resolution satellite images, IKONSS and Quickbird offer a good option for gully mapping, but processing requires a lot of time and effort. Other problems, time-consuming nature of obtaining validation data and the lack of standard validation approaches restrict the use of high resolution images for gully erosion mapping.

The Systeme Pour l’Observation de la Terre (SPOT) series satellites provide high spatial resolution sensors called High Resolution Visible (HRV) and High Resolution Visible and Infrared (HRVIR) and are capable of measuring reflected radiance in
three bands at a spatial resolution of 20m, or 10m panchromatic, and have proven better at distinguishing eroded areas compared to Landsat TM observations (Bocco and Valenzuela, 1993). Although SPOT HRV has proven better at mapping eroded areas, its low spectral sampling (4 bands) has proven to be a limitation in mapping gullies (Servenay and Prat, 2003).

Table 2.1 Sensors and their spatial and spectral resolution (Source: Satellite Imaging Corporation, 2010)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Spatial Resolution</th>
<th>Spectral Resolution</th>
<th>Revisit Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quickbird Panchromatic Multispectral</td>
<td>65 cm</td>
<td>Black &amp; White</td>
<td>2.5 days</td>
</tr>
<tr>
<td>Multispectral</td>
<td>2.62 m</td>
<td>4 bands</td>
<td>5.6 days</td>
</tr>
<tr>
<td>IKONOS Panchromatic Multispectral</td>
<td>1 m</td>
<td>Black &amp; White</td>
<td>3 days</td>
</tr>
<tr>
<td>Multispectral</td>
<td>4 m</td>
<td>4 bands</td>
<td></td>
</tr>
<tr>
<td>SPOT 5 Panchromatic HRV</td>
<td>2.5 m</td>
<td>Black &amp; white</td>
<td>2-3 days</td>
</tr>
<tr>
<td>HRV</td>
<td>10 m ( band 1-3)</td>
<td>4 bands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 m(Mid Infrared)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat TM</td>
<td>30 m (band1-7)</td>
<td>7 bands</td>
<td>16 days</td>
</tr>
<tr>
<td></td>
<td>120 m (band 6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landsat ETM+</td>
<td>30 m (band1-5 and band7)</td>
<td>7 bands</td>
<td>16 days</td>
</tr>
<tr>
<td></td>
<td>60 m (band 6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTER</td>
<td>15 -90 m</td>
<td>14 bands</td>
<td>16 days</td>
</tr>
</tbody>
</table>

Gullies also exhibit distinctive characteristics, such as subsoil exposure, low vegetation cover, or bare gully floors that can be distinguished by spectral bands of the images (Bocco and Valenzuela, 1993). Gullies can also be digitized from satellite imagery based upon their high reflectance characteristics (Bocco and Valenzuela, 1993). In addition to mapping of individual gullies, extensive areas affected by gully erosion have been mapped using visual interpretation techniques based on optical image composites (Bocco, 1991; Dwivedi et al., 1997).

Raoofi et al., (2004) reported the use of fusion images (i.e. merging bands of two images) to distinguish rill and gully erosion in the Taleghan basin, Iran by a visual
interpretation technique. Landsat ETM+ has a spatial resolution of 30×30 m and spectral resolution includes 7 bands. Based upon visual interpretation and field observation, a ground truth map of the eroded region is produced. Results indicate an accuracy level of 80% for rill and gully identification. Landsat Thematic Mapper (TM) images 30×30 m, have been used in Sudan to identify gullies based on topography, drainage pattern, tone, and landuse (Fadul et al., 1999). Similarly, gullies have been delineated based on colour, texture and pattern, using Landsat TM images in Tanzania (Kiusi and Meadows, 2006).

Vrieling et al., (2007) demonstrates the automatic classification of optical Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery in the Brazilian Cerrados for gully identification and mapping. The study used the maximum likelihood classifier to detect permanent gully erosion. The classifier was trained with two classes: gullies and non gullies, and applied to the March (wet season) and August (dry season) data. Classified images were then validated using a bi-temporal classification to ensure that a pixel labelled as a gully lies in the same class in images for both seasons. Results were validated against a QuickBird image and field data. The study concluded that a combination of ASTER bands 1, 2, 3, and 4 gave high accuracy for mapping of permanent gullies.

Relevant literature shows that gullies can be identified and mapped using satellite data (Langran, 1983; King et al., 2005) but accurate mapping is not possible without additional supporting data and expert knowledge (Bocco and Valenzuela, 1993). This is because the gullies are very heterogeneous in their appearance; heterogeneity is caused by a mixture of vegetation, bare soil, shadows, steep or inclined walls, and moist gully floors (Zinck et al., 2001; King et al., 2005). This heterogeneity means that gullies give a mixed spectral response and therefore generate a complex scenario for an automatic retrieval.

Eustace et al., (2009) have used Light Detection and Ranging (LiDAR): airborne imagery and optical remote sensing technology to measure the distance and other properties of a target by illuminating the target with light, often using pulses from a laser, and applied semi automated object oriented classification method to detect and map gullies and measure gully volumes in eastern Australia. Results of this study showed good gully mapping in comparison to using high resolution Quickbird
Satellite imagery, but no ground truthing was performed to validate the volumetric measurements.

Satellite imagery offers the potential for monitoring and modelling of gully erosion due to its frequency and large spatial coverage and data collection abilities (Bocco, 1991; Nachtergaele and Poesen, 1999). Unfortunately it currently has not been used for 3D gully mapping. Accurate gully mapping requires additional data and expertise. Landsat TM, ETM+ and ASTER images facilitate identification and mapping of gully erosion in 2D, but gully volume calculation is not possible from such datasets.

### 2.3.2.2.1 Stereo Satellite Imagery

Stereo satellite imagery offers the possibility for 3D visualization and feature extraction applications. Stereo images have the potential for DSM creation and DEM generation. Terrain attributes, such as, slope, aspect, and relief can be acquired using DEMs (Betts and DeRose, 1999; Toutin, 2001) or by using radar interferometry (Toutin and Gray, 2000).

Satellites acquire stereo pairs of images of the same location on Earth from two different angles during one orbital pass. The pair of images is collected consecutively by a single satellite along the same orbit within a few seconds time difference (known as ‘along the track imaging technique’) (Figure 2.4). Each stereo pair contains an image collected at a low elevation angle as well as an image collected at a higher elevation angle. The viewing angles of the stereo images are a critical issue, as it has been found that the base-to-height (B/H) ratio should be close to 1 to achieve a high-quality stereo model with high elevation accuracy (NRSA, 2005).

Many satellites offer stereo satellite imagery, such as Advanced Land Observation Satellite (ALOS), Quickbird, and Cartosat-1. ALOS (2.5 m spatial resolution) was launched in 2006. ALOS has a Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) for DEM generation. Quickbird (0.61 m spatial resolution) was launched in 2001 from the Vandenberg Air Force Base, California. Quickbird is able to collect along track stereo images in panchromatic mode with a B/H ratio 0.6 of and therefore a relatively high price per square kilometer.
The Cartosat-1, an optical remote sensing satellite, was launched on May 5, 2005 with the aim of providing data for topographic mapping based on DEMs, production of orthoimages, and 3D visualization of terrain (Srivastava et al., 2007).

Cartosat-1 is capable of providing an orbit stereo view (2.5 m resolution) with two identical panchromatic cameras; forward (Fore) and afterward (Aft) (Figure 2.4). The cameras have fixed tilts of +26 degrees (Fore) and -5 degrees (Aft) with a B/H ratio of 0.62, and cover a 27km swath with 52 seconds of time difference of stereo image acquisition. Beside the stereo mode, the satellite can function in wide swath mode so high resolution images with a swath up to 55km can be produced. The radiometric resolution of the sensor is 10 bit which allows identification of terrain features and assists topographic mapping at large scale (Table 2.2) (Krishnaswamy and Kalyanaraman, 2002). Cartosat-1 is a near polar sun synchronous satellite launched with an orbit inclination of 97.87° (Table 2.3). The orbit average altitude is 618 km out and the orbit revisit time is 126 days (Srivastava et al., 2007).

Baltsavias et al., (2008) have reported that regarding image quality Cartosat-1 is better than ALOS PRISM and can be used as a useful image source for 3D mapping and DSM generation. Crespi et al., (2007) have extracted and compared DSMs from Quickbird and Cartosat-1 stereo pairs and have concluded that a horizontal and vertical accuracy at sub pixel level for Cartosat-1 and 1.5 pixel level for Quickbird.
Mapping of gullies in 3D requires highly accurate and precise methods, moderated by cost of acquisition and processing. This is especially important for mapping gullies over large area. Very high resolution satellite images are therefore unlikely to be appropriate. The satellite images used in the research presented in this thesis have appeared to fulfil the requirements of sufficient accuracy and precision and reasonable cost for mapping gullies over a large area.
2.3.2.3 Digital Elevation Models

The advancement of photogrammetric methods and digital imaging technologies in the last two decades has created options for Digital Elevation Model (DEM) derivations (Kraus et al., 1982; Ackermann, 1991; Toutin, 2001), which has led to the increasing use of DEMs for studying landscape change and gully erosion (Prosser and Abernathy, 1996; Florinsky, 1998). In the Waipaoa River basin of New Zealand, the amount of sediment produced from gully erosion has been determined by using analysis of retrospective stereo photographs to construct a DEM (Derose et al., 1998). Quantitative assessment of gully dynamics and associated soil loss were carried out in Ethiopia, using a DEM based approach (Daba et al., 2003). The study used aerial photographs at a scale of 1:45000 from two dates 1966 and 1996 to digitize the gully boundaries. Two DEMs with grid widths of 20m and 2m were derived from stereo image pairs and gully boundaries were measured for identified gully systems. Gully profiles were measured at regular intervals of 20m along the gully length. Gully sections were defined as portions of a gully between neighbouring profiles. A closed polygon region was created using the boundary lines of neighbouring profiles and two lines running longitudinally on both sides of the gully, and the volume for each gully section computed. Intergraph’s soft copy station (Intergraph TDZ), with its modules Model Setup, Digital Terrain Model (DTM) Collection, Feature Collection, Image processing and DTM Analysis were used for photogrammetric measurements of the digitized images. The cut and fill method of the DTM system Stuttgart Contour Program (SCOP) (Daba et al., 2003) was applied for gully volume calculations. Accuracy of volume calculations is highly dependent on how accurately the hypothetical interpolated surface without gullies has been created.

Gully retreat rates have been determined using multitemporal aerial photographs and multitemporal DEMs, both of which have been processed using Geographic Information Systems (GIS) techniques (Martínez-Casasnovas, 2003). The study used aerial photographs at scale of 1:30000 from 1957 and orthophotos from 1993 to map gully erosion and determine erosion rates. The 1957 DEM at 25m resolution was constructed from 10m spaced contours and break lines, generated using the spatial interpolation algorithm of Topogrid ArcInfo. The rates of channel incision
and sediment production were computed from the subtraction of multitemporal DEMs.

Multitemporal DEM differencing is another method to compute sediment production, deposition and volumetric change of gully erosion (De Rose et al., 1998; Martínez-Casasnovas, 1998; Betts et al., 2003; Martínez-Casasnovas et al., 2004). The DEM differencing method incorporates overland flow, bank erosion, mass movement, downcutting and undercutting, thus generating high computed rates of sediment production as compared to the usual methods. This allows the gully erosion rate to be determined on a short term (<1-10 years) to long term (>70 years) basis. Resolution of the DEM determines its usefulness in investigating gully erosion parameters for short or long term periods. Medium resolution DEMs support the long to medium term erosion rate determination but short term exploration of gully dynamics requires high resolution DEMs (Pyle et al., 1997). High resolution description of gully behavior was explored in New Zealand’s North Island East Coast region to measure geomorphic changes over one year (Betts et al., 2003). Results of this study demonstrated gully morphometric changes and mass movement including slumping and debris flows.

DEM based studies provide a feasible method of mapping and quantifying gully erosion. The resolution of a DEM determines its suitability to achieve specific objectives in gully erosion investigations. The review of various studies (Betts et al., 2003; Daba et al., 2003; Martínez-Casasnovas et al., 2004) shows that DEMs have been used to find gully depth information or to measure volumetric changes either by measuring these features from a DEM or by the differences of DEMs. Gully dynamic (initiation, development, stability) exploration is not only dependent on gully extent information but also considers the surrounding topography, while the disadvantage is that the DEMs are bare earth models which provide elevation information but do not deal with the surface topographic detail.

2.3.2.4 Global Positioning System and Geographic Information System

Global Positioning Systems (GPS) are satellite based navigational systems that have been used for object positioning and navigational purposes for a wide range of applications (Theakstone et al., 1999; Brasington et al., 2000; Sjoberg et al., 2000). GPS provides the 3D position and time information for users with suitable ground
receiving equipment (Leick, 1995; Kaplan, 1996). A GPS receiver simultaneously tracks four or more GPS satellites to determine coordinates with respect to the centre of Earth (Kaplan, 1996). Improved accuracy of GPS enhances the use of this technology for morphological change studies and continuous monitoring of landforms.

Differential Global Positioning System (DGPS) uses a network of fixed ground based reference stations that transmit the difference between the position of the known point and the position indicated by the satellite system. DGPS works in a real time mode by transmitting the difference in position of a known point from a rover (i.e. mobile receiver) using a base receiver. The improved accuracy of DGPS makes it extremely useful for geographic applications (Higgitt and Warburton, 1999).

DGPS Real-time Kinematic (RTK) GPS, Trimble 4700) has been used to determine short term gully retreat rates in the black soil region of northeast China (Hu et al., 2007). RTK GPS, Trimble 4700, has a planimetric and altimetric precision of 1 cm±2 ppm and 2 cm ±2 ppm, respectively. Data were collected for two years, twice per year; one before rainfall and other after. Measurements of gully dimensions show variation in length, width and depth, that indicates a gradual change in gully morphology. Collected data points were processed in the software package Trimble Geomatics Office and then imported into a GIS based format to derive the topography. Furthermore, break lines were drawn on the collected points that were on the edges of gullies. Afterwards using spatial modeling in ArcGIS 8.3, a DEM of the gullies was created. The retreat rate of gully heads and the rate of soil loss caused by gully erosion was determined using DEM and DGPS data. Similarly, gully geomorphic changes have also been monitored using GPS in the Loess Plateau of China (Wu and Cheng, 2005). The study based on a topographic survey using a GPS aimed at collecting field measurements such as gully heads, gully edges, ephemeral gullies and terrace edges. GPS collected data were processed in the software package Trimble Geomatics and Mapinfo professional 6.0, in order to obtain morphological parameters (including length, width, depth and area). Based upon the processed data, a DEM with 2m pixel size was generated to calculate slope gradient and the upslope drainage area.
GPS based techniques work well with other field based methods and GIS based packages. Masoud et al (2009) used GPS to determine the position of rill and gullies on a topographic map and drainage network map. Data points were plotted using GIS based methods and tools. Basin area and boundaries of each rill or gully were also plotted using GIS. The dimensions of gullies and rills were measured in the field using a ruler, and tilt meter, and these field based measurements were combined with GPS points.

The GPS based approach to explore gully erosion is easy to perform and the use of a DGPS provides data with improved accuracy. However, the fact that this approach relies on time consuming field measurements is its big disadvantage. The use of this approach is convenient as a preliminary way of capturing data in areas where no previous data (map or images) exist about landforms, but to monitor the changes in geomorphic features, it is laborious and impractical for gullies found in large areas. Nevertheless, the use of this approach for data calibration, and for ground truthing purposes, is feasible.

2.3.2.5 Geoinformatics: an approach for gully mapping and quantification

Geoinformatics has been emerging as an integrated discipline that deals with the structure and character of geospatial data Duckham et al., 2007; Ehlers, 2008; Ramachandra, 2010; Dubois et al., 2011). It integrates geospatial technologies for acquisition, storage, processing, display, visualization and dissemination of information (Ratanaesermpong, 2000). These technologies include remote sensing, GIS, GPS, cartography, photogrammetry, and geodesy and incorporate the necessary infrastructure for information sharing.

Geoinformatics is sometimes used interchangeably with the term geomatics, but geomatics emphasizes surveying while geoinformatics integrates the use of technologies to handle geospatial data. Both disciplines, geoinformatics and geomatics, rely upon concepts, theory and practical techniques of geodesy.

The strength of this discipline is that it includes geospatial analysis and modelling techniques, development of geodatabase, spatial information systems and human computer interaction in a user friendly environment. Geocomputation and geovisualization are the main features to analyse the geoinformation. The most recent developments of 3D visualization and integration of GIS and
photogrammetry, offer new opportunities to analyse real word objects in 3D which facilitates improved mapping and geospatial analysis techniques.

The strength of geoinformatics and the integration of powerful spatial technologies enhance the application of such an approach for landform analysis, particularly for gully erosion research. Spatial technologies (and data) such as GIS, DEM, GPS, photogrammetry, and satellite imagery have been applied to gully erosion phenomena individually (as discussed in previous sections of this chapter) but the integrated use of these technologies for gully identification, mapping and quantification has not been explored before. The integration of these datasets offers many advantages over their separate application or traditional methodologies for exploring gully erosion, including efficiencies in terms of time and money, more robust and transferable techniques, and the creation and analysis of information at multiple temporal and spatial scales. In particular, large areas can be explored and investigated in a detailed manner which is not possible using conventional methods and approaches. Therefore, an integrative, geoinformatics based approach that utilizes the strength and power of various spatial technologies and applies it to 3D gully mapping and gully erosion volume calculation has been adopted and is explored in this research.

2.4 Summary

Various approaches for gully mapping and quantification have been reviewed. Conventional approaches consist of field based measurements, erosion pins and dendrochronology. Field base approaches provide reliable results but they are time consuming, laborious and usually have spatial coverage problems. Remote sensing overcomes the problems of spatial coverage and has been used to map gully extent. Satellite images provide planimetric solutions but do not contribute to gully volume calculation. Stereo satellite images provide the possibility for 3D gully mapping. Aerial photographs have been used as a source for historical gully mapping, whilst the use of stereo aerial photographs for gully erosion investigations has been recognized as an excellent resource. Stereo aerial photographs have been used for DEM construction and have contributed to the recognition of 3D representation of gully phenomena. DEM based approaches have been applied mainly to measure gully volumetric changes. GPS and GIS have been used to map and measure the
gully head cut position and gully edges. GPS based measurements have also been used for DEM construction by employing GIS based techniques. Geoinformatics integrates all of the above mentioned spatial technologies and data, and offers the possibility to most effectively explore, map, and quantify gully erosion. This approach has been adopted in this study to develop a framework for 3D gully mapping and erosion volume calculations.
Chapter 3: Description of Study Area
Chapter 3: Description of Study Area

3.1 Introduction

This chapter introduces the location, physiography, geology, soil, vegetation, climate, landuse/landcover, and drainage network of the study area, the Fergusson River catchment.

3.2 Location and Physiography

The Fergusson River drains a major sub catchment of the Daly River, and is located between longitudes 130° 30' & 132° E and latitude 14° & 15° S with a 4.8×10^3 km^2 catchment area (Figure 3.1). Important tributaries of the Fergusson River are the Cullen and Edith Rivers. Pontifex and Mendum (1972) have provided a physiographic division of the Fergusson River at 1:250000 scale. Following Pontifex and Mendum (1972), the study area can be classified into three landform classes; the Daly River Basin, Litchfield and Cullen Plains and the Northern Uplands. The Daly River Basin includes plains and undulating terrain in a geologic basin of Cambrian age. Further north-east and north-west low gently undulating areas are mainly comprised of Proterozoic granite. The Northern upland is a rugged landscape on folded Lower Proterozoic rocks stretching the northwest. These uplands consist of steep but low ridges and narrow valleys.

The Daly River is one of the important rivers in the Northern Territory with a 5.3×10^4 km^2 catchment area and the Daly River Catchment is significant due to its ecological, hydrological and biological values. This catchment is the focus of many future development plans including agricultural development, and is the habitat of many national threatened species. The region has been pinpointed as contributing to a future food bowl for Asia (Erskine et al., 2003). The Environmental health of the river is of great importance and requires research to underpin its protection from degradation. This research is part of a three-year, research project conducted by the Tropical Rivers and Coastal Knowledge (TRaCK) consortium which is examining the health and sustainability of Australia’s tropical rivers and estuaries. In this respect, the knowledge of local issues regarding erosion and sedimentation is a prime requirement. Once these issues are explored at local scales they can contribute to an understanding of the same issues at catchment scale.
Figure 3.1 Location of the study area

- Ferguson River Catchment
- Study Area
- Fergusson River

Northern Territory
The Fergusson River catchment is one of the major sub catchments of the Daly River catchment and is typical of the wetter part of the Daly River catchment in terms of hydrology and ecology. There are also a lot of gullies in the Fergusson catchment, which is why this study site was chosen for this research. This is important to mention that this area has not been explored before.

The study area extends 58km upstream of the junction of the Daly and Fergusson Rivers comprising of an area of 1242 km\(^2\) (Figure 3.1, study area marked by rectangle). Aldrick and Robinson (1972) have reported that this part of the catchment contains some alluvial plains that generate sediments that are transported by the Fergusson River to the Daly River.

The Department of Natural Resources, Environment, the Arts and Sport (NRETAS, 2008) has developed and collected a core set of attributes for land unit spatial datasets at 1:25000, 1:50000 and 1:100000 scales. The landform classification system is based upon the Australian Soil and Land Survey Field Handbook (McDonald et al., 1998). The adopted system has been applied to several surveys since 2000 to group land units in a standardized way and can be applied at 1:25000 and 1:50000 scales. According to this system, the study area has nine physiographic divisions (Hill and Napier, 2008) (Figure 3.2), as follows:

**Hills** - includes hilly terrain with slopes 3-9 degrees; rocky and boulder strewn,

**Low hills** - comprises gently undulating crests and upper slopes to 3 degrees; with frequent outcrops of sandstone or laterite and limestone.

**Rises** - consist of crests and upper slopes, sometimes containing minor drainage lines; frequent laterite outcrop.

**Plateaus** - flat to gently sloping plateaus, marginal rocky slopes up to 6 degrees, frequent outcrop of laterite or sandstone and limestone.

**Side slope to plateau** - comprised of rugged terrain, escarpments and dissected uplands; slopes greater than 22 degrees; boulder strewn slopes and rocky crests.

**Plains** - include lower slopes and valley floors in gently undulating terrain with slopes up to 2 degrees; occasional sandstone or limestone outcrop and undulating terrain with slopes to 2 degrees with intensive drainage pattern, valley floors or low lying seepage areas in sandy country, frequently abutting drainage lines on back-
Figure 3.2 Physiography of the Fergusson River catchment (Source: Hill and Napier, 2008)
plains; flat to gently sloping (less than 1 degree) scattered limestone pavement, indistinct drainage floors.

Alluvial plains - include levees along major rivers, rarely over 200m wide; back slopes to 3 degrees where the levee is narrow and 2 degrees where wider; occasional rock outcrop, low lying areas behind levees with slopes rarely in excess of 1 degree, major river back-plains or tributary drainage flats are also included under alluvial plains.

Swamps - very low-lying areas that are more or less permanently wet.

Drainage system - consists of rivers, major creeks and gullies with permanent and ephemeral waters; gullies associated with major river alluviums.

3.3 Geology

The geology of the Daly River catchment has been mapped (at 1:100000 and 1:250000) and described by the Northern Territory Department of Mines and Energy. The geology, geomorphology and land resources of this region have also been described and mapped at various scales (Sivertsen and Day, 1985; Baker and Pickup, 1987; Mulder and Whitehead, 1988). A Geological map of the study area is composed from 1:100000 scale maps published by Geoscience Australia and the Northern Territory Geological Survey (Geoscience Australia, 2007). Geological units have been simplified from 1:100000 and 1:500000 scale maps in Figure 3.3.

The Daly River Group includes Oolloo Limestone, Jinduckin Formation, Tindal Limestone, and Manbulloo Limestone member. The Jinduckin Formation includes sedimentary siliciclastics, sedimentary carbonate, siltstone, dolostone, sandstone, dolograinsone, dolomitic quartz sandstone, evaporite (principally anhydrite) common in siltstones and some sandstones, and flat pebble breccias. The Tindall Limestone contains partially dolomitised limestone with silt laminations, interbedded calcilutite and marl, bioclastic limestone, mudstone, siltstone, minor stromatolitic boundstone, cryptagal laminate, local bioclastic calcarenite, arkosic sandstone, and conglomerate (Opik, 1959).
Figure 3.3 Geology of the Fergusson River catchment (Source: Geoscience Australia, 2007)
The Burrell Creek Formation (Orosirian) belongs to the Finnis River Group (metasedimentary siliciclastic group) with fine to coarse feldspathic metagreywacke, minor phyllite, slate, mudstone, lenses of volcanolithic pebble conglomerate, and quartz-mica schist.

Alluvium is of Quaternary age and mainly comprises channel and flood plain alluvium including terrace deposits, with sand, silt, clay and some black soil and sandy soil.

Colluvium is of Quaternary age consisting of sand and gravel, and some loam.

Cretaceous Sediments: Undifferentiated sediments, largely previously mapped as Mullaman beds (now discontinued); quartzose to lithic and micaceous sandstone, siltstone, claystone, conglomerate, minor breccia; commonly ferruginised or silicified; locally fossiliferous.

Jindare Formation (Cambrian – Early Cambrian) consists of mottled ferruginous clayey sandstone, fine to medium grained and pebbly feldspathic and quartz sandstone, laminated chert, siltstone, conglomerate, silicified carbonate breccia, calcarenite; rare evaporite pseudomorphs and commonly limonitic.

Tennyson Leucogranite (Orosirian) consists of igneous felsic intrusives of granite and coarse porphyritic muscovite-biotite leucogranite.

Fingerpost Granodiorite belongs to the Fingerpost Suite (igneous felsic intrusive) and consists of coarse porphyritic biotite hornblende granodiorite. Driffield Granite includes coarse grained pink equigranular to porphyritic biotite leucogranite, medium-coarse grey or pink-green porphyritic hornblende biotite granite. Foelsche Leucogranite formation is comprised of fine to medium grained, equigranular leucogranite. Lewin Springs Syenite is comprised of porphyritic quartz syenite, quartz microsyenite, syenite, microgranite, microleucogranite, quartz micromonzonite, and microleucomonzonite.

Plum Tree Creek Volcanics (Orosirian) is comprised of rhyolite, ignimbrite, dacite, minor basalt, basaltic andesite, crystal tuff, lenses of tuffaceous and cherty sediments, and quartz (± feldspathic) sandstone.
3.4 Soil

Soil description of the study area is based on NRETAS working document on the Daly basin land unit description (Hill and Napier, 2008) (Figure 3.4). Soil description of the Fergusson River catchment includes; Elliott (Florina) shallow Loamy Yellow Earths; minor Jindabeth (Jindare), Sandy Yellow Earths, which are poorly drained soils with very slow runoff. Elliot (Florina) soils are sandy colluvium.

Very shallow soils are poorly drained soils, very erodible if disturbed with prolonged water logging on lower slopes, drainage floors and swamps associated with land unit 5f1. These are sandy colluvia and laterite.

Edith (Belbokie and Edith) soil series are fine Loamy Levee Red Earths with moderately well to imperfectly drained soils of slow run-off. These soils are subject to regular wet season flooding. These soils form on the older levees which are only extensive along the Daly River downstream from its junction with Stray Creek.

Banyan soil type includes grey and brown clays with minor Cununurra and Coolibah Grey and brown clays which are poorly drained with very slow run-off; between the areas being subject to regular wet season flooding.

Claravale soils (Lateritic Podzolics or shallow Earthy Sands) include minor Cockatoo Earthy sands with siliceous sands, are well drained soils that generate moderately rapid run-off.

Shallow or skeletal soils are either very shallow and gravelly or sandy on low hills. They are well drained soils with rapid run-off. Parent material includes siltstone and ferricrete.

Blain soils are sandy red with soft surface horizons of sand to loamy sand with minor Cockatoo Earthy sands which are well drained with slow run-off.

Jindabeth (Jindare) - Sandy Yellow Earths; minor Elliott (Florina) - Loamy Yellow Earths are imperfectly drained soils with slow to moderately rapid run-off. Parent material includes sandy colluvium.

Coolibah soils include grey and brown clays with minor Banyan that includes grey and brown clays. These are poorly drained soils with very slow run-off.
Figure 3.4 Soil groups of the Fergusson River catchment (Source: Hill and Napier, 2008)
Tippera soils are loamy Red Earths, deep with minor outcrop or shallow with small amounts of surface stone or gravel, are well drained soils with slow run-off. Land formation is flat to gently sloping; slopes less than 1 degree on scattered limestone pavement or outcrop with indistinct drainage floors. The parent material of Tippera series is recent alluvium and levee alluvium.

Tippera (Ooloo) - Loamy Red Earths with firm surface horizons of sandy loam to sandy clay loam; minor Blain (Ruby) deep Sandy Red Earths are well drained; slow to moderately rapid run-off.

3.5 Vegetation

Aldrick and Robinson (1972) have described the vegetation of the land units for the Katherine-Douglas area at 1:50000 scale. Vegetation along tributary creeks, drainage floors and back plains of Land Units has been described as woodland, open woodland, very open woodland and grassland. Vegetation associated with the major river alluvium is described as open forest, woodland, variable woodland and swamps.

A vegetation survey of the Northern Territory, was carried out by Wilson et al., (1990) and a vegetation map at 1:1000000 scale was produced. Faulks (1998b) regrouped the categories for this map based upon dominant vegetation communities (e.g. Eucalypt with grass understorey, Melaleuca) and structural formations (e.g. closed forest, open forest, woodland). The map showing the vegetation of the study area is based upon the regrouped map of (Faulks, 1998b) (Figure 3.4).

The dominant vegetation type occurring in the study area is Eucalypt Woodland with an understory of grass. Woodlands include trees up till 30 m high and density of 10-30%.

Open forest consists of eucalypt forest dominated by *Eucalyptus tetradonta* and *Eucalyptus miniata*, with the main understorey perennial grass species *Thedema australis*, and *Sorghum plumosum, Sehima nervosum* (Aldrick and Robinson, 1972).
Figure 3.5 Vegetation structure of the Fergusson River catchment (Source: Faulks, 1998b)
### Table 3.1 Vegetation description of the study area (Source: Faulks, 1998b)

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Vegetation Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Forest</strong></td>
<td><em>E. miniata</em> (Darwin Woolly Butt), <em>E. tetrodonta</em> (Stringybark) open-forest with <em>Sorghum</em> (Sudangrass) grassland understorey</td>
</tr>
</tbody>
</table>
| **Woodland**    | *E. bleeseri* (Variable-barked Bloodwood), *E. Dichromophloia* (*E. Ferruginea*)  
*E. latifolia* (Round-leaved Bloodwood), *E. miniata* (Darwin Woolly Butt), *E. papuana* (Ghost Gum), *E. Patellaris* (Weeping Box), *E. Polycarpa* (Swamp Bloodwood), *E. tectifica* (Northern Box), *E. tetrodonta* (Stringybark)  
*E. terminalis* (Inland Bloodwood) grassland understorey  
*Chrysopogon fallax* (Golden Beared Grass), *Sehima nervosum* (white Grass), *Plectrachne pungens* (Hummock Grass), *Sorghum* (Sudangrass). |
| **Low Woodland**| *E. chlorophylla* (Glossy-leaved Box), *E. Dichromophloia* (Variable-barked Bloodwood), *E. Microtheca* (Ghost Gum),  
*E. terminalis* (Inland Bloodwood), *E. Tintinnans* (Salmon Gum), *Excoecaria parvifolia* (Milky Mangrove), *E. pruinosa* (Silver Box) grassland understorey  
*Eualia aurea* (Silky Browntop), * Dichanthium* (Bluestem), *Chrysopogon fallax* (Golden Beared Grass), *Sehima nervosum* (white Grass), *Plectrachne pungens* (Hummock Grass), *Sorghum* (Sudangrass). |
| **Melaleuca**   | *Melaleuca viridiflora* (Broad Leaved Paperbark), Eucalyptus low open-woodland with *Chrysopogon fallax* (Golden Beared Grass) grassland understorey |

### 3.6 Climate

The Fergusson catchment is located in the monsoon tropics with two distinct seasons: dry season (May to September) and wet season (November to March) while April and October are transitional months. October and November are hot and humid and referred to as the ‘build up’ with mean relative humidity ranging from 66% at 9:00 a.m. and 37% at 3:00 p.m. There is not much variation in temperature through the year. The average annual maximum temperature is 34°C and the mean minimum is 20°C. The wet season is characterised by intense rainfall with thunder, lightning, tropical showers, fluctuations in the monsoon trough and occasional tropical cyclones (Bauer, 1964). The mean annual rainfall in this region is 1009 mm of which
nearly all falls in the wet season. The mean monthly rainfall ranges from 0.1-245.9 mm for Katherine.

**Table 3.2 Summary of climate data for the Katherine region. Source: (BOM, 1997)**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Daily Min-Max Temp. Range (°C)</td>
<td>20.4 – 34.3</td>
</tr>
<tr>
<td>Mean 9am Relative Humidity (%)</td>
<td>66</td>
</tr>
<tr>
<td>Mean 3pm Relative Humidity (%)</td>
<td>37</td>
</tr>
<tr>
<td>Mean Annual Rainfall (mm)</td>
<td>1,009.3</td>
</tr>
<tr>
<td>Mean Monthly Rainfall Range (mm)</td>
<td>0.1 – 245.9 (June – Feb)</td>
</tr>
<tr>
<td>Highest Recorded Daily Rain (mm)</td>
<td>128.5</td>
</tr>
<tr>
<td>Mean Number of Rain Days</td>
<td>79.8</td>
</tr>
</tbody>
</table>

Almost 90% of rainfall occurs during November to March and the dry season experiences very low rainfall. As a result, all understory vegetation and native grass dries out in the dry season and becomes fuel for fire and the catchment experiences high frequency of fire during the late dry season.

### 3.7 Landuse/Landcover

The Department of Infrastructure, Planning and Environment, Northern Territory Government, have developed a landuse/landcover map (NRETAS, 2008). Landuse/landcover information plays a significant role in natural resource management and planning. Mapping of landuse/landcover in Northern Territory is based upon the principles and methods adopted by the Bureau of Rural Sciences, Canberra (BRS, 2002). The landuse classification scheme incorporates the use of the Australian Land Use and Management (ALUM) Classification scheme. Owen and Meakin (2003) described the landuse/landcover classes used for landuse/landcover mapping of the Northern Territory. Land use information was collected through fieldwork, aerial photos, satellite image interpretation, local knowledge and ancillary digital datasets. Berghout et al., (2008) revised the landuse mapping for problem areas to produce an up to date landuse/landcover map for the Northern Territory.

Grazing of natural vegetation is the dominant landuse/landcover class in the study area. It includes areas with woody vegetation or native cover managed privately for
domestic stock, where the structure of native vegetation is intact. The second dominant class is Residual Native Cover attributed to the areas where natural land cover is present and there is no other prime use. Photo interpretation was insufficient to confirm whether grazing is occurring on natural vegetation cover so digital cadastre data was used to map the pastoral lease properties. Natural woody vegetation on these pastoral leases was described as ‘Grazing Natural Vegetation’, and the natural woody vegetation outside pastoral leases was described as ‘Residual Native Cover’.

‘Grazing Modified Pasture’ are areas where land use has changed the native vegetation substantially. Past and recent imagery was compared, and, where the satellite images showed different information, these areas were placed in this class. ‘Land in Transition’ is used to classify those areas where the change in landuse was in transition or landuse has recently changed. ‘Rural Residential’ is mostly hobby farms, that is, small areas used for residential purposes, small orchards, horses and other domestic animals. Government zoning plans and size of rural allotments were used to confirm the hobby farms. Rural blocks containing at least 90% native vegetation were assigned to ‘Rural living’. ‘Cropping’ is part of a crop/pasture or other rotation system, and has been classified according to the use at the time of mapping. ‘Traditional Indigenous uses’ are self explanatory and involve a variety of practices including burning.
Figure 3.5 Landuse/landcover of the Fergusson River catchment (Source: Owen and Meakin, 2003)
3.8 Topography and Drainage Network

The Fergusson River flows generally southwest. It originates at an elevation of 296m and joins the Daly River at an elevation of 54m. The Fergusson River catchment includes seven creeks and rivers, namely (ordered by descending elevation): Wandie Creek, Driffield Creek, Cullen River, Eight Mile Creek, Edith River, Bondi Creek and Polly Creek. The Fergusson River falls around 242m over its 144km length, with an average gradient of 0.00168.

The drainage pattern of a catchment often reflects the underlying geology while drainage density of a catchment is associated with the amount of rainfall and regolith type. The drainage pattern of the Fergusson catchment is dendritic, which develops in regions underlain by relatively homogeneous material that has a similar resistance to weathering and erosion so there is no apparent control over the direction of channels (LCCRS, 1989) (Figure 3.6), despite difference of geology (Figure 3.3).

The Fergusson River flow is groundwater fed during the dry season (Christian and Stewart, 1953). Chin (1995) has reported the minimum discharge between the gauging stations at Dorisvale and Beeboom crossing (distance 120km) as 12 m$^3$/sec.

Mean Annual discharge for the Fergusson River in 1957 was 4.4 × 10$^5$ Ml while minimum and maximum discharges were 0.7 × 10$^5$ and 12 × 10$^5$ Ml respectively (Jolly, 2001).

3.9 Summary

The study area, the Fergusson River catchment is one of the major subcatchments of the Daly River catchment and is typical of the wetter part of the catchment in terms of hydrology and ecology, and has a lot of gullies; therefore the study site is chosen for research. The study area consists of various physiographic divisions; including, hills, low hills, rises, plateau, and plain. Major geological units in the study area include Jindukin formation, cretaceous sediments, alluvium and colluviums. Major soil groups are, Elliott (Florina) shallow Loamy Yellow Earths; minor Jindabeth (Jindare), Sandy Yellow Earths, which are poorly drained soils with very slow runoff. The mean annual rainfall in the area is 1009.3mm. The dominant vegetation type in the study area is Eucalypt Woodland with an understory of grass. Major landuse/landcover in the study area includes, ‘grazing natural vegetation’, ‘residual
Figure 3.6 Digital elevation model and drainage network of the Fergusson River catchment
native cover’, and ‘grazing modified pasture’. The spatial layers describing geology, soil, landuse/landcover, vegetation, and slope are used for GIS based overlay analysis of gully control factors in Chapter 6.
Chapter 4: Method
Chapter 4: Method

4.1 Introduction

This chapter outlines the geoinformatics based framework developed for mapping the three dimensional (3D) characteristics of gullies identified in this thesis. More specifically, the methods used for processing Cartosat-1 stereo imagery and historical stereo aerial photographs and deriving Digital Surface Models (DSMs) from these data sources are described. The chapter also delineates the methods applied in this thesis for the calculation of gully erosion volume.

4.2 Geoinformatics Based Framework for Gully Erosion

A methodological framework based on geoinformatics (Figure 4.1) is developed to map gullies in 3D and calculate gully erosion volume. The framework is composed of several components including geospatial data, tools and techniques for 3D mapping and analysis of gully erosion. These components are discussed briefly below and the detail of these and how they are combined is discussed at length throughout this chapter.

4.2.1 Geospatial Data

Input datasets used in the model consist of topographic sheets (1:20000), Cartosat-1 stereo imagery (2.5 m spatial resolution), a 1-second DEM (~30 m resolution), and gully measurements based on airborne and ground surveys, ancillary data, DGPS measurements and historical stereo aerial photographs (1:30000). The framework integrates the geospatial datasets, which enables one to map gullies and provide a holistic view of gully erosion phenomena.

4.2.2 Tools & Techniques

The framework uses the standard tools (i.e. ArcGIS, ‘Image Analysis for ArcGIS’ and ‘Stereo Analyst for ArcGIS’). Techniques used in the framework are based on well developed concepts and standard methods of photogrammetry. The Rational Polynomial Coefficient (RPC) model (detail in section 4.3.2.1.2) is a validated and standardized sensor orientation model for high resolution satellite imagery that has been used for creating oriented images (Fraser et al., 2006). The single space resection method along with affine transformation has been used for image
Figure 4.1 Geoinformatics based framework to quantify gully erosion
processing. Stereo viewing is based upon an epipolar resampling method that provides the best possible 3D view. Image processing (details in sections 4.3.2, and 4.4.2), DSM generation (detail in section 4.3.3) and 3D gully mapping (detail in section 4.3.4 and 4.4.3) are based upon standard processes of Photogrammetry, and results produced are also in standard format (e.g. shape file) which gives the possibility of integration with other datasets for further analysis.

4.2.3 Three Dimensional Gully Mapping

3D gully mapping directly from a DSM, by storing geographic location (latitude, longitude) and elevation information is a unique characteristic of the framework. Stereo features can be collected through an automated or semi-automated way, which provides the possibility of creating a spatial database, by storing the spatial information (x, y, z) and attributes of gullies. Gully dimensions (length, width, depth, area, volume) can also be measured and this information is helpful to understand gully morphology and explore the gully dynamics.

Editing of existing mapped gullies and updating of gully attributes in a spatial database is possible in a user friendly way, so updates of gully erosion can be maintained easily.

4.2.4 DGPS Survey

A DGPS survey was carried out to measure the accuracy assessment of mapped gullies. Survey results showed that horizontally sub pixel level and 1 pixel level accuracy was attained vertically (section 4.3.5). A DGPS survey gives the possibility of collecting field measurements of gullies relating to headcuts, position and retreat.

4.3 Three Dimensional Mapping of Gullies Using Cartosat-1 Stereo Imagery

This section explores the use of Cartosat-1 imagery for 3D gully mapping and evaluates the suitability of this new dataset for measuring the morphometric characteristics of gullies. The methods are described to: (a) process Cartosat-1 imagery to generate a DSM; (b) identify and map gullies in 3D, and (c) develop a 3D spatial database of the morphometric characteristics of gullies.
4.3.1 Cartosat-1 Optical Stereo Satellite Imagery

Cartosat-1 stereo satellite images are used for 3D gully mapping, due to their image quality and accuracy (Crespi et al., 2007; Baltsavias et al., 2008). The spatial resolution (2.5 m) of Cartosat-1 is quite suitable to map gullies at large scale. Field observations show that most of gullies in the study area are larger than 6.25m² and that very few are smaller than this and therefore will be a negligible sediment source. High accuracy, optimal spatial resolution, 10 bit radiometric resolution and availability of Cartosat-1 imagery make it a cost effective solution in terms of time and money for gully mapping at a catchment as well as at a site scale.

Despite various advantages of using stereo imagery, their geometry is difficult, because it is based upon stereo pairs which are captured from two different angles, so a slight difference in the processing of geometric correction can lead to errors, therefore, it is necessary to understand the models that have been used in the acquisition of Cartosat-1 imagery that provide a basis to process the images in a logical way.

4.3.1.1 Rigorous Sensor and Rational Function Models

Geometric distortions of imagery are caused by topographic variation, camera geometry, and sensor-related errors. These distortions need to be corrected prior to any remote sensing application. Image orientation and orthorectification are logical procedures to correct geometrical distortions incorporating two main methods: Rigorous Sensor Model (RSM) and Rational Function Model (RFM) (Ahn et al., 2002).

The Rigorous Sensor Model (RMS) is based upon fundamental photogrammetric collinearity conditions that describes the transformation among image coordinates (2D image space, i.e. x and y on image), ground coordinates (3D object space, i.e. latitude, longitude, elevation), and orientation parameters. The basic purpose of the rigorous models is to provide a simple ground to image relationship of the physical camera. Rigorous models include interior (i.e. focal length of camera, pixel size, lens distortion, principal point) and exterior orientation parameters (i.e. roll, pitch and yaw) (detail in section 4.4.1.2) (Leica-Geosystems, 2006).
The Rational Functional Model (RFM) is a general polynomial model which uses the ratio of two polynomial functions to describe the transformation between image coordinates and ground coordinates. The image coordinates and ground coordinates are each offset and scaled to have a range of −1.0 to +1.0 over an image segment (Grodecki and Dial, 2003). The parameters of the RFM, which are derived from a rigorous sensor model and supplied with the imagery are termed Rational Polynomial Coefficients (RPCs) (Grodecki and Dial, 2003; Poon et al., 2005). The RPC model has been universally accepted, and validated, and is becoming a new standard for sensor orientation models for high-resolution satellite imagery (HRSI) (Fraser et al., 2006). The RPC model forms the coordinates of the image space scanline and number (S, P) as a ratio of the cubic polynomials in the coordinates of the world or objects space or ground point. Each scan line number can be expressed as a function of ground coordinates in terms of the ratio of cubic polynomials.

Taking into account object space coordinates \((x, y, z)\) (where \(x\) is geodetic latitude, \(y\) is geodetic longitude and \(z\) is height above the ellipsoid) and latitude, longitude, and height offset scale factors (LAT OFF, LONG OFF, HEIGHT OFF, with LAT SCALE, LONG SCALE, HEIGHT SCALE), the calculation of image-space coordinates begins by normalizing latitude, longitude, and height as follows:

\[
X = \frac{x - \text{LAT}_{\text{OFF}}}{\text{LAT}_{\text{SCALE}}} \tag{4-1}
\]

\[
Y = \frac{y - \text{LONG}_{\text{OFF}}}{\text{LONG}_{\text{SCALE}}} \tag{4-2}
\]

\[
Z = \frac{z - \text{HEIGHT}_{\text{OFF}}}{\text{HEIGHT}_{\text{SCALE}}} \tag{4-3}
\]

The normalized scanline and pixel number in image space coordinates (S, P) are calculated from the relevant rational polynomial function (Grodecki and Dial, 2003).

\[
S = \frac{P_a (X,Y,Z)}{P_b (X,Y,Z)} \tag{4-4}
\]

where \(P_a (X, Y, Z) = a_1 + a_2 Y + a_3 X + a_4 Z + a_5 YX + a_6 YZ + a_7 XZ + a_8 Y^2 + a_9 X^2 + a_{10} Z^2 + a_{11} XYZ + a_{12} Y^3 + a_{13} YX^2 + a_{14} YZ^2 + a_{15} Y^2X + a_{16} Y^2Z + a_{17} XZ^2 + a_{18} Y^2Z + a_{19} X^2Z + a_{20} Z^3 = a^T u \)
\[ P_\beta(X, Y, Z) = b_1 + b_2 Y + b_3 X + b_{13} YX + b_6 YZ + b_7 XZ + b_8 Y^2 + b_9 X^2 + b_{10} Z^2 + b_{11} XYZ + b_{12} Y^3 + b_{14} YZ^2 + b_{15} Y^2 X + b_{16} X^3 + b_{17} XZ^2 + b_{18} Y^2 Z + b_{19} X^2 Z + b_{20} Z^3 = b^T u \]

and

\[ u = [1 \ Y \ X \ Z \ YX \ YZ \ XZ \ Y^2 \ X^2 \ YZ^2 \ Y^2 X \ X^2 \ Y^3 \ YX^2 \ YZ \ X \ YX^2 \ YY^2 \ YZ \ X \ Y \ X^3 \ XZ^2 \ Y \ Y \ Z \ Z^3]^T \]

\[ a = [a_1, a_2, \ldots, a_{20}]^T \]

\[ b = [b_1, b_2, \ldots, b_{20}]^T \]

and

\[ P = \frac{P_\gamma(X, Y, Z)}{P_\varepsilon(X, Y, Z)} \] (4.5)

where \( P_\gamma(X, Y, Z) = c_1 + c_2 Y + c_3 X + c_4 Z + c_5 YX + c_6 YZ + c_7 XZ + c_8 Y^2 + c_9 X^2 + c_{10} Z^2 + c_{11} XYZ + c_{12} Y^3 + c_{13} YX^2 + c_{14} YZ^2 + c_{15} Y^2 X + c_{16} X^3 + c_{17} XZ^2 + c_{18} Y^2 Z + c_{19} YX^2 Z + c_{20} Z^3 = c^T u \]

and

\[ P_\varepsilon(X, Y, Z) = d_1 + d_2 Y + d_3 X + d_4 Z + d_5 YX + d_6 YZ + d_7 XZ + d_8 Y^2 + d_9 X^2 + d_{10} Z^2 + d_{11} XYZ + d_{12} Y^3 + d_{13} YX^2 + d_{14} YZ^2 + d_{15} Y^2 X + d_{16} X^3 + d_{17} XZ^2 + d_{18} Y^2 Z + d_{19} YX^2 Z + d_{20} Z^3 = d^T u \]

and

\[ c = [c_1, c_2, \ldots, c_{20}]^T \]

\[ d = [d_1, d_2, \ldots, d_{20}]^T \]

Using scanline and pixel offsets and scale factors (SCANLINE_OFF, PIXEL_OFF, SCANLINE_SCALE, PIXEL_SCALE), the de-normalized image-space coordinates (SCANLINE, PIXEL) can be expressed as:

\[ \text{SCANLINE} = S \cdot \text{SCANLINE\_SCALE} + \text{SCANLINE\_OFF} \]

\[ \text{PIXEL} = P \cdot \text{PIXEL\_SCALE} + \text{PIXEL\_OFF} \]
4.3.2 Processing of Cartosat-1 Stereo Images

Cartosat-1 stereo image processing involves steps and procedures necessary to remove geometric distortion and produce oriented image pairs which can be used for stereo visualization and mapping purposes.

4.3.2.1 Creating the Oriented Images

An oriented image incorporates the sensor model and spatial reference (projection and units) associated with it. A sensor model describes the 3D relationship between the image and Earth surface.

4.3.2.1.1 RPC Orthokit

Cartosat-1 stereo images were provided by ISRO as a Stereo Orthokit product comprised of geometrically raw but radiometrically corrected images in GeoTIFF format (Figure 4.2), an ancillary RPC file generated from ephemeris data, and a metadata file giving the description of the data. Typical image size is 12000 × 12000 pixels. The study area was covered by four stereo pairs; and they were captured in June & July 2008 (Table 4.1). The Stereo Orthokit product includes image data from both cameras; i.e. forward (Fore) and afterward (Aft) along with their corresponding RPCs.

Figure 4.2 Cartosat-1, non-oriented stereo pair
The Geo Orthokit is another form of Cartosat-1 product to supply geometrically correct images with relevant RPCs; but this product is still under consideration. Availability of this product will facilitate the user by saving processing time and enables direct usage of the product for various applications such as geomorphology, hydrology and landscape studies.

Table 4.1 Cartosat-1 stereo pairs used in the study area

<table>
<thead>
<tr>
<th>No.</th>
<th>Cartosat-1 Stereo Pair (Aft, Fore)</th>
<th>Path/Row</th>
<th>Date of Acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101A, 101F</td>
<td>855/456</td>
<td>05 June, 2008</td>
</tr>
<tr>
<td>2</td>
<td>201A, 201F</td>
<td>855/457</td>
<td>05 June, 2008</td>
</tr>
<tr>
<td>3</td>
<td>301A, 301F</td>
<td>856/456</td>
<td>03 July, 2008</td>
</tr>
<tr>
<td>4</td>
<td>401A, 401F</td>
<td>855/457</td>
<td>03 July, 2008</td>
</tr>
</tbody>
</table>

4.3.2.1.2 RPC based Orthorectification

Orthorectification is a procedure which converts imagery into map accurate form by removing distortion in spatial objects caused by topography, camera geometry, and sensor errors (Ford and Ogleby, 1997). RPC based orthorectification offers an efficient, accurate alternative to rigorous orthorectification. RPC orthorectification uses rational function information, provided by data vendors, to correct satellite imagery.

Cartosat-1 stereo images were processed using ‘Image Analysis for ArcGIS’ software (Booth-Lamirand, 2003), one of the extensions to standard GIS software ArcGIS. ‘Image Analysis for ArcGIS’ uses a Single Space Resection method for orthorectification (Booth-Lamirand, 2003). This method determines the exterior orientation parameters associated with one image, or many images, based on known Ground Control Points (GCP). Space resection is based on a least-squares solution of linearised collinearity equations (Kraus, 1993), which specifies that for any image the exposure station, the ground point and its corresponding image point, must lay along a straight line (Luhmann, 2009). Space resection requires only four control points for a unique solution, although three points are feasible when ambiguities can be solved through additional information such as a prior knowledge about the camera...
station coordinates. The method requires suitable approximate values of the six unknowns of exterior orientation (detail in section 4.4.1.2) (Kyle, 1990; Haralick et al., 1991).

Using the geo-correction functionality of the ‘Image Analysis software’, a RPC model was selected. Essential parameters include the GCPs, elevation, exterior and interior orientation information (Figure 4.3).

![Diagram](image-url)

**Figure 4.3 Creation of oriented images using RPC Method**

GCPs were gathered from topographic sheets at a scale 1:20000, and from the 1 second DEM (~30 m resolution) obtained from the Shuttle Radar Topographic Mission (SRTM) through Geoscience Australia (Geoscience Australia, 2007). The elevation range for each image was determined from the topographic sheets. Sensor exterior orientation parameters were taken from the RPC ancillary files provided by the data vendors. A second order Affine Transformation model (Falkner, 1995) was used for geo-correction. Although six GCPs are required using a second order affine transformation, the use of more GCPs enhances the accuracy level of the imagery.
Therefore 25-30 well distributed GCPs were used for each image for orthorectification.

Incorporating the above mentioned parameters, oriented images were created. Oriented images have the characteristics that they are oriented parallel to the direction of flight at the time of image capturing. Once oriented images are created, relevant orientation parameter information can be seen (Figure 4.4) on the oriented image tab (detail in Appendix B1).
Figure 4.4 Cartosat-1 (a) oriented stereo images of Fergusson River and (b) associated parameters

Figure 4.5 Study area covered by oriented stereo pairs of Cartosat-1 images
Four Cartosat-1 stereo pairs were processed in order to cover the study area (Figure 4.5). Boundaries of images are shown in red while the yellow boundary represents the overlapped image area with stereo view.

4.3.3 Digital Surface Model

Digital Surface Models (DSMs) are playing a significant role in object identification and the study of landforms, water resource management, forestry and geology (Baltsavias et al., 2008). DSMs depict the Earth’s topography inclusive of buildings and vegetation while DEMs provide a bare Earth model. The term DSM is generally applied regardless of whether the data are in gridded format as in the DEM or mass point format (Leica-Geosystems, 2006).

‘Stereo Analyst for ArcGIS’ (Leica-Geosystems, 2006) is an extension to standard GIS software that allows the display of stereo images to create a DSM (Kornus et al., 2006). The Stereo Visualization mode of ‘Stereo Analyst for ArcGIS’ is based upon epipolar resampling, that uses rectified images to eliminate the stereo disparities and provide advantageous conditions for automatic image matching, DSM generation, and stereo measurement (Bang et al., 2003; Morgan et al., 2004; Kornus et al., 2006). As a result of using automatic epipolar resampling display techniques, 3D GIS data can be collected to a higher accuracy. ‘Stereo Analyst for ArcGIS’ automatically rotates, scales, and translates the imagery to continually provide an optimum stereo view throughout the stereo model. Using OpenGL software, ‘Stereo Analyst for ArcGIS’ automatically accounts for the tilt and rotation of the two images as they existed when the images were captured (Curry, 2003).

Stereo viewing allows the human brain to judge and perceive changes in depth and volume. A great benefit of stereoscopic vision is a 3D representation of the Earth’s surface, which enables interpretation, measurement, and mapping of features in 3D. The use of along track stereo geometry and a short time lag between data acquisition of images forming the stereo pairs of Cartosat-1 images (detail in section 2.3.2.2.1, Figure 2.4) provides an improved basis for DSM generation. Oriented Cartosat-1 stereo images with 90% overlap between stereo pairs (Figure 4.6) were displayed in ‘Stereo Analyst for ArcGIS’ for stereo view (see appendix B2 for 3D view of DSM of upstream and downstream of Fergusson River). The DSM of the Fergusson River area provides a clear 3D view of the interrelationship between features and real
Figure 4.6 Digital surface model, anaglyph/stereo view
Note: Forward and Afterward images at left and right at the bottom of stereo window. 3D visualization of DSM can be seen using anaglyph/stereo glasses ( )
world objects. The DSM allows identification of various geomorphic features, and the 10 bit radiometric resolution of Cartosat-1 enhances the identification of gullies (Appendix B2 for 3D visualization of upstream and downstream of the Fergusson River). Depth information permitted gullies and bare soil patches to be distinguished, which is not possible in 2D. Another advantage of a DSM is the Earth surface information (e.g. vegetation, landcover) which provides additional insight into the landforms and associated processes which is not possible with a DEM.

4.3.4 Three Dimensional Mapping of Gullies

Digital photogrammetric techniques used in ‘Stereo Analyst for ArcGIS’ extend the perception and interpretation of depth to include the measurement and collection of features by storing relevant coordinates (latitude, longitude, height) in an interactive way. Gullies were mapped in a semi automated way, where the spatial information was ‘hand digitised’ utilizing the functionality of the ‘terrain following mode’ while the height information was automatically populated using the ‘3D floating cursor’ in
Figure 4.7 Three dimensional gully mapping (a) 2D view of gullies (b) stereo window with 3D view of gully

Note: Stereo window with 3D view ( ) at upper right corner and Fore and Aft images at the bottom. Mapped gullies with associated attribute table containing geometric information in small window at left side.

‘Stereo Analyst for ArcGIS’. Gullies were mapped in 3D directly from a DSM in a user friendly environment (Figure 4.7). Advantages of the DSM are discussed in section 4.3.3. The ‘terrain following mode’ works on the principle of image correlation and maintains the position of a 3D floating cursor on the ground and feature of interest, hence making it easy to collect 3D points.
4.3.5 Accuracy Assessment

Various studies have been conducted for Cartosat-1 data evaluation. Lehner et al (2006) reported that Cartosat-1 imagery is well suited for DSM generation and orthoimages, with half a pixel lateral and 1-2 pixel vertical accuracy in terrain with good pattern matching characteristics and moderate slope angles. Crespi et al (2007) showed that good orientation with horizontal and vertical accuracy at sub-pixel level, for Cartosat-1, can be obtained with a rigorous RPC model with corrections of order 1 (affine transformation). In this regard, DSM extraction from Cartosat-1 stereo pairs indicate that Root Mean Square Error (RMSE), of 1 to 2 pixels can be achieved with commercial and scientific image matchers, with smoothing effects over urban zones. Accuracy assessment for the Fergusson DSM was performed for mapped gullies with a DGPS. Various GCPs were checked with the Cartosat-1 generated DSM in different topographic settings; at gully headcuts, creek and path junctions, gully bottoms, hilltops (Figure 4.8, Figure 4.9, Figure 4.10, and Figure 4.11).

Figure 4.8 Author is recording DGPS readings at headcut near the Fergusson River, a little off the Stuart Highway
Figure 4.9 Author and Prof. Bob Wasson after setting the DGPS base station (near cross section of path and small creek in the Fergusson River catchment)

Figure 4.10 Author recording elevation points with DGPS Rover (Hilly terrain in the upstream of the Fergusson River catchment)
Data verification checks showed the DSM is of good quality. Accuracy level was high on plains as compared to hilly terrain. Overall the absolute accuracy of the DSM of the Fergusson River is sub pixel level planimetrically and 1 pixel level vertically. This accuracy is the absolute accuracy of the DSM and is consistent with the accuracy obtained for Maussane-les-Alpilles (Nogueras et al., 2000) Cartosat-1 DSM by Baltsavias et al (2008).

Relative accuracy within gullies has also been determined using check points located across randomly selected gullies using the DGPS. It has been found that relative accuracy is quite consistent within gullies. Based on the differences of GCPs (latitude, longitude, elevation) and gully measurements from DGPS survey (see Appendix B6 for more detail on field verification data), it is observed that there is not much difference in position of gullies but at some points where relief variations were high, difference in elevation is identified, that can generate approximately 10% error in volume calculation.
4.4 Three Dimensional Mapping of Gullies Using Historical Stereo Aerial Photographs

Aerial photographs are an excellent record of landscape features. Aerial photographs can be used to obtain important information about the condition and state of spatial features in the past (see section 2.3.2.1). They are particularly useful in geomorphologic studies which involve the description and behaviour of landforms over time (Mulders, 1987; Lucas et al., 2002). Historical aerial photographs can be used in conjunction with other maps and satellite imagery to trace changes in vegetation, landuse/landcover, and geomorphic features (Ebert et al., 1989).

Stereo aerial photographs provide a way to observe natural phenomena in 3D (detail in section 2.3.2.1.1). Stereo aerial photographs can also be compared with stereo satellite images to provide a quantitative analysis of change in both the spatial (size, shape and distribution) and 3D (depth/height and volume) properties of a landscape.

This section focuses on retrieving historical information on gully erosion from historical stereo aerial photographs. The processing of the aerial photographs, including the method used to orthorectify the images without a camera calibration report, creation of a DSM and 3D gully mapping are described.

4.4.1 Stereo Aerial Photographs

This section describes the geometry and relevant parameters of stereo aerial photographs. It provides a summary of the interior and exterior orientation of the camera model used to capture the images.

4.4.1.1 Interior Orientation

Interior orientation describes the internal geometry of the camera at the time of image capture and develops a relationship between the camera model and the aerial photograph. The internal geometry of the camera can be illustrated in terms of the principal point, focal length, fiducial marks and lens distortion (Figure 4.12). The principal point is the point where a perpendicular projected through the centre of the lens intersects the photo image. The length from the principal point to the perspective centre is called the focal length (Wang, 1990). The principal point plays a key role in determining the focal length and radial distortion in aerial photographs; and it is used
in operations such as aerial triangulation and construction of epipolar images (Morgan et al., 2004).

Fiducial marks establish the relationship between the image space coordinate system and pixel or file coordinate system (Leica-Geosystems, 2006). The fiducial marks are located in the camera body and are exposed to the film at the time of image acquisition of each photograph (Falkner, 1995). 2D affine transformations can be used to define the relationship between the pixel coordinate system and the image coordinate system (Leica-Geosystems, 2006).

![Figure 4.12 Interior orientation variables associated with internal geometry of the camera (Leica-Geosystems, 2006)](image)

Note: Principal point and image point are represented by o and a, respectively.

During the process of image capturing light rays passing through the lens, are bent and change direction. The result in the deviation of the image plane from normal is called lens distortion. Two kind of lens distortion occur: radial distortion and tangential distortion (Figure 4.13). The radial distortion ($\Delta r$) is derived from the perspective centre of the lens, and causes distortion of the objects in the image along radial lines from the principal point, and it is also known as symmetric lens distortion. The tangential distortion ($\Delta t$) occurs at right angles to the radial lines from the principal point. Since tangential lens distortion is much smaller than radial lens distortion, it is considered insignificant.
Figure 4.13 The radial distortion and tangential lens distortion (Leica-Geosystems, 2006)

The following polynomial can be used to approximate the effect of radial distortion by determining the coefficients associated with radial lens distortion (Wolf, 1983):

$$\Delta r = k_0 r + k_1 r^3 + k_2 r^5$$  \hspace{1cm} (4-6)

In the above equation $\Delta r$ represents the radial distortion along the radial distance $r$ from the principal point. The lens distortion is measured in the laboratory and is provided in the camera calibration report.

### 4.4.1.2 Exterior Orientation

The exterior orientation of a camera defines the position of the camera in space and view direction (Figure 4.14). The exterior orientation can be described by six parameters; the three spatial coordinates of the camera station and three angular measurements that define the spatial orientation of the image plane. Positional elements ($X_0$, $Y_0$, and $Z_0$) of the exterior orientation define the perspective centre ($o$) with respect to the ground coordinate system ($X$, $Y$, and $Z$). Camera height above sea level is represented by $Z_0$ and is usually defined by a sea level datum.
The angular or rotational elements ($\omega$, $\varphi$, $\kappa$) describe the relationship between the ground space coordinate system (X, Y, Z) and the image space coordinate system (x, y, z). Using the rotation angles the relationship between the image space coordinate system and the ground space coordinate system can be determined in the form of a 3x3 matrix; referred to as the orientation or rotation matrix, $M$ (Wang, 1990).

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

### 4.4.2 Processing of Stereo Aerial Photographs

In order to use stereo aerial photographs for gully mapping, it is important to have accurate geometry defined for each image. This is achieved through...
orthorectification of aerial photographs, and methods applied in this thesis are described below:

4.4.2.1 Data acquisition

The National Mapping and Information Group of Geoscience Australia hold the collection of Commonwealth photography flown by the RAAF (detail in section 2.3.2.2.1), Division of National Mapping, Bureau of Mineral Resources and the Australian Surveying and Land Information Group (AUSLIG) (Geoscience Australia, 2008).

Figure 4.15 Stereo aerial photograph pair from 1948, Fergusson River
Note: Photo number (5043 & 5074), survey no (342), aircraft run number (4), date of photograph (24-04-1948), focal length (153.9 mm) and altitude (15000 feet) of aircraft at left side strip.

Stereo aerial photographs (Figure 4.15) from 1948 of the Fergusson River catchment were acquired from the Department of Natural Resources, Environment, The Arts and Sport (NRETAS), Northern Territory. Flight diagrams which show aircraft flight paths or runs are held for 80% of the collection. Details such as photo number, run numbers, camera type, focal length, height and date are included on the flight diagrams (detail in Appendix B3). However, no camera calibration report was available for the data, therefore a major challenge was to accurately orthorectify the stereo aerial photographs without a camera calibration report in order to map the historical gullies and allow comparison with the Cartosat-1 derived gully mapping. Thirty six stereo aerial photographs were scanned at a resolution 600 dot per inch (dpi) using MicroTEC, ScanMaker-TMA-1000XL for digital photogrammetric processing and measurements.
4.4.2.2 Camera Model Based Orthorectification

Stereo aerial photographs were orthorectified in ‘Image Analysis for ArcGIS’ using the camera model that use, GCPs, a reference DEM, fiducial marks, interior and exterior parameters (Figure 4.16).

![Camera model based orthorectification diagram]

The camera model is derived from the concept of space resection; a non-linear method based on the least squares solution of linearised collinearity equations. The objective of space resection is to calculate the pixel coordinate of a point on an image from its ground coordinates. The space resection method works with four GCPs to generate orthoimages. However, three points can also provide a solution to solve ambiguities in combination with camera coordinate knowledge (Kyle, 1990; Haralick...
et al., 1991). The camera model in ‘Image Analysis for ArcGIS’ includes the parameters associated with specific camera models such as the Wild camera, RC30 camera, and Zeiss RMKA (FMC), with associated principle points and focal lengths. Prior to any processing, knowledge of camera type is an important step. The information available on flight diagrams states that a K-17 camera was used for image capture. Though, identification of fiducial marks on the middle of the edges of aerial photographs, and exploring the details of aerial cameras commonly used in the 1940s (appendices B4, and B5), it became clear that the stereo aerial photographs of the Fergusson River were captured by a Fairchild camera (K-17). The camera model in ‘Image Analysis for ArcGIS’ does not include that particular camera type. Therefore, interior orientation parameters (principal point, fiducial marks of the frame camera) were derived from the aerial photographs themselves or accompanying information. The focal length (i.e. 153.9 mm) of the camera was given on the flight line diagram. The principal point is the intersection of a perpendicular line through the perspective centre of the image plane. This point corresponds to the centre of a photograph, and therefore can be given the value x = 0 and y = 0 and identified by the intersection of perpendicular lines from the corners and middle of the sides of individual photographs (Figure 4.17).

Fiducial orientation defines the relationship between the image/photo coordinate system of a frame and an actual image orientation, as it is displayed in a view. The image/photo coordinate system is defined by the camera calibration information. The orientation of the image is largely dependent upon the way the photograph was scanned during the digitization phase. Fiducial marks are fixed on the frame, visible in each exposure, are used to compute the transformation from data files to image coordinates. The coordinates of the fiducial marks can be measured by ruler on the hardcopy photograph by taking the origin of the coordinates at the point where diagonal lines connecting fiducial marks meet. It is recommended that the y-axis should be taken in the direction of the photo title strip.
A vertical and horizontal distance between fiducial marks was measured and coordinates were defined (Table 4.2). A camera file was generated for the Fairchild (K-17) camera comprising the Film X and Film Y or fiducial coordinates and was used for orthorectification.

Elevation information is required to remove relief displacement in the aerial photographs, so the 1_second SRTM DEM (~30 m resolution) was used as a reference DEM. GCPs in photogrammetry are an essential part of producing accurate exterior orientations, DEMs and orthophotos (Lucas et al., 2002). In an ideal situation the coordinates of GCPs should be determined in the field at the time of image acquisition but considering the historic nature of photographs the GCPs for orientation were determined from Cartosat-1 oriented images. The alignment of these two image source is also important for accurate change detection. More than
four (5-6) GCPs were used for each photograph. Georeferencing was performed using the 2D affine transformation with a RMSE of 0.01-0.2.

Table 4.2 Coordinate values of fiducial marks

<table>
<thead>
<tr>
<th>No</th>
<th>Film X (mm)</th>
<th>Film Y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>w/2</td>
</tr>
<tr>
<td>2</td>
<td>-h/2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>-w/2</td>
</tr>
<tr>
<td>4</td>
<td>h/2</td>
<td>0</td>
</tr>
</tbody>
</table>

Exterior orientation parameters were determined by utilising the space resection technique based upon known GCPs. The process of space resection works on the assumption that interior orientation parameters are available and at least 3 GCP’s are present in each photo. ‘Image Analysis for ArcGIS’ allows the computation of exterior orientation either by using the values for six exterior orientation parameters or otherwise by selecting the option “account for earth curvature”. In this way photographs were orthorectified in a logical way based on interior orientation parameters and a space resection based method incorporating the GCPs. All the stereo photographs covering the gullied area were orthorectified and overlayed on oriented Cartosat-1 stereo images (Figure 4.18). It was noticed that linear features such as streams and tracks were well aligned between pairs of stereo aerial photographs. Features such as rocks and hills were observed carefully and no distortion in these features was seen.
Figure 4.18 Orthorectified historic stereo aerial photographs overlayed on oriented Cartosat-1 stereo images
4.4.3 Three Dimensional Visualization and Mapping of Gully Erosion

Orthorectified pairs of stereo photographs were displayed in ‘Stereo Analyst for ArcGIS’ to create a stereo model using two overlapping images. Photogrammetric techniques in ‘Stereo Analyst for ArcGIS’ extends the perception and interpretation of depth to include the measurement and collection of 3D information. The stereo model, from 1948 orthorectified stereo photographs of the Fergusson River was created, which enables the 3D view (Figure 4.19) and 3D mapping of gullies with a higher degree of accuracy than in 2D with a single image. By utilizing the 3D mapping techniques within ‘Stereo Analyst for ArcGIS’ gullies were mapped from the stereo model based upon pairs of stereo photographs.

Figure 4.19 Orthorectified stereo pair in anaglyph/stereo mode for 3D features collection
Note: Left and Right image, observe the overlapped area. Use stereo/anaglyph glasses ( ) for 3D view.
4.5 Calculating the Volume of Gullies from Cartosat-1 Stereo Images and Stereo Aerial Photographs

Gullies along the Fergusson River are mapped in 3D from Cartosat-1 and stereo aerial photographs. Relevant attributes of gullies such as area, and length of each gully were calculated using the ‘field calculator’ in ArcGIS. Digitized gullies in the 3D environment contain 3D (latitude, longitude, elevation) coordinates for each vertex in a polygon (detail in section 4.3.4). The average depth for each gully from both 1948 and 2008 datasets was measured using elevation differences among vertices of each polygon. Gully volumes were calculated by multiplying gully area and depth information for 2008 (Figure 4.20) and 1948 (Figure 4.21). Volume changes were measured by subtracting 1948 gully erosion volumes from the 2008 gully volume.

Figure 4.20 Gully volume, area and depth information from Cartosat-1 stereo satellite images
4.6 Application of Geoinformatics Based Framework

3D visualization of a DSM provides the possibility to observe the shape of mapped gullies and to understand the characteristics of the gullies. The framework described helps to identify the spatial distribution of gullies in the study area, which is important to understand the gully erosion processes. This information is linked with ground evidence based upon field surveys to find gully formation processes in the Fergusson River catchment and gully classification is performed (see section 5.3 for detail).

The framework is used to calculate gully erosion rates and volumetric measurements (detail in section 4.4). The approach integrates the historical stereo aerial photos with recent stereo satellite images because the use of satellite images for covering large areas is cost effective and also saves processing (i.e. orthorectification) time when compared with the use of recent aerial photographs.

This approach not only allows the 3D visualization of gullies but also allows mapping and measurement of sediment production from each gully class. The
technique for 3D gully measurement offers an efficient way to determine gully sediment production in remote locations and offers a way to avoid lengthy and time consuming field surveys.

The Geoinformatics based framework also provides a basis from which to determine the spatio-temporal changes of gullies. Gully growth is determined by overlying orthorectified stereo aerial photographs on oriented Cartosat-1stereo images. Change in position of gully heads is determined using the ‘measuring tool’ in ArcGIS, and gully retreat rates are calculated. In order to understand the gully growth and development stages, gully initiation and age is estimated using two techniques; one is Optically Stimulated Luminescence (OSL) that is a reliable technique for dating fluvial deposits (Olley et al., 2004). OSL relies that daylight releases charge from light-sensitive traps in the defects in crystals such as quartz and feldspar. The release of trapped charge by light resets the OSL signal. When grains of quartz are buried and hidden from light, they begin to accumulate a trapped charge population due to the effects of ionising radiation. This trapped-charge population increases with burial time in a measurable and predictable way (Aitken, 1998). As a result, the time elapsed since sediment grains were buried can be determined by measuring both the OSL signal and sensitivity from a sample of sediment, and by estimating the flux of ionising radiation to which it has been exposed since burial (Olley et al., 2004; Rustomji and Pietsch, 2007) (see section 5.4.2 for detail). A second approach is using a curve representing gully growth as a function of time and shows that rate of gully growth decrease with time due to the decrease in gully contributing catchment area (Graff, 1977; Rutherfurd et al., 1997) (detail in section 5.4.2).

4.7 Summary

Cartosat-1stereo imagery is a useful data source for 3D mapping and for DSM generation. The 10 bit radiometric resolution allows for the identification of erosion features and adds to the cartographic potential of the sensor. The DSM generated from Cartosat-1 images provides a clear and interactive stereo view with depth information which allows gully identification and mapping. The spatial resolution of Cartosat-1 stereo imagery (2.5 m) permits the study of erosion features at both catchment and site scale. Stereo visualization and 3D mapping directly from the DSM is an efficient way to identify and map gullies. The direct 3D mapping method also allows the calculation of relevant 3D attributes of gullies which not only form a
strong basis for volume calculations but also supports further GIS based analysis, such as overlay analysis, to determine the relationship of gully occurrences with soil types and topographic factors.

Stereo aerial photographs are an excellent source of data to interpret map and delineate historic information about gully features. However, the processing of aerial photographs without a camera calibration report is a difficult task. Nevertheless, photogrammetric techniques and the availability of user friendly tools (Image Analysis and Stereo Analyst for ArcGIS) allow this difficult task to be accomplished. Interior orientation parameters can be derived by taking measurement on photographs and exterior orientation parameters can be computed based upon GCPs and earth curvature information. The space resection technique forms the basis for orthorectification of stereo images for 3D visualization and gully mapping.

A methodological framework has been developed based on the tools and techniques of geoinformatics. The framework is comprised of Cartosat-1 stereo imagery (2.5m spatial resolution), topographic maps (1:20000), a 1 second (~ 30 m) SRTM level 2 DEM, stereo aerial photographs of 1948 (1:30000) and DGPS data points. This framework permits the calculation of the gully erosion volume, and forms a basis for gully classification, erosion volume calculation, rate of erosion determination and age estimation.
Chapter 5: Gully Dynamics and Erosion Rate
Chapter 5: Gully Dynamics and Erosion Rate

5.1 Introduction

This chapter deals with the process of gully formation, classification, and gully dynamics in a spatial and temporal context. It reviews the gully formation and development processes. In order to develop an understanding of gully erosion processes and development in the Fergusson River catchment, an attempt is made here to integrate laboratory based experiments for measuring gullies, field surveys and knowledge of the study area. Gully classification in the study area is performed based upon gully shape, spatial distribution and erosion processes. Spatio-temoral change of gully erosion is described by illustrating the gully growth, retreat rates and initiation age. Gully initiation and age estimates are used as an instrument to understand the gully dynamics and to find the gully development stage. Sediments produced from each gully type are calculated. Specific Sediment Yield (SSY) is calculated for the study area and compared with global and regional datasets.

Aims of this chapter are: (a) identify the processes that lead to gully formation, and classify the gullies based upon morphology, spatial distribution and underlying erosion processes, (b) describe the dynamics of gullies in space and time, (c) quantify the amount of gully erosion and determine the rate of gully erosion, and (d) determine the SSY generated from gully erosion in the study area.

5.2 Gully Formation Processes and Classification

This section reviews the gully formation and development processes based upon laboratory experiments and reported literature.

Gully processes have been described from a range of angles and viewpoints, from hydraulics, agricultural and forest engineering, through to hydrology and geomorphology (Poesen et al., 2003). Therefore, attempts to define gully types and processes reflect this diversity of opinion and criteria. Heed (1974) argued that any contribution of knowledge towards defining gully types and process requires comprehensive field measurements and laboratory analysis.

Gully erosion normally involves a range of processes, including landsliding, surface flow; and subsurface flow (Morgan, 1995). Surface flow is the most common
mechanism of gully erosion and causes both incision and initiation of a gully and upslope retreat of the gully-head (Morgan, 1996), but gully growth down slope has also been reported (Moeyersons, 1991). Subsurface flow also contributes to gully formation (Bryan, 2000; Froese et al., 1999; Istanbulluoglu et al., 2005) and plays a critical role in erosion by interacting with surface runoff mechanisms.

Subsurface erosion processes consist of seepage, sapping and piping. Fox et al. (2007) elucidated the role of groundwater by using lysimeter (a device that isolates a volume of soil or earth between the soil surface and a depth given and includes a percolating water sampling system at its bottom) for noncohesive sediments (Figure 5.1). Results of the experiment demonstrate the stages of initiation of seepage, expansion of seepage and undercutting. Seepage and undercutting cause the removal of negative soil pore-water pressure and cause large scale sapping failure (Chu-Agor et al., 2007). Lysimeter experiments also show the stages of undercutting and bank failure, that includes the wetting front migration which further results in seepage erosion and subsequently tensions crack formation and finally undermining and bank collapse (Figure 5.2). Tension cracks are formed due to the combined forces of reduced cohesion by the removal of negative soil pore-water pressure and by undercutting. Seepage erosion does not occur as the individual motion of sand particles but rather as intermittent mass wasting along bank slope slip (long low gentle slope) surfaces (Chu-Agor et al., 2007).

Seepage erosion occurs in a variety of ways depending on the characteristics of various soils and layers of alluvium (Hagerty, 1991). The materials form several gradational series depending upon whether the material is permeable or impermeable (Kirkby and Chorley, 1967; Dunne, 1990). In permeable soils, water flows through a layer of loose grains and washes them away and is known as extrusion sapping (Milton, 1971). Headward advancement by any kind of undermining is called sapping. As such if the whole soil layer is removed by extrusion then the mechanism is called ‘extrusion sapping’ and the removal of small areas is called ‘extrusion tunnelling’ (Milton, 1971). Extrusion sapping and extrusion tunneling occur in several different forms depending on the location of the eroding layer in a gully head.
Figure 5.1 View of seepage erosion from outflow flume (a) including initiation of seepage flow, (b) expansion of seepage face, (c) initiation of seepage erosion, and (d) and (e) undercutting (Source: Fox et al. 2007 [Figure 3])

Figure 5.2 Typical time series of bank failure due to subsurface erosion including (a–c) migration of the wetting front, (d–e) seepage erosion, (h) tension crack formation, and (i) bank collapse (Source: Fox et al., 2007 [Figure 2])
Sapping can occur deep in the profile, known as basal sapping, and sometimes there are several erodible layers, and the mechanism is called ‘multiple extrusion sapping’. If sapping is in the A2 horizon, and an impermeable layer is in the B horizon, then seepage concentrates in the A horizon and causes loss of this horizon and is called ‘A horizon extrusion sapping’. Basal and multiple sapping cause collapse and A horizon sapping opens up the subsoil to attack by waterfall or rainsplash action and scouring. Sapping occurs in association with other erosion mechanisms. If no other mechanisms operate with A horizon sapping, then only the topsoil is washed away, and is called A horizon sheet sapping. The resultant erosion is similar to sheet erosion (Milton, 1971).

In impermeable soils, seepage causes cracks and follows burrows and rootholes. Seepage along these channels slowly sluices out material to form a cavity known as a crevice tunnel (Milton, 1971). Slaking and dispersion work in combination to accelerate this process. Sometimes, tunnels collapse deep in alluvial deposits and cause gully formation. In this situation it is difficult to identify the gully head.

Another common kind of sapping by crevice tunnelling is found in young soils on alluvium (Jenkin, 1986). This causes the soil to crack in columns in the upper part during summer and runoff from thunderstorms scours out tunnels along the cracks (Milton, 1971). During winter, column collapse causes gully widening and progress upslope. This mechanism is called tunnel-sapping in columnar alluvial soils. Tunnel sapping can also occur in marshy soils. Extrusion sapping and tunnelling can occur in permeable layers or in impermeable layers with cracks or holes. Another favourable condition for sapping is in the noncohesive material where seepage is plentiful (Fernández et al., 2008).

Development of tension cracks are caused by potential energy changes which are influenced by the variation in soil moisture content or in unsaturated condition, and by the development of undercut hollows mainly caused by stress release at the base of the gully head rather than seepage (Collison, 2001). Surface runoff fills the tension cracks and increases the pore water pressure that results in wall failure (Bull and Kirkby, 2002; Poesen et al., 2002). In this regard, the presence of tension cracks in gully side walls indicates gully widening (Oostwoud Wijdenes et al., 2000). Undercutting of gully walls is influenced by the processes such as plunge pool
erosion and concentrated flow that also cause tension cracks (Blong et al., 1982; Poesen et al., 2002; Vandekerckhove et al., 2001b).

Slumping occurs when soil or alluvial material is wet, making it heavier and weaker. Previous weak lines or old cracks cause block fall and if material becomes very weak a headwall collapse may occur in the form of slump or earthflow (Milton, 1971; Higgins and Lehre, 1990).

The results of experiments (Chu-Agor et al., 2007; Fox et al., 2007) and field based studies (Hagerty, 1991; Fernández et al., 2008) dealing with subsurface erosion processes such as seepage and sapping reveal that circular or semicircular topsoil depressions ranging from 1 to 2 m in diameter have been evidenced as being the result of subsurface erosion. These depressions are caused by the settling of the topsoil due to internal erosion of fine material by sapping erosion processes.

In many cases, the depressions are connected to tensions cracks and evolve into scarp or shallow slides. Subsurface flow undermines and internally erodes weathered bedrock at the boundary between the permeable and impermeable layers, causing the topsoil to collapse (Lobkovsky et al., 2004). Subsurface flow modifies the surface morphology, thus leading to runoff acceleration and increase of erosion near the depressions (Dunne, 1990).

Gully formation is caused by several processes which may occur singly or together and have impact on gully shape. Gully morphology reflects the underlying erosion processes (Heed, 1970). Gullies have been classified based upon their size, outline shape, cross section shape, stage of development, and location in a drainage basin (Radoane et al., 1995). Various criteria and schemes for gully classification are in use. Ireland et al (1939) classified gully heads into four groups: pointed, rounded, notched and digitated (fingerlike) where rounded and digitated and notched or V shaped is created by seepage. They also classified the long profile of gullies into four groups as inclined, vertical, cave, and cave with overhanging root mat or sod. Hilsky (1973) proposed that classification of gullies should be based upon gully side morphology, and forms of longitudinal and transversal profiles. Heed (1970) classified gullies based on their evolutionary stages into continuous and discontinuous. Imeson and Kwaad (1980) classified gullies into four classes according to both gully morphology and erosion processes.
The cross-sectional shape of gullies has also been used as an indicator of type, and inferences have been drawn as to the mechanisms operating, such as in Morocco (Imeson et al., 1982). Harvey et al. (1985) considered gullies as incised channels (e.g., rill, gully, entrenched channels) and proposed a classification based upon their size from smallest to largest. Crouch and Blong (1989) classified gully sides according to morphology and processes, and assessed erosion rates for each form in order to identify the major sediment sources within gully systems.

### 5.3 Gully Formation Processes and Classification in the Fergusson River Catchment

Several field surveys have been carried out to collect ground evidence for gully erosion processes operating in the study area. Different types of gullies have been examined in the field and various erosion processes are observed, including tension cracks, slumping, headcuts, surface runoff traces along headcuts and sediment transport in gully floors, and rilling of gully walls (Figures 5.3, 5.4, 5.5, 5.6).

It has been observed that development of tension cracks by subsurface erosion processes appears to be the major processes of widening, aided by oversaturation and collapse. Over saturation causes instability in vertical or subvertical walls of a gully that is further enhanced by tension cracks. However, no evidence has been found of undercutting of gully walls in the study area which indicates that concentrated flow is not an important process for gully widening.

Slumping, soil falls and slides have also been observed as some of the most common erosion processes with gullies in the study area (Figure 5.4). It has been noted that slumping and soil falls are often dominant erosion processes in gully headwall retreat.

Evidence of surface runoff has been identified within gully floors (Figure 5.5) which shows that runoff contributes to transport of material eroded from gully walls. If velocity of runoff is low, the erosion will occur only when soil particles have already been lifted into suspension. High velocity surface runoff not only washes away eroded material but erodes the surface as well. Rills occur in association with surface runoff. Rills are formed when surface runoff concentrates into small channels. The velocity of water in these channels is high enough to disperse the soil particles and
wash them downstream forming a shallow channel. Rills have also been observed within gully walls during field investigations (Figure 5.6).

Ground evidence suggests that gully erosion processes are influenced by subsurface erosion processes because sapping erosion leads to the development of tension cracks, gravity collapse and land subsidence near the headwalls of the gullies, resulting from the internal erosion of fine particles through the soil. Subsurface processes do not operate individually but in combination with surface erosion processes such as runoff and rilling that also have been evidenced in the field. Field observation suggests that subsurface erosion processes are key mechanisms initiating erosion while surface erosion processes work as secondary mechanisms. Circular depressions have been identified in the Fergusson study area with evidence of tension cracks and collapse inside the depressions (Figure 5.5 & 5.7). It has also been noted that gullies exhibit the semicircular heads and gully head collapse that demonstrates gully subsurface erosion is playing a role for gully head retreat and gully widening.

![Figure 5.3 Tension cracks in gully wall (Photo by author, dated: 06-07-2008)](image)
Figure 5.4 Collapse and slumping in gully (Photo by author, dated: 06-07-2008)

Figure 5.5 Surface runoff (Photo by author, dated: 12-09-2009)
Note: The semicircular gully heads of this large gully.
Figure 5.6 Rilling in gully (Photo by author, dated: 12-09-2009)

Figure 5.7 Gully initiation (Photo by author, dated: 12-09-2009)
Note: The semicircular gully heads.
The gullies of the Fergusson River catchment have been observed through numerous ground surveys, airborne surveys, historical stereo aerial photographs and Cartosat-1 stereo satellite imagery. These information sources have been used to develop a database documenting the shape and spatial distribution of gullies in the study area. These patterns are closely linked with the dominant, erosion processes operating within the gullies and provide a useful basis of classifying gullies (Sattar et al., 2009). Four types of gullies are identified in the Fergusson River catchment, including amphitheatre gullies, gullied slumps, bank gullies and other gullies.

### 5.3.1 Amphitheatre Gullies

These gullies are wide and broad and not surprisingly amphitheatre shaped. Some have a drop like shape, drain into a narrow outlet that is linked to the main channel through a floodwater return channel; that is, through a natural channel that takes overbank Fergusson River flood water back to the river (Figure 5.8 and 5.9). Twenty two amphitheatre gullies have been mapped in this study from 2008 satellite imagery with the area extent ranging from 1002 to 127113 m² that cover 779100 m² of the study area (Table 5.1).

![Figure 5.8 Amphitheatre gully (Photo by author, dated: 06-01-2008)](image-url)
These gullies are characterized by semicircular shaped headcuts, vertical walls, and badlands topography on steep-sided ridges with rills, small channels (that direct water and sediment into main channel) and ridges within the amphitheatre (Figure 5.8). There is no structural control on these gullies. Once they initiate they will keep on expanding till they absorb their entire catchment area and reach adjacent bedrock (i.e. cretaceous sedimentary rocks) so that there is no material left to erode.

Figure 5.9 Diagrammatical representation of the location of the amphitheatre gullies and active gullied slumps. Only the right bank has been sketched
Table 5.1 Amphitheatre gullies size in 2008

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of Gullies Mapped</th>
<th>Minimum Size (m$^2$)</th>
<th>Maximum Size (m$^2$)</th>
<th>Average Size (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphitheatre</td>
<td>22</td>
<td>1002</td>
<td>127113</td>
<td>35411</td>
</tr>
</tbody>
</table>

Vegetation cover seems to be ineffective in erosion control for these particular gully types, once they initiate. In most cases the floors of these gullies have planar surfaces. These surfaces are being eroded by a new set of gullies that are migrating upslope thereby rejuvenating the gully systems. Additional evidence of rejuvenation have been observed in the form of exposure of the roots of small tree and shrubs that have germinated in the badland on ridge tops.

Gully morphology also reflects the position of the gully in the catchment. This study shows that amphitheatre gullies are spatially distributed on flood plains away from levee crest and the riparian zone (Figure 5.9 and 5.10). The reason for this spatial restriction might be a lack of space for the gullies to grow laterally, given that they are wide features. Semicircular depressions at gully heads and further development of tension cracks and slumping indicate that these gullies are the outcome of both a horizon extrusion sapping and surface runoff. The main erosion processes are development of tension cracks, slumping, and surface runoff. Undermining of weak gully walls and development of tension cracks causes the slumping and side wall collapse.

Surface runoff occurs as the outcome of intense storm events or flooding from the Fergusson River on floodplains. Runoff also causes the flooding and gully expansion by sidewall collapse and headward growth; therefore these gullies are wide and broad rather than incised. These gullies are linked with floodwater return channels which are comprised of clay rich sediments in their floors and are a major means by which sediments are transported from floodplains to the main channel. Flooding also causes overbank flows which assists with the removal of loose sediment as they drain to the river. Intense rainfall, either before or after overbank flows, is likely to be the major erosion agent in amphitheatre gullies; with A horizon extrusions a secondary process.
5.3.2 Gullied Slumps

Gullied slumps are lobate in shape with broad and arcuate headcuts (Figure 5.11 and 5.12). The main erosion processes to form these gullies are basal extrusion sapping in association with slumping and gravity collapse. Gullied slumps are not dependent on upslope catchment area, because they are formed by basal extrusion sapping so they are deep which indicates that the processes of erosion are deep in the soil profile. Gravity collapses and slumping is further triggered by surface runoff that creates rills and small gullies within gullied slumps and accelerates the erosion process in the form of slaking (the disintegration of large aggregates during wetting) and sluicing (the washing effect of running water on loose grains) (Milton, 1971).
Figure 5.11 Gullied slumps along the floodplain margin (Photo by author, dated: 12-09-2009)

Figure 5.12 Gullied slumps (Photo by author, dated: 12-09-2009)
Figure 5.13 Spatial distribution of gullied slumps in the Fergusson River catchment

Thirty eight gullied slumps have been mapped in this study from 2008 imagery. Most are very fresh and active, and exhibit a minimum and maximum area of 760 and 39220 m$^2$ respectively (Table 5.2). Gullied slumps are located at the margins of the floodplain and hillslope, in the riverside/ streamside alluvial benches and levee crest (Figure 5.13). They all are fresh, with very few small trees and shrubs in their beds. Gravity collapse is the most dominant erosion process. Some old gullied slumps have been observed in the levee crest ~ 60 m from the riverbank. These gullied slumps are not active; their beds are vegetated by large trees and shrubs. Sidewalls of the old gullied slumps seem to be stable due to vegetation.

Table 5.2 Gullied slumps size in 2008

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of Gullies Mapped</th>
<th>Minimum Size (m$^2$)</th>
<th>Maximum Size (m$^2$)</th>
<th>Average Size (m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gullied Slums</td>
<td>38</td>
<td>760</td>
<td>39220</td>
<td>9200</td>
</tr>
</tbody>
</table>
Bank gullies are linear land forms characterized by vertical side walls with low variability of depth and width. One of the characteristics of the bank gully is that it develops considerable length and later cuts downwards and sideward (Figure 5.15). Bank gullies are formed by surface runoff. The initial headcut may develop during intense rainstorms facilitated by vegetation removal by animals and/or drought. Once developed, surface runoff contributes to incision and the development of linear channels.

A total of, fourteen bank gullies have been mapped in this study in 2008 with a minimum size of 3150 m$^2$ and maximum 31710 m$^2$ (Table 5.3). Bank gullies are located along channels and streams, and are affected by overbank flooding and runoff from rainstorms that also contributes to gully expansion and widening. There are fewer bank gullies than either amphitheatre gullies or gullied slumps because of their location on levee which have a small area.
Figure 5.15 Bank gully at its initial stage of development (Photo by author, dated: 06-07-2008)
Note: Bank gully can be incised by concentrated runoff and expand laterally by sidewall rilling and collapse.

Figure 5.16 Spatial distribution of bank gullies in the Fergusson River catchment
Table 5.3 Bank gullies size in 2008

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of Gullies Mapped</th>
<th>Minimum Size (m²)</th>
<th>Maximum Size (m²)</th>
<th>Average Size (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank Gullies</td>
<td>14</td>
<td>3150</td>
<td>31710</td>
<td>13050</td>
</tr>
</tbody>
</table>

Bank gullies play an important role in transporting sediments to the main channel due to their connectivity to the streams and the Fergusson River.

5.3.4 Other Gullies

Other gullies are incipient gullies that do not possess any specific shape and usually are small in size. Field examination reveals that incipient gullies are very actively eroding with vertical head cuts and steep side walls. Spalling and slaking have also been observed in these gullies. Most of the incipient gullies are lying on floodplains with sapping and surface runoff acting as the main erosion processes (Figure 5.17). Analysis of historical aerial photographs and satellite images shows that most ‘other gullies’ initiated after 1948 (Table 5.8); therefore few gullies have been mapped for this year. But satellite images for 2008 shows an increased number for this gully type. A total of fifty ‘other gullies have been mapped in this study from 2008 satellite images, exhibiting a minimum size 205 m² and a maximum size 113590 m² (Table 5.4).

Table 5.4 Other gullies size in 2008

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of Gullies mapped</th>
<th>Minimum Size (m²)</th>
<th>Maximum Size (m²)</th>
<th>Average Size(m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other Gullies</td>
<td>50</td>
<td>205</td>
<td>113590</td>
<td>7250</td>
</tr>
</tbody>
</table>

Gullies lying in this class have shown a lot of variation of gully size. Most of the gullies appearing on 1948 aerial photographs have become stable in 2008; that is fully vegetated with trees and grass on the gully beds. New gully development has been observed on 2008 imagery.
Figure 5.17 Actively eroding gully (Photo by author, dated: 06-07-2008)
Note: The vertical head cut.

Figure 5.18 Spatial distribution of ‘Other gullies’
5.4 Temporal Changes of Gully Erosion

Mapped gully data created as part of this study demonstrates spatio-temporal changes in gully growth (Sattar et al., 2010a) over the study period, and can assist in providing some information on gully development stage by helping to determine gully ages.

5.4.1 Gully Growth Change

Gully growth is one of the prime determinants in understanding gully behaviour. Growth processes include crumbling, spalling, wall collapse, direct attack by rain drops, slope wash, incision of the floor, undercutting, collapse of feeder pipes, and sapping due to seepage of groundwater out of the bases of the walls and headscarp. Growth patterns reflect gully expansion mechanisms allowing assessment of erosion rates.

The observation of gully growth over sixty years demonstrates the variable growth rate among the gullies. The growth pattern demonstrates that amphitheatre gullies close to each other (Figure 5.19) have expanded and merged overtime to produce large gullies. This growth pattern might have an effect on gully growth rate because gully drainage area is divided between two gullies so it can cause different rates of erosion at that particular part of the gully in comparison to other parts where gully drainage area is contributing to only one gully (Faulkner, 1974).

Vegetation establishment of the downstream portions of the amphitheatre gullies and active headcuts at the upper parts has created an interesting phenomenon where the downstream portion is heading towards stability but the upstream portion, with active headcut, is generating sediment. Measurements of headcuts (method in section 4.6) for amphitheatre gully growth in the study area shows that these gullies are growing with an average retreat rate of $0.93 \pm 0.09$ m yr$^{-1}$ (Table 5.5). The semicircular shape of gully heads, collapse and slumping indicates that headwards retreat is influenced by extrusion sapping (Moeyersons, 1991; Montgomery and Dietrich, 1994) while surface runoff traces at gully floor and above gully headcuts indicates, the expansion of amphitheatere gully is also effected by surface runoff. From 1948 aerial photographs 14 amphitheatre gullies were mapped and 22 were mapped from Cartosat-1 stereo images (Table 5.5). It is important to mention that the resolution of
the 1948 aerial photographs (1:30000) was good enough to identify the gullies. Low vegetation cover in 1948 combined with 3D visualization was a supporting factor for gully identification.

Table 5.5 Amphitheatre gully retreat rate

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of gullies in 1948</th>
<th>No of gullies in 2008</th>
<th>Gully Average Retreat Rate (m yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphitheatre gullies</td>
<td>14</td>
<td>22</td>
<td>0.93 ± 0.09</td>
</tr>
</tbody>
</table>

Figure 5.19 Growth of amphitheatre gullies

Note: Three amphitheatre gullies (in pink colour) were mapped from 1948 aerial photographs but 2008 satellite image shows one massive amphitheatre gully (peach colour).

Groundwater plays an important role in triggering gullied slumps. Knapton (2006) has reported that increased rainfall has increased the groundwater level in the Daly Basin. Groundwater levels increased from ~1970 to 1979, fell to 1995, and have risen since. River mean annual flows have followed the same trend. Groundwater sources in combination with mean river flow enhance the potential for alluvial
benches to become saturated and collapse. The growth patterns of gullied slumps shows the lateral and upslope expansion by episodic failure. This study shows that gullied slumps are expanding with an average retreat rate of $1.72 \pm 0.17$ m yr$^{-1}$ (Figure 5.20). The number of gullied slumps increased (Table 5.6) in 2008, 38 gullied slumps were identified as compared to the 30 in 1948.

**Figure 5.20 Growth of gullied slumps**

**Table 5.6 Gullied slumps retreat rate**

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of gullies in 1948</th>
<th>No of gullies in 2008</th>
<th>Gully Average Retreat Rate (m yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gullied slumps</td>
<td>30</td>
<td>38</td>
<td>$1.72 \pm 0.17$</td>
</tr>
</tbody>
</table>

Bank gullies are characterized by vertical sidewalls that are maintained by concentrated flow leading to collapse and gully widening. Concentrated flow with high velocity incises the river levee and causes the bank gully to increase in length. This study shows that bank gullies are growing with an average retreat rate of $1.15 \pm$
0.11 m yr\(^{-1}\) (Table 5.7). Their growth may have been affected by flooding and over bank discharge that contributes towards an increased gully length and width. Sidewall collapse has been identified as an important process for gully widening, while concentrated flow is likely to increase as gullies lengthen. This is the only gully type in the Fergusson River catchment with a linear shape that indicates these gullies are more affected by surface runoff. Their downslope development supports this hypothesis (Figure 5.21). In 2008, 14 bank gullies are found in the study area while there were only 8 in 1948 (Table 5.7).

![Figure 5.21 Growth of bank gullies](image)

**Figure 5.21 Growth of bank gullies**

Note: Bank gully is growing upslope and downslope, with an increase in both length and width. Note the gully boundary mapped from 1948 aerial photograph (pink colour) and gully expansion; boundary of gully expansion mapped from 2008 Cartosat-1 satellite image (peach colour).

**Table 5.7 Bank gullies average retreat rate**

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of gullies in 1948</th>
<th>No of gullies in 2008</th>
<th>Gully Average Retreat Rate (m yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank gullies</td>
<td>8</td>
<td>14</td>
<td>1.15 ± 0.11</td>
</tr>
</tbody>
</table>
‘Other gullies’ are also triggered and influenced by subsurface and surface erosion mechanisms. This gully class has shown most variability in gully development and stability in this study, therefore it has been difficult to determine their growth pattern. However, 28 have been found on aerial photographs in 1948, but 50 appear in 2008 (Table 5.8). Most of the gullies in this class mapped from 1948 aerial photographs were stabilized in 2008. Growth measurements conducted on ‘other gullies’ in the study area demonstrate that the headcuts of these gullies are growing on an average retreat rate of 0.68 ± 0.06 m yr⁻¹ (Figure 5.22). A variation in size has also been observed for these gullies; some are very small and some are big.

Volume differences from 1948 to 2008 are calculated for the gullies that extended from 1948 to 2008 and plotted against total volume in 2008 (Figure 5.23). The plots of amphitheatre gullies (r² = 0.11) show no relationship while bank gullies (r² = 0.98), gullied slumps (r² = 0.85) and ‘other gullies’ (r² = 0.75) demonstrate a strong relationship.

Figure 5.22 Growth of ‘other gully’
Note: The gully boundary mapped from 1948 aerial photograph (pink colour) and gully expansion; boundary of gully expansion mapped from 2008 Cartosat-1 satellite image (peach colour).
(a) Amphitheatre gullies

(b) Gullied slumps
Figure 5.23 Gully growth: relationship of increased volume with total volume of gully (a) amphitheatre (b) gullied slumps (c) bank gullies and (d) ‘other gullies’
Comparison of gully growth patterns and retreat rates in the study area indicate that
gullied slumps are growing more rapidly than other gully types. One reason for this
rapid growth might be environmental factors (detail in section 6.2) or it might be the
case that these gullies are in their initial phase of development therefore growing
more rapidly (Nachtergaele et al., 2002; Thomas et al., 2004; Valentin et al., 2005;
Vanwallegem et al., 2005b).

### 5.4.2 Gully Initiation and Age

Gully initiation and evolution can be either natural or anthropogenic in cause. The
age estimates can provide an idea of the possible causes of gully initiation and
development (Cooke and Reeves, 1976; Wells and Andriamihaja, 1993) by
determining if a particular causative agent could have been responsible. Gully
development has been reported through various stages that regulate gully
morphology (Heede, 1974). Gully head retreat declines over time after it initiates
(Schumm et al., 1987; Howard and McLane, 1988). Graff (1977) demonstrated that
the rate of gully growth decays exponentially with time, because of declining
catchment area contributing to runoff and therefore, gully erosion. Kosov et al.,
(1978) showed experimentally that gully formation in sand has several stages. The
first stage is short taking 5% of gully lifetime, but 90% of gully length, 60% of
gullied area and 35% of gully volume. The last stage is the longest when a gully is
morphologically almost or near stable. Sidorchuk (1999) reported that the first stage
is affected by hydraulic and mechanical action of water on the soil. Therefore the
gully bottom is vulnerable to erosion and gully sidewalls also erode rapidly. Gully
formation is intense during the initial phase of development, representing very
unstable morphology of gully (Sidorchuk, 1999).

Rutherfurd et al., (1997) reformulated Graf’s original function in a more useful form
that expresses gully length \( L \), at time \( t \), as a function of the decay constant \( b \), with \( L \)
approaching the final equilibrium length \( L_f \). Thus, gully length at a given time, \( L_t \), is
given by:

<table>
<thead>
<tr>
<th>Gully Type</th>
<th>No of gullies in 1948</th>
<th>No of gullies in 2008</th>
<th>Gully Average Retreat Rate (m yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other gully</td>
<td>28</td>
<td>50</td>
<td>0.68 ± 0.06</td>
</tr>
</tbody>
</table>
\[ L_t = (L_f - L_o) \left(1 - e^{b(t-t_o)}\right) \quad (5-1) \]

Where \( L_o \) is the original channel length and \( t_o \) is time when the gully initiated. Parallel to half-lives of radioactive materials, the half-life time of gully extension (T) can be defined as the time needed to erode half of the gully length. The remaining gully length is the difference between the final equilibrium gully length \( (L_f) \) and the actual gully length at time \( t \) \( (L_t) \). T is calculated as follows:

\[ T = \frac{\ln(2)}{b} \quad (5-2) \]

Rates of increase in length, area and volume of a gully decreases with time as a gully grows, and, at the last stage, there is no morphological change and the gully has reached a stable stage. Therefore, the total life time of a gully can be expressed as an exponential (or sometimes a logistic) curve which states, that gullies grow rapidly early on in their development with a high rate of erosion that starts to decline with age until they produces zero volume change (Figure 5.24).

Figure 5.24 Exponential curve representing gully total life time

Two methods have been used to determine the time of initiation of the Fergusson gullies. Optically Stimulated Luminescence (OSL) dating technique (see section 4.6) is used in the Fergusson River catchment to find the gully age. An inset alluvial terrace (latitude -14.3553445, longitude 131.7308597 and altitude 73.2 m) in a
floodwater return channel (Figure 5.25) of the Fergusson River called Farha creek, which drains a large fresh gully, was selected for OSL dating. The description of the alluvial bench profile is given in Table 5.9; sand and loam are dominant soil types. Fresh gullies occur at the head of the tributary some of which have cut headward into the bedrock hills removing hillslope soils and even incising the soft rocks. The alluvial terraces are believed to be the result of deposition of sediments as a result of gully expansion. A phase of increased sediment yield is followed by decreased sediment yield and incision of the alluvium deposited in the channel, thereby creating the inset terrace. However, the decreased sediment yield could be the result of decreased rainfall.

Figure 5.25 Alluvial bench of one tributary of the Fergusson River (Photo by Author: 12-09-09)
Table 5.9 Description of soil on one tributary of the Fergusson River

<table>
<thead>
<tr>
<th>Profile Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4cm</td>
<td>Mud drape, cracked, fine sandy loam; sharp undulating boundary</td>
</tr>
<tr>
<td>1-12cm</td>
<td>Interbedded very fine sand and organic debris (leaves and twigs); lamina to 3mm thickness; sharp, straight boundary</td>
</tr>
<tr>
<td>12 – 18cm</td>
<td>Interbedded mud (fine sandy loam) to 1cm thick and very fine sand, red-brown and grey-brown mottling; sharp wavy boundary</td>
</tr>
<tr>
<td>18 – 26cm</td>
<td>Flat bedded fine sand; sharp wavy boundary</td>
</tr>
<tr>
<td>26 – 35cm</td>
<td>Laminated fine sandy loam and fine sandy organic rich layers; red-brown mottling; sharp, sub-horizontal boundary</td>
</tr>
<tr>
<td>35 – 38cm</td>
<td>Stiff fine sandy loam, no lamination; red-brown mottling; sharp irregular boundary</td>
</tr>
<tr>
<td>38 – 45cm</td>
<td>Fine sand un laminated; one discontinuous mud (fine sandy loam) layer near base; sharp, wavy boundary</td>
</tr>
<tr>
<td>45 – 52cm</td>
<td>Fine sand un laminated; red-brown mottling; sharp, irregular boundary</td>
</tr>
<tr>
<td>52 – 58cm</td>
<td>Fine sand, un laminated; sharp irregular boundary</td>
</tr>
<tr>
<td>58 – 96cm</td>
<td>Loam, poorly defined wavy laminated with laminae up to 2cm thick; red-brown and grey mottling; sharp boundary inclined upstream ~10º</td>
</tr>
<tr>
<td>96 – 113cm</td>
<td>Loam, very poorly defined wavy lamination; top 1cm is grey coloured from organic matter; sharp, wavy boundary</td>
</tr>
<tr>
<td>113 – 132cm</td>
<td>Fine sand un laminated; sharp irregular boundary</td>
</tr>
<tr>
<td>132 – 137cm</td>
<td>Dense light clay; grey-brown mottling; sharp irregular boundary</td>
</tr>
<tr>
<td>137 – 154cm</td>
<td>Loam to light clay laminated with laminae up to 1.5cm thick; some organic colouration on the top of laminae; sharp, sub-horizontal</td>
</tr>
<tr>
<td>154 – 162cm</td>
<td>Loam, weakly laminated, grey; sharp sub-horizontal boundary</td>
</tr>
<tr>
<td>162 – 172cm</td>
<td>Loam to light clay, moderately well laminated; red-brown mottling; sharp, sub-horizontal boundary</td>
</tr>
<tr>
<td>172 – 181cm</td>
<td>Loam to light clay, poorly laminated; grey-brown mottling; sharp horizontal boundary</td>
</tr>
<tr>
<td>181 + cm</td>
<td>Bedrock (fine sandstone)</td>
</tr>
</tbody>
</table>

The alluvial deposit is 181cm thick and rests on bedrock. Three OSL dates and one \(^{14}C\) date show that the base is \(~1993\) AD and the top \(~2007\) AD, with an average sedimentation rate of 14cm/yr. The site was sampled in November 2009, so the
incision occurred over a period of ~2 years. The fresh gully at the head of Farha Creek already existed in 1948, according to the aerial photos. So the inset terrace is probably the result of the increased rainfall beginning ~1992 AD rather than gully initiation. The decreased sediment yield and incision after 2007 is not as readily explained, but may be the result of the gully headcut reaching its limit.

Fresh sediment (of the kind seen at Farha creek); the floodwater return channels, downstream of fresh gullies, are in different states of sedimentation and incision. Some are rapidly aggrading, others appear to be just starting to aggrade, others are not aggrading, and others are incising (or have incised) previous deposits to produce in set terraces. These observations suggest that the fresh gullies are dynamic and in many different states of development. Analysis of aerial photos and satellite images from 1948 to 2008 reflect this view. Most have expanded, but some have shrunk and become partially vegetated. The OSL dating has not determined the age of one of the fresh gullies and even the age of one is inefficient given the apparent diversity just described. Without a clear idea of their age it is difficult to identify the causes of the gully initiation.

Another method of dating has been performed for the Fergusson gullies. The method relied upon using the exponential curve representing gully growth as a function of time (Figure 5.24). The estimates of volumes in 1948 and 2008 have been plotted. The gullies expanded in this period, linear growth is assumed, and back extrapolation is applied to the line that joins the two data points for each gully to estimate the age of initiation (Burkard and Kostaschuk, 1995). Despite the suspicion that the growth curves for the gullies follow negative exponentials, the most parsimonious way of analysing the available data is to use linear interpolation because there is no way of knowing where the two data points lie on an exponential curve. Even if seepage is the only process of gully formation and growth, it is likely that it scales with both catchment area and slope. This is because the volume of seepage water will be controlled in part by the catchment area and its velocity in part by catchment slope. Floodwaters add to the seepage flow but this source of water does not obviate the likely scaling relationship. This would not be the case if floodwaters were the only process of gully growth and expansion, but this is clearly not the case given the evidence of seepage processes and headcuts downstream of small runnels that are most likely the result of local rainfall induced runoff.
A set of five representative gullies is plotted from each gully class. Plots of amphitheatre gullies demonstrate that most of them initiated ~ 100 years ago. A few are even initiated earlier according to the linear growth model. Gullied slumps have an apparent time of initiation between 1830 and 1930. Estimated age of bank gullies is between 1900 and 1940. ‘Other gullies’ have a more variable age with apparent age between X and Y. As noted above, the Fergusson River gullies are at many stages of development. They are therefore likely to lie at different points on an exponential curve (Figure 5.24). Estimates of age of initiation of the gullies by back extrapolation are therefore likely to vary considerably.
Figure 5.26 Estimation of gully initiation time using extrapolation (a) amphitheatre gullies (b) gullied slumps (c) bank gullies (d) ‘other gullies’

If the small gullies are in the early stages of development, their estimated ages of initiation are likely to be most reliable (points 1 and 2 on the Figure 5.27). The age estimates for the large gullies that are approaching the rollover near the top of the curve will be the least reliable. Back extrapolation from the initial parts of a logistic curve will be reliable, but will overestimate the age of initiation at the top and upper middle part of the logistic curve. Interestingly, if extrapolated from the middle of the curve (points 3 and 4 in Figure 5.27) the estimate will be almost reliable. Large
gullies yielding high volumes will lie on the upper middle and top of the curve that over estimates gully age (Point 4 and 5 in Figure 5.27).

From these considerations, it is most likely that most of the gullies, that have continued to expand since 1948, formed between ~1900 and ~1930. This time period is after the introduction of domestic stock and grazing feral animals (Leichhardt, 1847; Mitchell, 1848). While this observation does not prove a role for overgrazing as a trigger for gully formation, it at least shows that such a role is possible.

Figure 5.27 Estimating the gully age and time of initiation

Using Figure 5.27 it should also be possible to estimate the stage of development of a particular gully. Where a gully is estimated to be old, it is likely to be large and near the asymptote at the top of the curve. Where a gully is estimated to be young, it is likely to be near the bottom of the curve. A large gully, that is estimated to be about the same age as most of the small gullies, is likely to be near the rollover near the top of the main growth phase of the curve.

The gullies whose estimated age clusters between the oldest and youngest estimates are likely to be in the middle stages of development. If most of the analysed gullies began to form between ~1900 and ~1930, and have followed the average trajectory of the curve, then their rates of development must have been different if the conclusions just reached about their positions on the curve are correct. That differences of rates exist is clear from the observation that sediment yield
downstream of gullies is also at different stages as seen by channel aggradation and incision, described earlier.

Different stages of gully development have been evidenced by the comparison and 3D visualization of stereo aerial photographs and satellite images. This comparison demonstrates overall landscape change in the Fergusson catchment and particularly considerable change in gully appearance. Vegetation increase is prominent in the whole study area. Reestablishment of vegetation has been noticed on the large gully floors (Figure 5.28 and 5.29) indicating reduced runoff and sediment deposition with a future decrease in gully volume likely (Nachtergaele et al., 2002). Reduction of soil erosion is affected by the height and continuity of the canopy of vegetation on the gully floor. If the canopy is near the ground, it dissipitates the kinetic energy of rain. Also, vegetation on the ground increases roughness and reduces the velocity of flow. Roots play an important role in reducing erosion by binding the soil mass to decrease surface erosion. Height of vegetation and canopy may indicate the relative gully ages. Gullies with low density of vegetation indicate younger gullies in comparison of those which has big trees or small plants on gully floors. Therefore, a comparison of different stage of development can be made (Zierholz et al., 2001).

Opposite to gully growth, gully area reduction has also been observed. Many gullies have disappeared over time and it was difficult to identify some gullies which have been mapped from stereo aerial photographs but were not visible on Cartosat-1 images due to vegetation on gully floors and side walls. Many gullied slumps on levees are completely revegetated while gullied slumps on alluvial benches and along river banks are fresh and still actively eroding. 3D visualization of both datasets showed that many gullies have disappeared in the area adjacent to middle section of the river, while downstream few gullies have disappeared. If a gully is near the top of the exponential curve, revegetation is likely. But even more so if rainfall increases as it has.
Figure 5.28 3D view of amphitheatre gully in 1948. Use anaglyph glasses ( 🌋️ )
Figure 5.29 3D view of amphitheatre gully in 2008. Use anaglyph glasses ( 🦉 )
5.5 Volumetric Change and Gully Erosion Rate

Determining the rate and mass of gully erosion is important as an input to a sediment budget for the Daly River Catchment and an important aspect of gully erosion research (Wu et al., 2008). Gully volume is calculated for each class of gully and volumetric changes estimated. The total gully volume in the Fergusson River catchment determined in this study was found to be $(3.4 \pm 0.3) \times 10^6$ m$^3$ in 1948. The minimum and maximum volume of gullies in 1948 is recorded to be $660 \pm 99$ m$^3$ and $(7.9 \pm 1.2) \times 10^5$ m$^3$, respectively. The total volume of sediment removal in the study area by gully erosion in 2008 is $(7.9 \pm 0.7) \times 10^6$ m$^3$. The minimum and maximum gully volume/soil loss is 123 m$^3$ and $7.9 \times 10^5$ m$^3$ respectively. Volumetric gully erosion measurements in the study area show a gradual increase in volume from 1948-2008 (Figure 5.30) with sediment production during this period found to be $(2.8 \pm 0.03) \times 10^3$ m$^3$ km$^{-2}$, these results are consistent with other studies (Williams, 1976; Skeat et al., 1996; Erskine and Saynor, 2000; Brooks et al., 2008).

Figure 5.30 Gully erosion volumes in 1948 and 2008

Note: Volume of gully erosion in 1948 is $(3.4 \pm 0.3) \times 10^6$ m$^3$ and in 2008 is $(7.9 \pm 0.7) \times 10^6$ m$^3$.

Previous studies using aerial photographs have determined gully volume in an indirect way either by taking the difference of Digital Elevation Models (DEM)s of two time periods (Thomas et al., 1986; De Rose et al., 1998; Betts and DeRose, 1999; Ciccacci et al., 2008) or by mapping the gully area from aerial photographs in 2D combined with depth information from field survey (Nachtergaele and Poesen, 1999) or by overlaying the mapped gullies on a DEM to get the depth information (Martínez-Casasnovas, 2003; Wu et al., 2008).
Geoinformatics based method is used to calculate the volume of gully erosion which provides a direct way to calculate the relative gully morphology measurement and support to calculate erosion volume in an efficient way.

The quantitative analysis in this study demonstrates that all gully classes show increased sediment production (Figure 5.31). Amphitheatre gully volumes have increased by 84%, gullied slumps 218%, bank gullies 440% and other gullies 104%. Amphitheatre gullies exhibit the lowest rate of increase compared to the other three classes of gullies. The low rate of erosion for amphitheatre gullies infers that they might be the oldest gullies in the catchment. Low growth rate can also be attributed to revegetation or gully floor stabilization at downstream for these gullies.

![Figure 5.31 Gully volume from different gully types](image)

Note: The volumes calculated for 1948 are: amphitheatre gullies \((1.6 \pm 0.2) \times 10^6\) m\(^3\); gullied slumps \((0.7 \pm 0.1) \times 10^6\) m\(^3\); bank gullies \((0.2 \pm 0.02) \times 10^6\) m\(^3\); other gullies \((0.8 \pm 0.1) \times 10^6\) m\(^3\); volumes for 2008 are: amphitheatre \((2.9 \pm 0.3) \times 10^6\) m\(^3\); gullied slumps \((2.2 \pm 0.2) \times 10^6\) m\(^3\); bank gullies \((1.1 \pm 0.1) \times 10^6\) m\(^3\); other gullies \((1.7 \pm 0.2) \times 10^6\) m\(^3\).
In order to calculate the mass of material eroded by gullies the value of soil dry bulk density is needed to convert volume to mass. Dry bulk density, is the weight of dry soil divided by the total soil volume and total soil volume is the combined volume of solids and pores which may contain air or water, or both. The estimated clay soil bulk density is 1.3 (McIntyre and Loveday, 1974; Standards Association of Australia, 1977), giving a specific yield of gully erosion in the Fergusson River catchment between 1948 and 2008 of \((6.1 \pm 0.6) \times 10^3\) t km\(^{-2}\) yr\(^{-1}\).

### 5.6 Specific Sediment yield: regional and global comparison

Total sediment yield (TSY) is defined as the total sediment outflow from a catchment, measurable at a point of reference and for a specified period of time (Vanoni, 1975) and is expressed in absolute terms; tonnes per year (t y\(^{-1}\)) or in area specific terms as SSY expresses as tonnes per square kilometres per year (t km\(^{-2}\) y\(^{-1}\)). The sediment yield of a catchment represents only a part of the total erosion or sediment production within a catchment, as often-important masses of sediment are deposited before they reach the outlet. Sediment yield therefore only provides a useful source of information about the net erosion intensities within catchments (Walling, 1994).

SSY (t km\(^{-2}\) y\(^{-1}\)) has been determined for each gully in the Fergusson River catchment based upon the calculated gully volume mass and time period (i.e. 60 years). Using 1_second DEM (~30 resolution), and 3D visualization of the DSM, gully contributing areas have been measured using the ‘measuring spatial feature’ functions (standard functions) in ArcGIS 9.2. Drainage density (DD) is an important determinant of sediment yield and is defined as the quotient of total stream length and drainage area and can be expressed as of kilometres per square kilometre (km/km\(^2\)). Gullies form when the forces due to flowing water, in terms of boundary shear stress, overcome the cohesion and weight of soil particles and aggregates such that the flowing water transports them. Gullies provide pathways to generate and transport sediments to large channels. Drainage density is a useful independent variable given that in catchments where gullies are important most sediment comes from them. SSY and DD of the Fergusson gullies were calculated to make global and regional comparisons using these parameters.

Given that amphitheatre, gullied slumps and other gullies are non-linear gullies, the perimeter of these gullies are halved to calculate gully length, and DD (km/km\(^2\)) of gullies is obtained. SSY is calculated for each gully type (Figure 5.32). Linear regression analysis of SSY and
(a) SSY of amphitheatre gullies

(b) SSY of gullied slumps

(c) SSY of bank gullies
Figure 5.32 Specific sediment yield vs drainage density: (a) amphitheatre gullies, (b) gullied slumps, (c) bank gullies and (d) ‘other gullies’

DD of amphitheatre and bank gullies exhibits a weak statistical relationship ($r^2 = 0.2$ and $r^2 = 0.27$; $p = 0.005$, respectively). Results indicate that only 20% of the variation in SSY is accounted for by DD. Gullied slumps regressed better ($r^2 = 0.4$, $p = 0.005$) in comparison to amphitheatre and bank gullies, which indicates that DD influences 40% of SSY.

Regression analysis of ‘other gullies’ demonstrates a very weak statistical relationship between SSY and DD ($r^2 = 0.08$; $p = 0.005$).

Figure 5.33 shows a comparison of regressions for SSY and DD in different parts of Australia and different parts of the world. The SSY of Fergusson gullies varies between $293 \text{ t km}^{-2} \text{ yr}^{-1}$ and $3.6 \times 10^5 \text{ t km}^{-2} \text{ yr}^{-1}$ with an average rate of $(1.9 \pm 0.1) \times 10^3 \text{ t km}^{-2} \text{ yr}^{-1}$. SSY and DD of Fergusson gullies are positively correlated ($r = 0.71$, $p = 0.005$).

Linear regression analysis of the Fergusson River SSY and DD demonstrates that DD explains almost 50% of the variation in SSY and about 50% is unexplained. The unexplained portion might be related to other environmental factors (detail in Chapter 6) and to different stages of gully development.

Plotted Australian datasets include the Kangaroo Hills Queensland (Prove, 1992) ($r^2 = 0.56$), Nelson Springs, Northern Territory (Wasson et al., 2002) ($r^2 = 0.95$), and Whiteheads Creek, Southern Tablelands, New South Wales (Olley et al., 1993) ($r^2 = 0.42$).
Figure 5.33 Specific sediment yield vs drainage density: regional and global comparison
Prove (1992) demonstrates that data from the Kangaroo Hills basins (0.03-0.31 km$^2$) show that sheet erosion yields 260 t km$^{-2}$ yr$^{-1}$, minor gully and sheet erosion 420 t km$^{-2}$ yr$^{-1}$, and severely gullied basins yield on average 1830 t km$^{-2}$ yr$^{-1}$. In the southeastern part of Australia the mean annual specific yield of ungullied basins has been estimated at 19 ± 5 t km$^{-2}$ yr$^{-1}$, and for gullied basins, the specific yield is 161 ± 68 t km$^{-2}$ yr$^{-1}$; gullies produce 9 ± 5 times more sediment than ungullied land in this region (Wasson, 1994).

Global data come from Chaleela Lesotho, Africa (Christiansson, 1981) ($r^2 = 0.14$), New Mexico, USA (Hadley and Schumm, 1961) ($r^2 = 0.91$), and the Loess Plateau, China (NNSFMP, 1993) ($r^2 = 0.32$). SSY of Fergusson gullies shows the highest erosion rates as compared to other regional and global datasets, but to some degree overlap with the Loess Plateau. Some of the Fergusson gullies are producing SSY at the same rate as of the Loess Plateau of China which is considered as one of most erosion prone areas in the world (NNSFMP, 1993).

It is important to mention that the Fergusson gullies are alluvial gullies while the gullies of the Loess Plateau are badland gullies. Alluvial gullies are incised in unconsolidated material and have high sediment delivery ratio (Brooks et al., 2009). It is difficult to compare the SSY of Fergusson Gullies with other global and regional datasets because Fergusson gullies are alluvial gullies while other datasets includes hillslope or gullies in colluvium. No data are available for alluvial gullies at regional and global scale. More research is needed on alluvial gullies as an important part of the gully continuum. Also detailed studies of alluvial gullies are required to understand the alluvial gully process, estimate sediment yields, and compare the erosion rate with other gully types and contribute to sediment budgets.

The high sediment yield of Fergusson gullies may be attributed to the subsurface processes which are responsible for eroding large volumes of soil. Differences in the $r^2$ value of regional and global datasets can probably be attributed to differences in overall geomorphology, climate, landuse or soil erodibility of different landscapes.

5.7 Summary

The Fergusson catchment includes a very heterogeneous system of gully erosion. Field observations, aerial photographs and satellite image analysis demonstrate that
the Fergusson gullies are in different states of development. Some are still very actively growing while others are slowing possibly towards a stable state. A few have already reached stability; producing little or no sediment. Vegetation on the gully floor and on side walls indicates that a gully is no longer active.

Gully position in the catchment has an impact on gully morphology. Amphitheatre gullies are located on the floodplain and are wide and broad because low slope variation and low velocity of runoff on floodplains have resulted into shallow and wide gullies. But in the case of gullied slumps and bank gullies, they are deep because of the relief afforded by alluvial benches and levees that become saturated during rainfall and flood events causing slumping and sidewall collapse followed by gully by runoff. Steep slopes of levee and concentrated surface runoff might be another reason for the deep linear shape of bank gullies. The slumping and side wall collapse is controlled less by catchment size than by local site characteristics. Field observations, aerial photographs and satellite images show that gully shape is the result of underlying erosion processes and its location in the catchment.

The spatial distribution of gullies has an impact on gully growth. In the Fergusson catchment amphitheatre gullies are affected by extrusion sapping and surface runoff and apparently are less affected by overbank flow discharge in comparison with bank gullies and gullied slumps. Gully growth is the result of various erosion mechanisms.

Fergusson gullies exhibit a gully head retreat rate on average ranging from 0.7 to 1.72 m yr\(^{-1}\). Gullied slumps show on average the highest gully head retreat followed by bank gullies and amphitheatre gullies. ‘Other gullies’ show the lowest average gully head retreat rate in comparison to all gully types but have shown more variability in size, erosion rate and stability.

Gully erosion rates and their contribution to total catchment sediment yield has been recorded globally; 30% in Europe (Poesen et al., 2003), Kenya 53% (Oostwoud Wijdenes and Bryan, 1994), Vermont, USA 58% (USDA-NRCS, 1997), 80% in north-western Australia (Wasson et al., 2002), and 95% in south eastern Australia (Krause et al., 2003). The volume of gullies on the Russian Plain is estimated to be about 4 × 10^9 m\(^3\) (Sidorchuk, 1999). Wasson et al. (1996) reported the volume of gully erosion at 14 × 10^9 m\(^3\) in Australia mainly on pasture land. International aid and development agencies have designated Madagascar’s erosion rate the highest in
the world (USAID, 1998; World Bank et al., 1988) ranging from 20,000–40,000 t km⁻² yr⁻¹ (Randrianarijaona, 1983; Lal, 1988; Grieser, 1994; Ralison et al., 2008). Note that this is higher than on the Loess Pleatue, but there are no estimates of DD so that the data cannot be included in Figure 5.33.

The gully erosion rate in the Fergusson river catchment is (6.1 ± 0.6)×10³ t km⁻² yr⁻¹ is high by world standards. Elliott et al (2002) reported that soil erosion rates are high and unsustainable for grazed and cropped areas in the Northern Territory. Brooks et al., (2008) have estimated in northern Australia that active gullies covers up to 1% of the land area of the lower alluvial portions of the Mitchell River catchment but represent a substantial component of the total sediment budget. Such gully erosion in alluvium is often concentrated along the riparian margins of major river channels. Williams (1976) reported a sediment yield of 9.3 × 10⁴ t km⁻² yr⁻¹ for a single gully at Jabiru, Northern Territory, Australia, which was further reviewed and assessed by Erskine and Saynor (2000) and concluded that this was the highest yield reported even for a disturbed mine site. Skeat et al., (1996) computed that a single gully on the floodplain of Fisher creek (South Aligator River basin) eroded 53000 t over 15 years due to buffalo damage and caused a major increase in the sediment yield from the entire catchment. Gully erosion research findings in the Northern Territory, Australia indicate that this part of the country generates high gully erosion rates. The causes of the high rates are uncertain but probably relate to the landuse with environmental factors (detail in chapter 6) making the region vulnerable to gully erosion thus producing high amounts of sediments.
Chapter 6: Analysis of Gully Control Factors
Chapter 6: Analysis of Gully Control Factors

6.1 Introduction

As previously discussed, gullying is a dynamic process dependent on, and controlled by, a range of factors. Different erosion processes and mechanisms can be involved in gully initiation and development, such as overland flow, subsurface flow (seepage, piping), and different types of mass movement. Various factors e.g. topography, soil properties, climate, and landuse can be related to gully erosion mechanism (Valentin et al., 2005). A knowledge of the factors controlling gully erosion is necessary in order to design and implement effective management programs to reduce the impact of gully erosion.

Four types of gullies have been identified to exist in the study area, namely amphitheatre, gullied slumps, bank gullies and ‘other gullies’. These were classified based upon shape and location (see section 5.3 for detail). Field observations, Cartosat -1 stereo images and stereo aerial photographs have shown that the Fergusson gullies have heterogeneous morphology and are at different stages of growth and development. The heterogeneity in gully form is likely to be the outcome of single or multiple causes that can be linked to potential gully control factors (e.g. vegetation, runoff, and groundwater) that affect gully initiation and growth.

This chapter examines the relationship of gully erosion to potential control factors in the Fergusson River catchment taking into account the gully types and likely formation processes (described in Chapter 5). The examination of gully control factors is undertaken by comparing the distribution of each gully type with spatial layers (detail in Chapter 3) describing geology, soil, landuse/landcover, vegetation and slope using GIS based overlay analysis, field observations and general literature.

6.2 Analysis of Gully Control Factors

This section presents analysis of the gully control factors thought to be important in the study area using overlay analysis. Overlay analysis integrates spatial and attribute data by combining information from one Geographic Information System (GIS) layer with another GIS layer to infer an attribute for one of the layers.
6.2.1 Geology/Soil

Geology is thought to play a significant role in gully development having a direct control on soil type and underlying rock erodibility (Beavis, 2000). Subsoil determines the shape of the gully and the depth of a gully is sometimes controlled by depth to, and the nature of, bedrock (Avni, 2004).

All of the mapped gullies (Figure 6.1) lie within the Daly Basin, a Cambrian age basin covered by alluvium and colluvium. Overlay analysis shows that almost 98% of gullies identified are found on alluvium, mainly on floodplains and channel banks consisting of sand, silt and clays with some black soil (Vertosols). Only 2% of gullies have been observed on sandy colluvium and Ooloo Dolostone.

The upper part of the study area, upstream of the Daly Basin, is dominated by rugged terrain and hills (detail in section 3.2 and 3.3) and is dominated by Tennysons Leucogranite (Orosirian). No gullies have been observed on this geological unit. Other geological units in the Daly Basin, such as the Jinduckin formation and Tindall Limestone, are also without gullies. This implies that unconsolidated alluvium (of Quaternary age) is most susceptible to gullying. These observations are consistent with a number of other studies where gullies exist only on alluvium (Avni, 2004, 2005; Bacella et al., 2005; Brooks et al., 2009).

Groundwater is also thought to affect the formation of amphitheatre gullies, which are the result of sheet sapping (Figure 6.4) (section 5.3). These gullies initiate from any headcut eroding headward. They are partly affected by groundwater and partly by surface runoff. Sapping and slumping are dominant erosion processes provided that there is an unconfined aquifer in which groundwater levels rise and fall with each wet season (Tickell, 2010). Brooks et al., (2006) have similarly reported alluvial gullies in tropical savanna catchments in northern Queensland, Australia, where basal sapping is the dominant erosion process for amphitheatre gully formation.

Sapping erosion (Figure 6.2 and 6.3) occurs when subsurface flow undermines or erodes the regolith usually at the boundary of permeable and impermeable layers. This internal undermining weakens the support for surface soil and reduces the cohesion of the affected layer resulting in circular or semicircular depressions at the
Figure 6.1 Geology and gullies in the study area (Source: GeoScience Australia, 2007)
Figure 6.2 Gullied slump with rills developed on the edge of the floodplain on the left bank of the Fergusson River. (Photo by author, dated: 13-09-2009)

Figure 6.3 Sapping erosion and related processes in Gullied slump and rilling by surface runoff (Photo by author, dated: 13-09-2009)
surface. As the surface structure weakens, tension cracks develop around the depression and the whole soil mass is detached from the cracks and collapses (Hagerty, 1991; Fernández et al., 2008). Surface runoff can washout the collapsed material and a semi conical landform, the result of tension cracking, is a result of this process.

The form and rate of gully network development and geometry is to some extent controlled by soil, or lithological properties (Bryan, 2004). In order to understand the relationship between gully patterns and growth it is necessary to understand soil types and characteristics. The main soil classes in the study area are identified as Hydrosols and Tenosols (developed mostly on alluvium). This classification is based upon the Australian Soil Classification System (Isbell, 2003). Hydrosols are permanently or seasonally wet soils, which are saturated for two to three months or more and are most common in high rainfall areas. In northern Australia, Hydrosols can be seen on floodplains, swamps and along drainage lines. These soils have a perched water table usually caused by a slowly permeable horizon, or layer, within the soil profile. Tenosols are weakly developed, often shallow sandy soils.
Overlay analysis shows that almost 98% of Fergusson gullies are on alluvial soils (Hydrosols and Tenosols) (Figure 6.5) with variable content of clay, silt, sand and gravel and some rock. Alluvial soils are young soils that have not had time for full profile development. These soils are the outcome of deposition from rivers, on flood plains. The deposition by still or moving water from river can be seen in the form of layers (see Appendix C). Alluvial soils have high infiltration rates and have moderately rapid run-off.

Poorly drained alluvial soils are vulnerable to gully erosion because saturation makes the soil structurally weak, providing a favourable situation for gully initiation by surface scour and formation of an initial head scarp. Deep gullied slumps can be formed in alluvial soils where there is dispersible subsoil that leaves the surface soil unsupported after mass failure. Even amphitheatre and bank gullies can be formed on this soil due to their water retaining capability which is a triggering factor for sapping and slumping, gully widening, and head scarp advancement. Saturation of soils causes the slumping of gully head walls and side walls, and gullies can expand with little surface water flow. However, moderate and rapid run off can be generated on alluvial soils which enhance the erosion process so gullies expand during the wet season depending upon the severity and intensity of the rainfall. Rapid run off can also initiate the head scarp in these weakly structured soils and can cause gully initiation (Sattar et al., 2010b).

Gullies initiated in poorly drained alluvial soils may expand into other soil groups (such as Daly (Katherine), Edith (Belbowie and Edith), Elliot (King and Flemming)) where resistance to erosion and soil depth apparently limit gully erosion. It has been observed through overlay analysis and found that these gullies are not expanding on these mentioned soil groups, however gully expansion has been observed on the Elliot (Florina) soil group that is also Hydrosols in type. The mechanism of expansion is dependent upon the characteristics of the soil types which affect the rate of gully growth and types of gully erosion. Soil type, soil drainage, and runoff are important parameters to be considered when analysing the rate of gully growth. Thickness of alluvium in the study area is 0-15 m while colluvium is 0-12 m deep (GeoScience Australia, 2007). Usually gullies can not incise bedrock, but where the alluvium or colluvium is deep, gullies can reach depths of 10 -15 m (Carey, 2006).
Figure 6.5 Soil groups and gullies of the Fergusson River catchment (Source: Hill and Napier, 2008)
Considering the thickness of alluvium in the study area, it may be inferred that Fergusson gullies may incise in alluviums, and may gain the depth of 15 m.

### 6.2.2 Vegetation/Landuse/landcover

Vegetation cover is an important erosion-controlling factor (Gyssels and Poesen, 2003). Vegetation cover absorbs some of the energy of raindrops and running water, and contributes mechanical strength to the soil (Morgan, 1995). Vegetation type and structure have an impact on gullying. The study area contains forest, woodland, low woodland and native grasses with the trees dominated by various species of *Eucalyptus* and *Melaleuca* genera (Table 6.1). Dominant species on the alluvial plains are *Eucalyptus microtheca* and *Eucalyptus papuana*. Overlay analysis of gullies and vegetation shows that all gullies occur in areas of open forest riparian assemblages (Figure 6.6) (see Appendix A1 for the description of other vegetation classes).

**Table 6.1 Major vegetation species recorded at study site (Faulks, 1998a)**

<table>
<thead>
<tr>
<th>Plant Name – Genus species</th>
<th>Structural Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Barringtonia acutangula</em></td>
<td>Low tree / shrub</td>
</tr>
<tr>
<td><em>Casuarina cunninghamiana</em></td>
<td>Tree</td>
</tr>
<tr>
<td><em>Chara sp.</em></td>
<td>Forb</td>
</tr>
<tr>
<td><em>Coldenia procumbens</em></td>
<td>Forb</td>
</tr>
<tr>
<td><em>Cynodon dactylon</em></td>
<td>Grass</td>
</tr>
<tr>
<td><em>Dentella repens</em></td>
<td>Forb</td>
</tr>
<tr>
<td><em>Eucalyptus camaldulensis</em></td>
<td>Tree</td>
</tr>
<tr>
<td><em>Melaleuca argentea</em></td>
<td>Tree</td>
</tr>
<tr>
<td><em>Melaleuca leucadendra</em></td>
<td>Tree</td>
</tr>
<tr>
<td><em>Nauclea orientalis</em></td>
<td>Tree</td>
</tr>
<tr>
<td><em>Passiflora foetida</em></td>
<td>Vine</td>
</tr>
<tr>
<td><em>Xanthium occidentale</em></td>
<td>Forb</td>
</tr>
</tbody>
</table>
Gully headcut advancement and expansion can be limited by tall tree roots that strengthen the soil by binding and enhance the cohesion of the soil (Archibold et al., 2003). Plant root density also affects gullying by providing resistance to surface flow. Li et al (1991) have reported that effective root resistance to surface flow is by means of fibrils less than 1 mm in diameter and distributed densely from 0 to 30 cm depth. A decrease in root density has a direct effect on gully incision in grassland. A significant decrease in concentrated flow erosion rate has been observed in the loess belt in Europe by increasing the root density of various cereal and grass plants (Gyssels and Poesen, 2003).

Spatial heterogeneity of vegetation cover is also a key determinant of susceptibility to erosion. It has been observed that gullies predominantly developed in the study area where there are tall trees but low grass cover. This refers to the current state not the state when the gullies formed. The cover lessens during the dry season, often leaving bare soil patches vulnerable to erosion by early wet season (‘build up’) rainfall activity. These events are often dominated by thunderstorms with high intensity rainfall.

**Table 6.2 Structural categories present in the riparian zone and cover for all vegetation (Native and Exotic)**

<table>
<thead>
<tr>
<th>Structural Category</th>
<th>Mean Percent Cover and Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees (10-30m)</td>
<td>30 (10-50)</td>
</tr>
<tr>
<td>Trees (2-10m)</td>
<td>21 (15-25)</td>
</tr>
<tr>
<td>Regenerating Trees (&lt;2m)</td>
<td>6 (4-8)</td>
</tr>
<tr>
<td>Woody Shrubs (&lt;2m)</td>
<td>5 (4-5)</td>
</tr>
<tr>
<td>Forbs (or Herbs)</td>
<td>6 (4-10)</td>
</tr>
<tr>
<td>Grasses</td>
<td>6 (4-10)</td>
</tr>
</tbody>
</table>

* Contains exotic species
Figure 6.6 Vegetation and gullies in the Fergusson River catchment (Source: Hill and Napier, 2008)
Figure 6.7 Gully headscarp development in low open woodland (Photo by author, dated: 08-01-2008)

Figure 6.8 Amphitheatre gully in woodland (Photo by author, dated: 08-01-2008)
Fire is another phenomenon that damages the landcover. Weak cover does not provide resistance to concentrated flow and surface runoff, and if initial storms of the wet season are intense, this weak cover provides almost no resistance to concentrated flow and surface runoff.

Ground surveys and field observation (Figure 6.7 and 6.8) has shown that once gullies form, vegetation has little effect with gullies expanding through high cover vegetation. Furthermore, vegetation also appears to provide limited resistance to slumping. All gullied slumps located on major streams and river banks occur in areas of dense vegetation and ground cover. Slumping undermines vegetation and because this is caused by groundwater, surface flow is not needed to initiate a headcut (Fox et al., 2007).

The main landuse of the gullied area is grazing of native vegetation. Land tenure categories in the Fergusson River catchment include Pastoral lease, Crown lease, Perpetual and Freehold. Overlay analysis of gullies and landuse shows that gullying is observed on what is designated pastureland (Figure 6.9). Overgrazing has been shown to be one of the triggering factors for gully formation elsewhere (Podwojewski et al., 2002; Nyssen et al., 2004). Extensive grazing pressure in the Northern Territory since European settlement has been noted to have resulted in the partial disappearance of deep rooted native grasses (Wilson et al., 1990). Most of the pasture land now consists of shallow rooted native grasses and exotic weeds (Wilson et al., 1990). This alteration has the potential to have significant effect on land degradation and surface erosion. Animal tracks also act as an initial phase of land degradation and later contribute to the development of rills and gullies (Podwojewski et al., 2002).

Domestic stock may have had an impact on gully formation in the Fergusson River catchment, as the region has been used for grazing since 1880. It is noteworthy that a cattle yard (Claravale cattle station) was located on the right bank of the Fergusson River (Figure 6.13). This was in use around 1900’s and as a result this part of study area was under heavy grazing pressure (Howe, pers comm.). Later on it was destocked but actual dates of when Claravle cattle station was stocked and destocked are not available (Howe, pers comm.).
Figure 6.9 Landuse/Landcover and gullies in the study area (Source: Owen and Meakin, 2003)
Since no stock data are available, it is not possible to assess the potential impact of grazing in this area and how it might have changed over time. However, gully concentration in the study area is along drainage lines and near the Fergusson and Daly Rivers, which are likely to have been a source of water for stock and therefore a location of increased grazing activity.

Overgrazing along streams and pool sides has been shown elsewhere to cause vegetation damage, reduced resistance to surface flow and an increase in surface vulnerability to erosion (Neville et al., 1994). Furthermore, limited access to the river pools may have contributed to the formation of animal paths to the river, with soil compaction and disturbance providing a potential point for gully initiation. Faulks (1998b) reported that grazing occurred on thinned native pastures along the Fergusson River. In addition to domestic stock, feral animals recorded in the study area include buffaloes, wild cattle, wild horses, and pigs (Figure 6.10). All of these animals may cause soil compaction, disturbance and vegetation removal.

Aerial photographs from 1948 and Cartosat-1 satellite data from 2008 show 23 (Figure 6.11) and 48 (Figure 6.12) gullies on the left bank and 57 (Figure 6.13) and 76 (Figure 6.14) on the right bank of the Fergusson River, which implies that the number of gullies is increasing on both left and right banks. As mentioned previously there is evidence of a cattle yard on the right bank of the Fergusson River which suggests that the grazing intensity may have been higher on that side of the river. Given that the environmental conditions (i.e. geology, soil, rainfall, vegetation, topography) are similar on both sides of the river, it is possible the differences in grazing intensity has given rise to the formation and development of more gullies on the right bank prior to 1948. The similar number of new gullies (1948-2008) on each side of the river may be attributed to grazing pressure being more similar post 1948 on each side of the river. The fact that fewer new gullies were detected on the right bank from 2008 images may be attributed to the decrease in grazing pressure by the domestic animals during this time frame. However, this needs further research to isolate the role of grazing in gully formation. Nevertheless the idea that grazing has impacted on the area and contributed towards gully erosion is supported by analysis of the time of initiation of Fergusson gullies in Chapter 5 (section 5.4.2) which indicates they are all post 1880 when domestic cattle were introduced to the region (Mitchell, 1848).
Figure 6.10 Domesticated (cattle) and feral animals (pigs) in the Fergusson River catchment (Photos by author, dated: 12-04-2009)
Figure 6.11 Gullies on the left bank of the Fergusson River in 1948

Figure 6.12 Gullies on the left bank of the Fergusson River in 2008
Figure 6.13 Gullies on the right bank of the Fergusson River in 1948

Figure 6.14 Gullies on the right bank of the Fergusson River in 2008
Table 6.3 Increase in the number of gullies on the left and right bank of the Fergusson River from 1948 to 2008

<table>
<thead>
<tr>
<th>Fergusson River</th>
<th>Number of Gullies</th>
<th>Increase in Number of Gullies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year 1948</td>
<td>Year 2008</td>
</tr>
<tr>
<td>Left Bank</td>
<td>23</td>
<td>48</td>
</tr>
<tr>
<td>Right Bank</td>
<td>57</td>
<td>76</td>
</tr>
</tbody>
</table>

6.2.3 Topography

Topographic threshold conditions play a role in gully formation and development (Vandaele et al., 1997). Gully erosion is a threshold phenomenon of slope and catchment area (Knighton, 1998), and is initiated when the characteristics of flow (shear stress) exceeds a critical value (Sidorchuk, 2006). The topographic threshold concept describes a relationship between local slope and upslope drainage area and has been used to predict the location of gullies in concentrated flow areas (Horton, 1945; Patton and Schumm, 1975; Montgomery and Dietrich, 1994; Vandaele et al., 1996; Moore et al., 1998; Martinez-Casasnovas et al., 2003). Patton and Schumm (1975) express the topographic threshold as:

\[ S = \alpha A^\beta \]  

(6-1)

where A is upslope drainage area and S is the local slope gradient at a gully head, \( \alpha \) is a constant and \( \beta \) is a relative area exponent or relative shear stress indicator (Begin and Schumm, 1979). The value of \( \alpha \) depends upon catchment characteristics and varies with soil, lithology, vegetation cover and climate (Vandaele et al., 1996). The value of \( \beta \) is related to the dominant erosion processes of gully initiation and development.

A one second (~30m resolution) Digital Elevation Model (DEM) was derived from data collected by the Shuttle Radar Topographic Mission (SRTM), and obtained from GeoScience Australia. A slope map (Figure 6.15) was derived using standard ArcGIS ‘Spatial Analysis’ procedures and an overlay analysis was performed to determine the slope at the headcuts of mapped gullies.
Figure 6.15 Slope and gullies of the Fergusson River catchment
Slopes at the heads of gullies (S) and drainage area (A) were calculated and the values of S and A were plotted on a double logarithmic graph.

The best fit line through the cloud of points represents the mean topographic threshold line (Figure 6.16). Another line parallel to the mean topographic threshold line can be drawn which represents that below which no gully initiation has taken place. The dashed line in Figure 6.15 represents the threshold line.

A negative power relationship exists for the data in the form:

\[ S = 0.9315 A^{-0.179} \quad (r^2 = 0.26; \ p = 0.001) \quad (6-2) \]

The coefficient of determination shows a weak relationship between slope and gully drainage area. The \( r^2 \) value for the slope area relationship is low but comparable with other studies (Vandekerckhove et al., 2000), where a value of \( \beta = 0.104 \) has been reported. Morgan and Mngomezulu (2003) have obtained a value for \( \beta = 0.11 \) for Mbothoma, Swaziland and relate it to subsurface erosion processes.

![Figure 6.16 Mean topographic threshold for gullies in the study area](image)

The value of the exponent \( b \) reflects the dominant erosion process in the catchment. Montgomery and Dietrich (1994) propose that values of \( \beta \) greater than 0.5 indicate Hortonian overland flow while Vandekerckhove et al., (2000) obtained values of
0.2-0.3 for sites on rolling topography in Portugal where overland flow is the dominant gully initiation process. Vandekerckhove et al., (1998) reported values of $\beta$ between 0.13 and 0.4 for Spain and Portugal, respectively. Values less than 0.2 are normally interpreted as indicators of subsurface processes and mass movement (Morgan and Mngomezulu, 2003). The value of $\beta$ obtained for the Fergusson catchment is 0.17 that falls in the range obtained by other studies (Vandaele et al.,1996; Vandekerckhove et al.,1998). The low value of $\beta$ does not indicate overland flow as the dominant gully initiation process. This low value of $\beta$ perhaps indicates subsurface erosion processes. The influence of subsurface flow weakens the negative trend found for overland flow. Another reason for a low value of $\beta$ is the low relief variation of the area. All gullies are on alluvial floodplains where the average mean slope of gully drainage areas is 1.5°. No slope variation has been observed for particular gully types. These observations suggest that a critical threshold for gully initiation in the study area exists but is not a strong control on gully initiation. However, these topographic controls are likely to contribute to the gully development through runoff washing away eroded material from gullies and contribute to the maximum threshold of gully expansion.

Further, gully expansion rate and gully drainage area is plotted for each gully type (Figure 6.17). Amphitheatre gullies ($r^2 = 0.83$, $p = 0.05$) and bank gullies ($r^2 = 0.77$, $p = 0.05$) demonstrate strong linear relationships between rate of gully expansion and gully drainage area, suggesting that surface runoff contributes to gully expansion for amphitheatre and bank gullies.

A very weak relationship exists for gullied slumps ($r^2 = 0.005$, $p = 0.05$) and other gullies ($r^2 = 0.11$, $p = 0.05$). These regression results indicate that gullied slumps are not dependent upon upslope drainage area for their expansion, with sapping erosion being the main process driving their initiation and expansion. ‘Other gullies’ also demonstrate the same behavior.
6.2.4 Rainfall/Groundwater/Flooding

Rainfall in the study area is highly variable, the result of varying penetration of the monsoon. Katherine (the nearest rain gauge station to the Fergusson River) annual rainfall data from 1873 till 2008 has been plotted in Figure 6.18. The mean annual rainfall at Katherine is 992.7 mm and almost 90% occurs between November and March (see Appendix A2 for mean monthly rainfall of the Katherine region). Overlay analysis of gully types with rainfall data cannot be performed due to the non availability of the spatially distributed points of rainfall.
The minimum annual rainfall for the wet season at Katherine was 439.5 mm in 1951/52 and the maximum was 1772.5 mm in 1998/99. The mean annual runoff in the Fergusson River is 294 mm with a minimum of 47 mm and maximum of 784 mm (Jolly, 2001). Rainfall data shows repetitive quasi-cycles of low and high rainfall. The intensity of rainfall is important in relation to the rate of runoff and soil erosion. Some intense monthly rainfall events in the Katherine/Daly River region have been given in Table 6.4. The intense nature of rainfall in the region both in terms of seasonality and individual rainfall events promotes gully erosion. Saturation of the soils is likely at a seasonal, level making them structurally weak and very susceptible to erosion while high intensity, short rainfall events generate surface runoff that can initiate gullies and transport sediment from existing gullies.

River flooding is likely to affect the gullies in the study area. Since 1873 there have been five major flood events (Table 6.5) in the Katherine/Daly River, all of them during the wet season. The highest was in January 1998 with a peak level of 20.4 m (gauge height) at the Railway Bridge at Katherine. The previous peak flow occurred in 1957 with a peak height of 19.29 m.
Table 6.4 Intense rainfall events 1873-2008

<table>
<thead>
<tr>
<th>Years</th>
<th>Annual Rainfall (mm)</th>
<th>Intense Monthly Rainfall (mm) Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1897</td>
<td>1393.5</td>
<td>Dec-752.1</td>
</tr>
<tr>
<td>1904</td>
<td>1480.2</td>
<td>Jan-704.6</td>
</tr>
<tr>
<td>1906</td>
<td>995.5</td>
<td>Dec-334.9</td>
</tr>
<tr>
<td>1907</td>
<td>1266.6</td>
<td>Feb-489.7, Dec-429.2</td>
</tr>
<tr>
<td>1910</td>
<td>1121.1</td>
<td>Jan:391.0</td>
</tr>
<tr>
<td>1914</td>
<td>903.6</td>
<td>Jan:429.7</td>
</tr>
<tr>
<td>1915</td>
<td>1130</td>
<td>Dec:444</td>
</tr>
<tr>
<td>1918</td>
<td>843.2</td>
<td>Jan:419.5</td>
</tr>
<tr>
<td>1931</td>
<td>1011.6</td>
<td>Jan-316.0, Mar-242.0, Apr-98.9</td>
</tr>
<tr>
<td>1940</td>
<td>1321.9</td>
<td>Jan-490.9</td>
</tr>
<tr>
<td>1957</td>
<td>1400.6</td>
<td>Mar-463.2</td>
</tr>
<tr>
<td>1963</td>
<td>1041.4</td>
<td>Jan-477.5</td>
</tr>
<tr>
<td>1967</td>
<td>1084.3</td>
<td>Feb-460.5</td>
</tr>
<tr>
<td>1969</td>
<td>1169.9</td>
<td>Feb-430.2</td>
</tr>
<tr>
<td>1985</td>
<td>1051.4</td>
<td>Nov-242.8</td>
</tr>
<tr>
<td>1987</td>
<td>1208.8</td>
<td>Nov-222.2</td>
</tr>
<tr>
<td>1991</td>
<td>1182.7</td>
<td>Jan-416.6, Feb-408.3</td>
</tr>
<tr>
<td>1996</td>
<td>905</td>
<td>Dec-405.4</td>
</tr>
<tr>
<td>1997</td>
<td>1232.9</td>
<td>Jan-502.0</td>
</tr>
<tr>
<td>1998</td>
<td>1772.5</td>
<td>Jan-913.8, Dec-419</td>
</tr>
<tr>
<td>1999</td>
<td>1106.2</td>
<td>Oct-122.6</td>
</tr>
<tr>
<td>2000</td>
<td>1249</td>
<td>Mar-300.4, Oct-1222.2, Nov-121.0</td>
</tr>
<tr>
<td>2001</td>
<td>1520.9</td>
<td>Jan-539.9, Feb-308.8, Oct-123.8, Nov-238.6</td>
</tr>
<tr>
<td>2002</td>
<td>885</td>
<td>Feb-444</td>
</tr>
<tr>
<td>2003</td>
<td>1500</td>
<td>Dec-574.6, Jan-433.4</td>
</tr>
<tr>
<td>2004</td>
<td>1374.3</td>
<td>Feb-387</td>
</tr>
<tr>
<td>2005</td>
<td>1129.6</td>
<td>Nov-194.4, Dec-393.4</td>
</tr>
<tr>
<td>2006</td>
<td>1228.3</td>
<td>Mar-455.8, Apr-212.6</td>
</tr>
<tr>
<td>2007</td>
<td>1309.4</td>
<td>Nov-105.6, Dec-330.6</td>
</tr>
<tr>
<td>2008</td>
<td>1348.7</td>
<td>Feb-447, Dec-398.1</td>
</tr>
</tbody>
</table>
Figure 6.19 Effect of rainfall on gullies and sedimentation. (Photos by author, dated: 08-01-2008)

Note: Photos were taken after tropical cyclone Helen on 4th January, 2008. Still water on gully floor causes soils to weaken and be eroded (a) Amphitheatre gully under water, (b) Sediments in transport in the Fergusson and Edith Rivers.
Table 6.5 Katherine River recorded floods (Source: KPL, 1998)

<table>
<thead>
<tr>
<th>Date</th>
<th>Flood Level Gauge Height</th>
<th>Flow m³/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 1897</td>
<td>19.0-19.5</td>
<td>4,800-6,500</td>
</tr>
<tr>
<td>April 1931</td>
<td>19.05</td>
<td>4,828</td>
</tr>
<tr>
<td>January 1940</td>
<td>19.26</td>
<td>5,500</td>
</tr>
<tr>
<td>March 1957</td>
<td>19.29</td>
<td>5,677</td>
</tr>
<tr>
<td>January 1998</td>
<td>20.40</td>
<td>*12,000</td>
</tr>
</tbody>
</table>

*Based on preliminary analysis.

“Katherine Flood Report – Hydrology Study”.

Flood data for Katherine shows that flood peaks occur after heavy rainfall, particularly late in the wet season. High flows cover the alluvial levees, and spread onto floodplains and into depressions, carrying sediments from gully floors into the main channels and downstream via the flood return channels (see section 5.3.1). These events also rapidly recharge the unconfined alluvial aquifers (‘bank storage’), and are likely to lead to these soils becoming saturated and vulnerable to slumping. This process may trigger gully erosion incision and slumping, particularly for bank gullies which are located along the main channels and are likely to be more affected by overbank flooding as compared to the amphitheatre gullies located on floodplains.

6.3 Causes of Gullying

As already discussed gullies in the Fergusson River catchment have been classified into four types namely amphitheatre, gullied slumps, bank gullies and other gullies, based upon shape and location (described in section 5.3) and are the outcome of various erosion processes (Table 6.6). The result of reviewing detailed field observations, satellite images and aerial photographs interpretation and analysis of the slope area relationship have shown that sapping is a primary process for gully initiation (detail in section 5.3) in three of the gully types and different types of sapping have produced different types of gullies with impact on their shape. For example, deep gullies (e.g. gullied slumps) are the outcome of mass failure followed by sapping deep in the soil profile (detail in section 5.3.2). Shallow gullies (e.g. amphitheatre gullies) have been produced by extrusion sapping within the ‘A
horizon’ (detail in section 5.3.1). Bank gullies, however, are likely to be initiated by surface runoff (detail in section 5.3.3).

Gully development processes include slumping, surface runoff and rilling. Overlay analysis of gully types and geology and soils group layer have demonstrated that alluvium is most susceptible to gully erosion (see section 6.2.1). Sapping is major processes for gully initiation particularly for Hydrosols and Tenosols. Processes of gully initiation and development are active in poorly drained alluvial soils where almost 98% gullies are initiated and developed. Sapping processes might be accelerated by increased groundwater during wet period and reduced evapotranspiration in overgrazed areas that are not compacted also enhance the gullying processes.

Table 6.6 Gully initiation and development processes

<table>
<thead>
<tr>
<th>Gully Processes</th>
<th>Gully Types</th>
<th>Amphi theatre</th>
<th>Gullied Slumps</th>
<th>Bank Gullies</th>
<th>Other Gullies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiation processes</td>
<td>Sapping Erosion</td>
<td>Sapping Erosion</td>
<td>Surface Runoff</td>
<td>Sapping Erosion</td>
<td></td>
</tr>
<tr>
<td>Development processes</td>
<td>Sapping Erosion and Surface Runoff</td>
<td>Sapping Erosion and Surface Runoff</td>
<td>Surface Runoff</td>
<td>Sapping Erosion and Surface Runoff</td>
<td></td>
</tr>
</tbody>
</table>

Rainfall also triggers gully erosion processes. Rainfall data indicates the increased intensity of rainfall events in the study area, particularly for last decade. Intense storm also generate local runoff which can also accelerates gully development processes by enhancing slumping, rilling and overland flow. Intense rainfall causes the flooding, that accelerates gullying, and produces surface wash and removal of eroded material from gullies and plays a role in gully development and widening.

In relation to gully formation processes the time of gully initiation is important to identify whether a gully is the outcome of natural processes or is human-induced. For instance, if a gully was initiated ~ 300 years ago in Australia when landuse practices are unlikely to have caused a significant reduction in resistance to erosion, then the gullying might be the outcome of natural processes. But if gullying has been initiated ~100 years, after the initiation of landuse practices that reduce resistance to erosion (e.g. grazing by domestic stock), gullying might be linked to landuse. As previously
mentioned gully age estimates for the Fergusson gullies (see section 5.4.2) demonstrate that many gullies were initiated around 1880 AD coinciding with the arrival of cattle in northern Australia (Leichhardt, 1847; Mitchell, 1848). Therefore, the role of cattle in gully initiation cannot be ignored (Condon, 1986; Makin, 1970). Further, gully age can be related to the landuse/landcover overlay analysis (detail in section 6.2.2), that shows that all gullies are developed in the areas designated as being ‘grazing of native vegetation’. These observations and analysis suggest that grazing has formed preconditions for gully formation. Low vegetation cover produced by grazing reduces the resistance to overland flow by vegetation removal. The low vegetation cover patches makes favorable conditions for undermining as the result of groundwater sapping and contributes to formation of initial topsoil depressions for gully initiation as is evidenced by field observation (section 5.3, Figure 5.7).

The spatial distribution of gullies is also affected by factors controlling gully processes (detail in section 5.3, for gully types and spatial distribution). Field observation shows that the study area has flat topography that may not contribute significantly to gully initiation; but slope-area relationship calculations demonstrates that a weak slope-area threshold exists, that may permit sufficient runoff to accelerate the gully development process. The relationship of gully expansion rate to gully drainage area is explored for each gully type, suggesting that amphitheatre and bank gullies expand as a combination of seepage erosion and surface runoff. For gullied slumps and other gullies, sapping is the dominant erosion process for gully initiation and expansion but these gullies are also affected by surface runoff.

6.4 Summary

Within any given area, several gully initiation processes may be active, reflecting the variations in slope, soil types and thickness, and vegetation types and density (Montgomery and Dietrich, 1994). As already discussed, almost 98% of the gullies in the study area are on alluvium. Overlay analysis suggests that soil is the most important factor in gullying in the Fergusson River catchment. Although various types of soil exist on alluvium (see section 6.2.1, Figure 6.5) the gullies are formed only on Hydrosols and Tenosols particularly on poorly drained soils, which remain saturated three to four months for a year, effecting groundwater sapping. These
observations and analysis suggest that seepage erosion is only a viable gully initiation mechanism in cohesionless materials (Montgomery and Dietrich, 1994).

Gullies can be initiated by extreme rainfall rather than average events (Zachar, 1982; Morgan, 1995). High rainfall gives rise to runoff and adds to groundwater, and also causes flooding. Groundwater plays an important role for gullied slumps and amphitheatre type gullies, but both are also affected by surface runoff because all the eroded material is washed out by surface runoff during the wet season. Rainfall and flooding enhances the slumping by means of groundwater and gully extension by removing the eroded material from gully floors and side walls. It has been reported that gullies up to 1 m deep have formed during one wet season on disturbed slopes of less than 2° in the seasonally wet tropics of the Kakadu region, Australia (Duggan 1998).

It has been noticed that the area of one to two meters upslope of gully heads has low vegetation cover as compared to other area around gullies that provides low resistance to surface runoff and accelerates the gullyhead advancement process. But overall, neither vegetation structure nor vegetation cover have a significant control on gully erosion once it has begun, partly because of low vegetation cover, lack of deep rooted native grasses and undermining of vegetated soil.

Gullying may be a response to destruction of vegetation, the causes of which are as follows. Given the heterogeneity (i.e. gullies are at different stages of development) of the gully system in the Fergusson River catchment, the most likely causes would have been spatially patchy. Vegetation may be affected by cyclones, fire, drought and grazing (Johns, 1989; Tropical Savannas CRC, 2006; Catterall et al., 2008). Cyclones usually destroy the tall trees but not the vegetation cover (Tropical Savannas CRC, 2006). Fire usually occurs on a large scale, so, both cyclones and fire are unlikely causes for vegetation patchiness (Catterall et al., 2008). Droughts are wide spread phenomena, therefore, are unlikely causes for patchiness of vegetation.

The major landuse of the catchment is ‘grazing natural vegetation’ which may have contributed to gullying by creating vegetation patchiness by differential grazing and preferential occupation of sites for camping. The presence of feral animals in the catchment may also have contributed to gully initiation in the form of overgrazing and disturbance of soils along pathways and animal tracks. The estimated age of
gullies also suggests that landuse might have played a role in initiating gullying in the region.

The role of grazing in gully erosion is known from other areas. Introduction of stock in the 1840s and 1850s resulted in degradation of vegetation of valley bottoms in the upper Murrumbidgee River, NSW, and Australia, triggering a massive phase of gully erosion (Olley and Wasson, 2003). In South Africa, an increase in both human population density and the number of cattle during the 20th century resulted in vegetation and cover reduction (Boardman et al., 2003; Keay-Bright and Boardman, 2007). Increased cattle movement along paths and drainage lines caused high compaction rates in clay soils and subsurface erosion consequently. Therefore it is possible to speculate that the introduction of cattle to the Fergusson catchment would also have played a potential role in gully erosion.

Seepage erosion and gullying would be expected to occur in response to local disturbance in low gradient areas (Montgomery and Dietrich, 1994). This is true in the study area where most gullies are on alluvial floodplains that have very low relief variation and the area is characterized by highly weathered bedrock that may have contributed towards local disturbances. Low relief variation may have resulted in a very weak slope area relationship. No previous studies have attempted to analyse the threshold conditions under which gullies in the Fergusson River catchment are initiated. The slope area relationship of Fergusson gullies demonstrates a weak inverse relationship, showing that threshold for gully initiation in the study area exists that might contribute to gully development processes rather than initiating gully erosion. An inverse slope area relationship indicates that surface runoff might be attributed to the saturated soils in the study area which generate saturation overland flow produced sufficient runoff to trigger the gully erosion development process and contribute to entrain the sediments from gullies. The relationship of gully expansion rate and gully drainage area shows that amphitheatre and bank gullies are affected by surface runoff that depend upon sufficient drainage area to saturate the soil profile in order to cause the gullyhead to fail and provide overland flow runoff to remove the eroded material.
Chapter 7: Summary and Conclusion
Chapter 7: Summary and Conclusion

7.1 Introduction

This chapter presents the summary and conclusions of the research. The conclusions of this study are given by, first, summarizing the findings and their implications, and then focusing on the significance of the results with respect to the aims of the study. In addition, directions for future research are identified.

7.2 Summary of the Findings and Implications

7.2.1 Geoinformatics Based Framework for 3D Gully Mapping

A geoinformatics based framework for Three Dimensional (3D) gully mapping (section 4.1) has been developed, and therefore the first objective of this study has been achieved. The framework has been implemented successfully in the study area to classify, analyse and quantify gully erosion (section 5.3, 5.4 and 5.5). The gully erosion information generated by the author has been used and acknowledged by Rustomji and Caitcheon (2010) (see Appendix D) for the development of a sediment and nutrient budget for the Daly River catchment, Northern Territory.

This project demonstrates the first ever application of Cartosat-1 stereo imagery for 3D mapping of gully erosion. Previous studies (Lehner et al., 2006; Srivastava et al., 2007; Srivastava et al., 2008; Gianinetto, 2009) have only concentrated on Digital Elevation Model (DEM) derivation and topographic map updates. Use of stereo imagery enables the production of a Digital Surface Model (DSM) that provides the possibility to visualize land forms in 3D combined with Earth surface cover information. This 3D visualisation of land forms and surface cover condition is helpful in distinguishing landform features and provide basis for accurate 3D mapping which is not possible using DEMs.

The creation of oriented images for the study area utilizes a rational polynomial coefficients based method, a standardised and validated sensor oriented method for the correction of high resolution satellite images and includes a 1_second Shuttle Radar Topographic Mission (SRTM) DEM (~30 m resolution), Ground Control Points (GCPs), elevation, exterior and interior orientation information. The accuracy of the DSM was verified in the field using a Differential Global Positioning System
(DGPS) by checking ground control points in various topographic settings and by measuring gullies. Horizontally sub pixel level and vertically one pixel level, absolute accuracy of the DSM was achieved. Relative accuracy assessment shows consistency within gullies and overall ~ 10% error is found within mapped gullies and volume. Farai, and Hilda (2011) have also measured the gully erosion accuracy in the Zhulube Meso catchment, Limpopo basin and reported that Landsat TM error, Spot and orthophoto interpretations produced 64%, 46%, 23% errors, respectively. Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) data is used in Ethiopia for gully erosion mapping and generated 33-11% error (Bouaziz, et al., 2009).

Stereo aerial photographs at a scale of 1:30000 from 1948 have been used to obtain historical information on gully erosion. No camera calibration report was available for the aerial photographs so orthorectification was challenging. Manual measurements were taken on aerial photographs to find the principle point and vertical and horizontal distances between fiducial marks. Further, this information was placed in the form of a Fairchild camera model in ‘Image Analysis for ArcGIS’, to define the position of fiducial marks on the photographs and to run the camera model. Orthorectification of stereo aerial photographs was performed using GCPs (i.e. latitude, longitude, and elevation), 1_second SRTM DEM (~30 m resolution), interior orientation parameters (i.e. principal point, focal length and coordinates of fiducial marks) and exterior orientation information (i.e. derived by camera model). The Root Mean Square Error (RMSE) for the aerial photographs was 0.02 and they were overlayed on Cartosat-1 oriented images without any geometric distortion.

Pairs of orthorectified 1948 stereo aerial photographs were used for 3D visualization and mapping of historical gullies in the study area for comparison with gullies mapped from the 2008 Cartosat-1 image and to find the retrospective information. Relevant information for gully volume calculation was collected. The geoinformation based framework therefore provides a basis for quantifying the spatial, 3D and temporal characteristics of gullies using data sources that are widely available.
7.2.2 Gully Classification and Spatio-Temporal Changes

Based upon field observations and gully morphology, a gully classification was developed taking into account gully shape, spatial distribution and dominant erosion processes. Four classes of gullies were identified in the study area; amphitheatre gullies, gullied slumps, bank gullies and ‘other gullies’ and as such the second objective was achieved. It has been identified that groundwater sapping is the main process for initiation of gullied slumps, ‘other gullies’ and for amphitheatre gullies. Surface runoff also contributes in combination with groundwater sapping to gully growth. Slumping, with side wall collapse and tension cracks and surface runoff are the main erosion processes associated with gullied slumps, bank gullies, amphitheatre gullies and ‘other gullies’. Amphitheatre gullies have some of the characteristics described by Brooks et al., (2006) and bank gullies show some similarity with gullies described by Vandekerckhove et al., (2000). One thing is special about Fergusson gullies: they all occur on floodplains and alluvial soils particularly on Hydrosols and Tenosols and are distinct from most studies of gullies which are on hillslopes.

Mapped gullies from 1948 aerial photographs and 2008 stereo images provided data for a comparison of the gullies in space and time; therefore, part of third objective was accomplished. Spatio-temporal analysis of gullies demonstrates both gully growth and reduction where some gullies are completely revegetated, others are heading towards revegetation but are still eroding, and some are eroding very actively. Gully head retreat rates for gullied slumps have shown the fastest rate of 1.72± 0.17 m yr⁻¹ followed by bank gullies 1.15 ± 0.11 m yr⁻¹, amphitheatre gullies 0.93± 0.09 m yr⁻¹ and other gullies 0.68 ± 0.06 m yr⁻¹. Variation in gully types, forms, size and state demonstrate a heterogeneous gully system in the Fergusson study area. Despite gully system variability, knowledge of gully classes and information on gully growth can be used as an important tool for understanding gully erosion processes and sediment budget calculations.

7.2.3 Quantification of Gully Erosion

Quantification of gully erosion is an important issue. From a sediment budget perspective it is important to know the gully erosion contribution to total soil loss and relative contribution of each gully to the total sediment yield for the construction
of a sediment budget. Using stereo aerial photographs and images from 1948 and 2008, gully dimensions were measured and gully volumes were determined, and therefore the third objective was attained. Volumetric changes for 1948-2008 showed an increase of \((4.5 \pm 0.4) \times 10^6 \text{ m}^3\). Volumes were calculated for each gully and for all gully classes. The results demonstrate that the total quantity of soil eroded by gullies was highest for amphitheatre gullies and lowest for bank gullies. Gullied slumps have shown the second highest volume. Further, the percentage increase in gully volume was calculated for each class for 1948-2008, with bank gullies having the highest increase in percent volume while amphitheatre gullies showed the least percentage increase. Volumetric change in gully erosion from 1948 to 2008 was \((2.8 \pm 0.03) \times 10^3 \text{ m}^3 \text{ km}^{-2}\).

The Specific Sediment Yield (SSY) from gully erosion was determined and a regression analysis was performed relating SSY with Drainage Density (DD). Regression analysis showed a significant positive relationship between specific sediment yield and drainage density. Furthermore, a regional and global comparison of SSY was performed which shows that the SSY of the Fergusson River area overlaps with the highest global erosion rates. The high rate of erosion is most likely because of the particularly susceptible soils caused by alluvial sediment deposition and interaction with a highly variable flood and groundwater regime. The factors contribute to a predominance of subsurface erosion processes, with it having been suggested that gully heads advance most rapidly when subsurface processes are dominant.

The quantitative measures of gully erosion can be used for soil erosion studies in the Daly River catchment and provides a basis for understanding gully erosion processes in alluvial soils regionally and globally.

### 7.2.4 Gully Control Factors

Gullying is controlled by various environmental factors in terms of geology, soil type, vegetation, topography, landuse and climatic conditions. A GIS based overlay analysis was performed for the mapped gullies and gully control factors in order to describe the relationship of these factors with gullying, and therefore the fourth objective was achieved. Results of the overlay analysis show that all mapped gullies are found on alluvial soils, namely Hydrosols and Tenosols, which are wet for most
of the year. Alluvial soils are unconsolidated channel and floodplain material which is highly sensitive to erosion and are affected by intense rainstorm and flood events. Mean annual rainfall in the study area is 993 mm and most of this falls during the wet season (November and March). The alluvial soils are therefore subjected to a highly variable groundwater regime, associated with wet season rainfall and overbank recharge and runoff during high flow events and surface inundation and return flow to the river. ‘Grazing of natural vegetation’ is identified as a major landuse, and the presence of feral animals has also been observed in the field. Overgrazing may have contributed towards accelerating the erosion processes and formation of gullies. Gully age estimates indicate that Fergusson gullies were initiated ~ 100 years ago which coincides with the time of arrival of cattle in the Northern Territory.

Topography may play a role for gully development in the study area. The critical topographic thresholds for gully erosion is calculated in the form of a gully slope-area relationship ($S = 0.9315 \ A^{-0.179}, \ r^2 = 0.26$). The result demonstrates an insignificant relationship between slope and area, and indicates that slope/surface catchment area do not necessarily contribute to gully initiation. However, analysis of gully expansion rates indicate catchment area (and therefore surface runoff) is important for the expansion of amphitheatre and bank gullies. Field observations and analysis suggests that both subsurface and surface process contribute to gully development and progression.

The analysis of gully control factors indicates that alluvial soils should be given high priority when formulating management strategies for gully control.

7.3 Significance of the Findings and Conclusions

This thesis addresses gully erosion dynamics for the first time in the Fergusson river catchment and explores the potential of new data (Cartosat-1 images) for volumetric measurements of gully erosion.

7.3.1 Significance of a Geoinformatics based Method for Gully Mapping

Cartosat-1 imagery for gully erosion mapping and quantification has been explored and applied. Results show that:
• The spatial resolution (2.5 × 2.5 m) of Cartosat-1 images is an optimal resolution to study gullies at a site and catchment scale. The geoinformatics based method provides a cost effective solution in terms of time and money and a reliable way to investigate gully morphology.

• DSMs are an excellent and efficient source for understanding gully spatial distribution and classification. The 3D representation of gullies helps observers to understand gully morphology and formation processes.

These findings introduce a new framework and dataset to quantify gully erosion and have been recognized at geotechnical, and remote sensing and photogrammetric conferences (Sattar, 2010a, b) (See Appendix E).

7.3.2 Significance of Gully Classification and Spatio-Temporal Changes

The gully classification and spatio-temporal analysis of gullies found that:

• Four types of gullies exist in the study area; amphitheatre, gullied slumps, bank gullies and other gullies.

• Groundwater sapping is a key process for gully initiation while slumping, riling, surface runoff and tension cracks are identified as secondary erosion processes.

• Spatio-temporal changes demonstrate a heterogeneous gully system in the study area with evidence of both gully size increase and decrease for all gully types. This indicates the gullies were not triggered by a single event but various factors have contributed to gully initiation and development.

The knowledge of dominant gully erosion processes and temporal changes in gullies will assist with future land management practices in the catchment and other areas where these gully types exist.

7.3.3 Significance of Quantification of Gully Erosion

Quantification of gully erosion volume reveals that:

• Volume of gully in 2008 (7.9 ± 0.7)×10^6 m^3 is approximately twice the gully volume in 1948 (3.4 ± 0.3)×10^6 m^3 in the study area, and
• Gully erosion volume in 1948 from amphitheatre gullies was \((1.6 \pm 0.2) \times 10^6\) m\(^3\), gullied slumps \((0.7 \pm 0.1) \times 10^6\) m\(^3\), bank gullies \((0.2 \pm 0.03) \times 10^6\) m\(^3\), and other gullies was \((0.8 \pm 0.1) \times 10^6\) m\(^3\).

• Gully erosion volume in 2008 from amphitheatre gullies was \((2.9 \pm 0.4) \times 10^6\) m\(^3\), gullied slumps \((2.2 \pm 0.3) \times 10^6\) m\(^3\), bank gullies \((1.1 \pm 0.2) \times 10^6\) m\(^3\) and other gullies was \((1.7 \pm 0.2) \times 10^6\) m\(^3\).

• Increase in erosion volume as a percentage of gully size is highest in bank gullies, seven times more than gullied slumps, three times more than in both amphitheatre and other gullies and two times more in 2008 as compared to the erosion volume in 1948. The specific sediment yield in the study area for 1948-2008 was calculated \((6.1 \pm 0.6) \times 10^3\) t km\(^{-2}\) yr\(^{-1}\).

Global and regional comparison of the specific sediment yield of the gullies in the study area indicates that this is extremely high. The results are consistent with a few other studies in northern Australia (Williams, 1976; Erskine and Saynor, 2000; Brooks et al., 2008; McCloskey, 2009) and in the Loess Plateau of China (NNSFMP, 1993). This can be attributed to the fact that these gullies are alluvial gullies, while other available data is from hillslope or colluvial gullies. Alluviums are unconsolidated material and have more potential for erosion. There is no other published data available for the alluvial gully types (i.e. amphitheatre gullies, gullied slumps, bank gullies and other gullies) identified in the study area. Therefore direct comparison of the specific sediment yields of alluvial gullies is not possible. However, an overall comparison of the specific sediment yield of the alluvial gullies in the study area has been made with the specific sediment yield in the published data for colluvial and hillslope gullies. Therefore, although in a global context the erosion rates observed in the study area are high, it is difficult to conclude whether erosion rates in the Fergusson River catchment are high for alluvial gullies.

7.3.4 Significance of Control Factors in Gully Erosion

Analysis of gully control factors (i.e. geology, soil, vegetation, landuse, topography and climate) demonstrates that soil is the most important factor influencing gully formation in the study area. Sapping erosion is the primary erosion process for gully initiation in poorly drained alluvial soils. Slumping and surface runoff has been identified as secondary erosion processes contributing to gully development. The
properties of alluvial soil and its location on the floodplain of the Fergusson River are vulnerable to gullying. The role of other factors, particularly landuse require further investigation.

7.3.5 Significance of Gully Erosion in Catchment Management

Gully erosion has not been considered as a major sediment source in a sediment budget for the Daly catchment (Rustomji and Caitcheon, 2010) prior to this study, either due to the non availability of data or being ignored relative to hillslope erosion. The high specific sediment yield from gully erosion in the study area indicates that this source cannot be ignored and should be given a high priority in the sediment budget construction for this area and in future catchment management.

7.4 Limitations of Research

The resolution of the satellite images limits the mapping of gullies to those which are larger than 6.25 (2.5×2.5) m². However, field observations indicated that gullies smaller than 6.25 m² are very few and are therefore a negligible sediment source.

Rates of gully erosion are calculated based upon 3D measurements of historical stereo aerial photographs from 1948 and stereo satellite Cartosat-1 images from 2008. It would have been ideal to have more time series data between 1948 and 2008 in order to identify the temporal changes of gullies in relation to gully formation and development stages, but complete sets of aerial photographs of the study area were not available for other time periods. The limited temporal sequence makes investigation of the role of rainfall and hydrology (flood regimes) in gully formation difficult to quantify in this study.

Information on grazing is inferred from the evidence of a cattle yard (Claravale station) close to the gullies in the study area, but stock data were not available. Therefore the occurrence of gullies on the left and right bank can not be comprehensively linked to grazing.

Analysis of gully control factors has shown soil as the most important gully controlling factor. However, further information on soil properties, such as soil texture and chemical properties were not available making it difficult to comment on the soil’s dispersibility and erodibility characteristics, and thereby identifying why these soils are so susceptible to erosion.
Age of gully initiation is inferred from an assumed exponential curve representing gully growth as a function of time. These growth curves are recognised in the literature but have not been established or validated for the gullies in the study area. Therefore interpretation of the extrapolated dates should be approached with caution. However, given this assumption, the results of this study indicate that most of the gullies in the Fergusson River catchment, that have continued to expand since 1948, formed between ~1900 and ~1930. This observation does not prove a role for overgrazing as a trigger for gully formation; it at least shows that such a role is possible and requires further study.

7.5 Directions for Further Research

The results of the study raise a number of new issues and questions as follows:

- Alluvial gullies have been shown to form and behave quite differently from colluvial and hillslope gullies. Alluvial gullies are a widespread phenomenon in northern Australia and more studies are needed in order to build an understanding of the different gully types and associated erosion processes.

- The research shows temporal changes in gully behaviour between 1948 to 2008, but more detailed monitoring of gully growth in relation to seasonal conditions should be undertaken to provide a better understanding of gully formation and growth processes, to develop an understanding of which rainfall and runoff characteristics are important for gully initiation and expansion.

- Many of the gullies in the study area had formed prior to 1948. Issues regarding alluvial gully age and initiation need to be explored further to identify and better understand gully control factors. The use of radionuclide tracers for quantifying gully age, particularly beyond the aerial photographic record, needs further research. Furthermore, more sophisticated statistical analysis (e.g. Generalised Linear Model (GLM) should be applied to determine statistically which factors most affect gully formation.

7.6 Final Remarks

This thesis has achieved its major objectives. The results of this study will contribute to the understanding of gully erosion phenomena in the region and globally.
Furthermore, this research will provide a basis for understanding sediment dynamics in the Daly River catchment and will help improve catchment management by contributing to establishing the sediment budget.
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Appendices
Appendices

Appendix A

A1 Description of Vegetation classes and species in the study area

Generally Elliott (Florina) and Jindabeth (Jindare) soil has the tall open shrubland and specifically comprised of Melaleuca viridiflora, Grevillea pteridifolia and Petalostigma pubescens.

Tall sparse shrubland are found on the soils description; Elliott (Florina) - shallow Loamy Yellow Earths; minor Jindabeth - Sandy Yellow Earths with vegetation species Petalostigma pubescens and Terminalia pterocarya. Vegetation description is comprised of tall mixed shrubland with scattered low emergent Eucalyptus latifolia, Eucalyptus tectifica, E. alba and E. tetradonta and poor annual Sorghum grass layer.

Edith (Belbowie and Edith) soils have generally medium-high open woodland; Eucalyptus foelscheana, Eucalyptus patellaris, Eucalyptus tectifica.

Banyan - Grey and Brown Clays; minor Cununurra and Coolibah - Grey and Brown Clays contain Mid-high open woodland; Eucalyptus microtheca, Eucalyptus papuana. Eucalyptus microtheca open woodland with frontage grasses on the back-plains; elsewhere either grassland or E. papuana and Terminalia carpentariae open woodland.

Clavaverle contain Woodland composed of Eucalyptus miniata. Eucalyptus miniata open forest with a frequently well developed shrub layer and Spinifex and annual Sorghum grass layer.

Low open woodland are found on Shallow or skeletal soils. Low woodland or tall shrubland on shallow gravelly soils and open forest on rocky sandy soils with mainly Spinifex and annual Sorghum grass layer. Dominant species are Eucalyptus tectifica, Eucalyptus clavigera, Erythrophleum chlorostachys.

Mid-high open woodland are found on Blain soils. Main species includes Eucalyptus miniata, Eucalyptus tetrodonta, Erythrophleum chlorostachys, Eucalyptus tetrodonta and E. miniata open forest with subordinate Erythrophleum chlorostachys and Eucalyptus foelscheana with annual Sorghum grass layer.

Low open woodlands with dominant species; Eucalyptus tectifica, Erythrophleum chlorostachys, Brachychiton diversifolius are found on Jindabeth (Jindare) soil. Open woodland with a wide range of species with a scattered shrubs layer of Grevillia heliosperma and Petalostigma and predominately annual Sorghum grass layer.
Mid-high open woodland; Eucalyptus tectifica, Eucalyptus grandifolia, Lophostemon grandiflorus are observed on Coolibah soil. Eucalyptus tectifica, Eucalyptus grandifolia and Tristania woodland with perennial grasses; tributary drainage floors have very scattered E. papuana with very dense perennial grasses dominated by Themeda.

Tippera series contain Woodland with species Eucalyptus foelscheana, Eucalyptus tectifica, Eucalyptus confertiflora. Eucalyptus foelscheana low woodland with few shrubs and mainly perennial Sehima tall grass layer.

Low open woodland are found on Tippera (Oolloo) soil. It includes main species Eucalyptus miniata, Eucalyptus tetrodonta, Eucalyptus confertiflora. Eucalyptus tetrodonta and Terminalia grandiflora low woodland to woodland with perennial ground cover.

**A2 Mean rainfall (mm) for Years 1873 to 2010, Katherine Council**

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Appendix B

B1 Oriented images and relevant Information

Figure B-1 Cartosat-1 oriented images

Figure B-2 Layer properties of oriented images
Figure B-3 Projected raster space attribute

B2 Three Dimensional View of Cartosat-1 Digital Surface Model

Figure B-4 3D view of middle section of the Fergusson River
Figure B-5 3D view of upstream of Fergusson River

Figure B-6 3D view of downstream of the Fergusson River
B3 Historical aerial photography

**Figure B-7 Flight Line Diagram of the Fergusson River**

**B4 1940’s Aerial Camera**

**K-20:** Most comfortable and manoeuvrable aerial camera, used for low spotting oblique. Focal length 6 3/8, plate size 4"x5". Max. exposures per roll, 50. Shutter speeds: 1/25 to 1/500.

**K-17:** An all purpose reconnaissance camera designed for vertical and oblique work. Two types: K-17-A, 12 volts and K-17-B, 24 volts. Focal lengths: 6", 12", 24".


Capacity: 175 feet or 250 exposures. Also a B-1 cut film adapter for 8" x 10" film.

Shutter speeds: 1/50 to 1/300.

**F-56 Fairchild:** An all purpose camera featuring a quick-wind handle and oblique shutter release. Focal lengths: 5 1/2, 8 1/4, 20, 40. Plate size 7” X 7”. Max. exposures, 200. Shutter speeds: 1/75 to 1/225. This camera has a film marking device which photographs a stop watch and records the time on the film. There is also a 5”X7” cut film, 12 exposure adapter.
B5 Fiducial marks of Fairchild Camera

According to the preliminary edition of the Manual of Photogrammetry (1944), this kind of fiducials was approved for general use by the United States Department of Agriculture in 1937. Their design appears in the “Standard Specifications for Aerial Photography for General Map Work and Land Studies Approved for Federal Use on May 27, 1937”.

Photos with these fiducials are found in several books for aerial photo interpretation training from the fifties. This kind of marks was useful for recovering the interior orientation in an analogue way. The straight side of the markers pointing to the centre was aligned with the reference lines of the stereo plotting instrument without
the necessity of calibrated coordinates of the fiducial marks as it was usual in the era of analogue photogrammetry.

Figure B-10 Collimation (Fiducial) Mark Design. The example refers a rectangular photo format 7”x 9” (McCurdy et al., 1944)
Figure B-11 3D view of stereo aerial photographs of Fergusson River
**B6 Field verification of Cartosat-1 data**

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<td>-0.001</td>
<td>Base station set at the junction of stream and path near Fergusson River bridge.</td>
</tr>
<tr>
<td>Ev02</td>
<td>821249.9</td>
<td>8441866</td>
<td>113</td>
<td>821250</td>
<td>8441866</td>
<td>112.78</td>
<td>-0.042</td>
<td>-0.035</td>
<td>-0.022</td>
<td>Shallow linear gully near the Fergusson bridge path. <strong>Gully Bottom</strong></td>
</tr>
<tr>
<td>Ev03</td>
<td>821249.9</td>
<td>8441866</td>
<td>113.25</td>
<td>821250</td>
<td>8441866</td>
<td>113.18</td>
<td>-0.04</td>
<td>-0.035</td>
<td>-0.007</td>
<td>Shallow linear gully near the Fergusson bridge path. <strong>Gully Top</strong></td>
</tr>
<tr>
<td>Ev04</td>
<td>821501.4</td>
<td>8442048</td>
<td>129</td>
<td>821501.4</td>
<td>8442048</td>
<td>128.85</td>
<td>0.007</td>
<td>-0.005</td>
<td>-0.015</td>
<td>Right side hill at path.</td>
</tr>
<tr>
<td>Ev05</td>
<td>820254.8</td>
<td>8441597</td>
<td>115</td>
<td>820254.9</td>
<td>8441597</td>
<td>114.898</td>
<td>-0.099</td>
<td>-0.008</td>
<td>-0.102</td>
<td>Creek 6m debris</td>
</tr>
<tr>
<td>Ev06</td>
<td>819820.5</td>
<td>8441208</td>
<td>112</td>
<td>819820.5</td>
<td>8441208</td>
<td>111.89</td>
<td>0.005</td>
<td>-0.04</td>
<td>-0.102</td>
<td>Creek &amp; path junction-1.</td>
</tr>
<tr>
<td>Ev07</td>
<td>819722.7</td>
<td>8440830</td>
<td>116</td>
<td>819722.7</td>
<td>8440830</td>
<td>115.95</td>
<td>0.003</td>
<td>-0.001</td>
<td>-0.005</td>
<td>Creek &amp; path junction-2.</td>
</tr>
<tr>
<td>Ev08</td>
<td>819570.4</td>
<td>8440764</td>
<td>110</td>
<td>819570.4</td>
<td>8440764</td>
<td>109.98</td>
<td>0.02</td>
<td>-0.004</td>
<td>-0.004</td>
<td>Lunch point</td>
</tr>
<tr>
<td>Ev09</td>
<td>820702.3</td>
<td>8441475</td>
<td>160</td>
<td>820702.3</td>
<td>8441475</td>
<td>159.21</td>
<td>0.018</td>
<td>-0.011</td>
<td>-0.079</td>
<td>Second highest hill on small track at left from main path.</td>
</tr>
<tr>
<td>Ev10</td>
<td>820624.1</td>
<td>8441331</td>
<td>187</td>
<td>820624</td>
<td>8441331</td>
<td>186.589</td>
<td>0.021</td>
<td>-0.001</td>
<td>-0.411</td>
<td>Highest hill on small track at left from main path.</td>
</tr>
<tr>
<td>Ev11</td>
<td>817975.5</td>
<td>8458266</td>
<td>89</td>
<td>817975.5</td>
<td>8458266</td>
<td>88.968</td>
<td>0.019</td>
<td>-0.012</td>
<td>-0.032</td>
<td>Linear gully in the way of Edith River.</td>
</tr>
<tr>
<td>Ev12</td>
<td>812664.3</td>
<td>8423388</td>
<td>77</td>
<td>812664.3</td>
<td>8423388</td>
<td>76.99</td>
<td>0.003</td>
<td>-0.004</td>
<td>-0.01</td>
<td>Edith Gully: Gully bottom on Edith River.</td>
</tr>
<tr>
<td>Ev13</td>
<td>812664.3</td>
<td>8423388</td>
<td>80</td>
<td>812664.3</td>
<td>8423388</td>
<td>79.55</td>
<td>0.003</td>
<td>-0.004</td>
<td>-0.45</td>
<td>Edith Gully: Gully top on Edith River. Same gully.</td>
</tr>
<tr>
<td>Ev14</td>
<td>812726.2</td>
<td>8423538</td>
<td>80</td>
<td>812726.2</td>
<td>8423538</td>
<td>79.968</td>
<td>0.042</td>
<td>-0.001</td>
<td>-0.032</td>
<td>Edith Gully: Edith Gully: headcut top.</td>
</tr>
</tbody>
</table>

- RMSE(X) = 0.03
- RMSE(Y) = 0.011
- RMSE(Z) = 0.261

Mean RMSE = 0.1
Appendix C
Alluvial soil profile in the Fergusson River catchment

Figure C-1 Exposed layers of alluvium in the Fergusson River catchment
Appendix D
Applicability / use of research in sediment budget formation for Daly River Catchment
This research was funded as part of the Tropical Rivers and Coastal Knowledge (TRaCK) Research Program. TRaCK is funded jointly by:

- the Australian Government Department of the Environment, Water, Heritage and the Arts
- the National Water Commission’s Raising National Water Standards Programme
- Land & Water Australia’s Tropical Rivers Programme
- the Queensland Government’s Smart State Strategy
- the Fisheries Research and Development Corporation
- and CSIRO’s Water for a Healthy Country Flagship.

The Northern Territory Government collected and provided the hydrologic data. Danny Hunt, Jim Brophy, Chris Leslie and Colin McLachlan are thanked for providing field and laboratory technical support pertaining to the collection and analysis of the geochemical tracer data. Chris Leslie and Gary Hancock are thanked for reviewing a draft version of this manuscript.

Farah Sattar (Charles Darwin University) is thanked for sharing her knowledge of gully erosion within the Daly River catchment.
Appendix E

E1 Research Papers Presented/Published in the Refereed International Conferences


Best student presentation award for the paper titled 'Identification and mapping of alluvial gullies using remote sensing in subcatchment of Daly Basin' presented in 14 ARSPC, Australian Remote Sensing & Photogrammetry Conference held from 29 Sep to 3 Oct, Darwin, Australia.
Best presentation award for paper titled ‘The Development of Geoinformatics Based Framework to Quantify Gully Erosion’ presented in the International Multidisciplinary Scientific Geo-Conference & Expo, Surveying Geology & Mining Ecology Management (SGEM), held in Albena, Bulgaria from June 20-25.

E3 Media Presentations/News

Sattar, F., 2010a, Gully Erosion in Daly River, in Menzie, D., ed., Territory Talk: Australia, Territory FM 104.1, Darwin, 9:00-11:00 a.m.

Sattar, 2010b, Sediment flows into the Daly in Perry, L., ed., Country Hour: Australia, ABC Radio, Darwin, 1:00-2:00 p.m.

NT Country Hour on ABC Radio

Sediment flows into the Daly - 19/07/2010
http://www.abc.net.au/rural/nt/content/201007/s2957966.htm

ABC Rural

Sediment flows into the Daly

By Lorna Perry

Monday, 19/07/2010, Latest country hour stories
GIS pioneer tackles Daly River troubles

By Richie Hodgson

A woman who came to the Northern Territory after a chance meeting in Pakistan with an Australian academic is gaining an international reputation for her research work based in the Daly River.

Farha Sattar is undertaking a PhD at Charles Darwin University in which she is analysing gully erosion in the Daly River catchment. And she is receiving major awards for her work.

Farha recently returned from the 16th International Multidisciplinary Scientific Geo-Conference held in Bulgaria, where she took the award for Best Presentation and beat 350 other scientific papers.

Farha and husband Muhammad, also a PhD candidate with CDU, have become known as the pioneers of Geographic Information Systems (GIS) education in Pakistan after the pair identified a gap in the market and built the first Centre for Postgraduate Studies in GIS.

A chance meeting in Pakistan in 2004 with CDU Deputy Vice-Chancellor Research and International Professor Bob Wasson led to Farha undertaking her doctorate in spatial and temporal analysis of gully erosion in the Daly River catchment.

In 2008, Farha won the Best Student Presentation award in the 14th Australian Remote Sensing and Photogrammetric Conference held in Darwin for her research paper entitled “Identification and mapping of alluvial gullies using remote sensing in sub-catchment of the Daly Basin”.

Farha said she believed that gullies were one of the major sediment contributors to soil erosion.

“My research focuses on the spatial and temporal analysis of gully erosion in the Daly River catchment using remote sensing and GIS based techniques,” she said.

“The underlying gullies formation factors such as land use/land cover changes, climatic factors, geomorphic, lithologic, and topographic conditions will be identified and analyzed in a detailed manner”.

Farha’s research is considered integral for water resources management across the world.
PhD candidate shines at remote sensing conference

Parke Selvan, a PhD candidate in the School of Environmental and Life Sciences, has won the Best Student Presentation award in the 14th Australian Remote Sensing and Photogrammetry Conference.

The conference, held at the Darwin Convention Centre, was attended by more than 300 researchers from all over the world.

In this prestigious forum, Parke (pronounced ‘parke’) presented her research paper titled ‘Identification and mapping of alluvial gullies using remote sensing in sub-arid regions of Daly River’.

She is using state-of-the-art technology CARTOSAT-1 satellite images for mapping gully erosion in 3D perspective.

Her innovative techniques will assist in improving soil erosion models used in northern Australia.

Parke is supervised by Dr. Yi Qian Ahmad and Professor Rob Warrren.