# A comparative study of gully erosion contributing factors in two tertiary catchments in Mpumalanga, South Africa

by

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# DECLARATION

I, Ndifelani Mararakanye declare that the dissertation, which I hereby submit for the degree MSc: Geography at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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# ABSTRACT

Gully erosion is one of the most important forms of soil erosion due to the loss of agricultural production land, sediment generation that leads to siltation of reservoirs, and damage to infrastructure such as roads, bridges, buildings and water pipes. Gully erosion has attracted the interest of many scientists worldwide, but some key priority research areas have not yet been widely reported on. A review of gully erosion research in South Africa presented in this study shows that contributing factors have not been addressed sufficiently and that most of the previous research has been confined to the Eastern Cape and KwaZulu Natal regions. This study quantifies, compares and contrasts the influence of various biophysical and land use factors controlling gully erosion, including land use history, from the two tertiary catchments (X12 and W55) of the Komati and Usutu Rivers in the Mpumalanga province.

A desktop-based research approach was followed, which includes the extraction of topographic variables, including the slope, upslope contributing area, planform curvature, Topographic Wetness Index and Stream Power Index from contours' derived Digital Elevation Models. The study used existing contributing factor datasets including soil, geology, rainfall erosivity and vegetation cover and type. Gullies were digitised manually from a background 0.5m spatial resolution aerial photographs. Land use history and gully dynamics were studied from historical aerial photographs within two selected gully systems. The influence of a contributing factor class on gullies was assessed based on the proportion of gullies in each class, calculated using a zonal approach in ArcGIS®. Zonal results were analysed further using Information Value statistic to assign the weight for each class.

Numerous gully erosion features were observed in tertiary catchment X12 (n = 5 397) compared to W55 (n = 1 654). An Information Value statistic in tertiary catchment X12 shows that gullies are influenced by soils with varied depths belonging to oxidic, vertic, duplex, lithic and melanic soil groups. These soil groups overlie ultramafic rocks, colluvium and alluvium deposits and granite rock of Swazian age. Topographic variables influencing gully location include low to moderately steep slopes, concave curvature, higher upslope contributing area, high Topographic Wetness Index and both low and high Stream Power Index. Other contributing factor classes influencing gullies include lower erosivity values, Swaziland sour bushveld, Barberton serpentine sourveld, moderate Normalised Difference Vegetation Index, moderate to high Normalised Difference Vegetation Index and cultivation. In tertiary catchment W55, gullying significantly affects the very deep Hutton dominated soil form with texture varying from loamy sand, sand and very sandy, underlain by granitic rock of Randian age. A topographic influence was observed on moderate to steep slopes on an area where flow accumulates and is characterised by concave and convex planform curvatures, low and high Topographic Wetness Index and high Stream Power Index. Both moderate and moderate to high Normalised Difference Vegetation Index classes have a significant influence on gully location, as does indigenous forest and thicket/ bushland. An historical land use analysis showed that cultivation was responsible for the initiation and expansion of gullies at two selected sites. The findings confirm that factors important in one area are not necessarily important in the other due to factors spatial variability. However, results can be improved by applying and comparing further statistics, deriving new datasets for the study and detailed historical land use and gully dynamics analyses.

# OPSOMMING

Sloot-erosie is een van die belangrikste vorms van gronderosie omdat dit aanleiding gee tot die verlies aan produktiewe landbougrond, die vorming van afsaksel wat lei tot die toeslikking van opgaardamme, en skade aan infrastruktuur soos paaie, brûe, geboue en waterpype. Sloot-erosie het die belangstelling van baie wetenskaplikes oor die wêreld heen geprikkel, maar sekere sleutel navorsingsareas is nog nie goed gedek nie. Die oorsig oor navorsing aangaande sloot-erosie in Suid-Afrika wat in hierdie studie aangebied word wys dat bydraende faktore nog nie genoegsaam aangespreek is nie en dat die meeste van die navorsing beperk is tot die Oos-Kaap en KwaZulu-Natal. Hierdie studie kwantifiseer, vergelyk en kontrasteer die invloed van verskeie biofisiese en grondgebruikfaktore wat sloot-erosie bepaal in twee tersiêre opvanggebiede (X12 en W55) van die Komati- en Usuturiviere in Mpumalanga, insluitende grondgebruikgeskiedenis.

’n Lessenaargebaseerde navorsingsbenadering is gevolg, wat die onttrekking van topografiese veranderlikes, insluitende die helling, opdraande bydraende oppervlak, vormkromming, die topografiese natheidsindeks (Topographic Wetness Index), en die stroomkragindeks (Stream Power Index) van kontoere afgelei digitale elevasiemodelle. Die studie het gebruik gemaak van bydraende faktor datastelle, insluitende grond, geologie, reënval eroderendheid en plantegroeidekking en -tipe. Slote is met die handdigitalisering uit 'n agtergrond 0.5m ruimtelike resolusie lugfoto's. Grondgebruikgeskiedenis en slootdinamika is bestudeer aan die hand van historiese lugfoto’s van twee geselekteerde slootsisteme. Die invloed van ’n bydraende faktorklas op slote is geassesseer aan die hand van die proporsie van slote in elke klas, bereken deur die gebruik van ’n sonale benadering in ArcGIS®. Sonale resultate is verder geanaliseer met die gebruik van inligtingswaardestatistiek om die gewig vir elke klas toe te ken.

Verskeie sloot-erosiekenmerke is waargeneem in tersiêre opvangsgebied X12 (n = 5 397) in vergelyking met W55 (n = 1 654). ’n Inligtingswaardestatistiek van tersiêre opvangsgebied X12 wys dat slote beïnvloed word deur grondsoorte met verskillende dieptes uit die oksidiese-, vertiese-, dupleks-, litiese- en melaniese grondgroepe. Hierdie grondgroepe oordek ultramafiese rots, kolluvium- en alluviumafsettings en granietrots uit die Swaziese era. Topografiese veranderlikes wat slootligging beïnvloed sluit in lae tot gemiddelde steil hellings, konkawe krommings, ’n hoër opdraande bydraende oppervlak, hoë topografiese natheidsindeks en beide lae en hoë stroomkragindeks. Ander bydraende faktorklasse wat slote beïnvloed sluit in laer erosiwiteitswaardes, Swaziland suurbosveld, Babertonse serpentynsteensuurveld, gemiddelde Genormaliseerde-verskil Plantegroei-indeks, gemiddelde tot hoë Genormaliseerde-verskil Plantegroei-indeks en kultivering. In tersiêre opvangsgebied W55 affekteer slootvorming die baie diep Hutton-gedomineerde grondvorm met ’n tekstuur wat wissel van leemagtige sand tot sanderig en baie sanderig, onderlê deur granietrots uit die Randiaanse era. ’n Topografiese invloed is opgemerk by gemiddelde tot steil hellings in ’n gebied waar vloei akkumuleer en dit word gekenmerk deur konkawe en konvekse vormkurwes, lae tot hoë topografiese natheidsindeks en hoë stroomkragindeks. Beide gemiddelde en gemiddelde tot hoë Genormaliseerde-verskil Plantegroei-indeksklasse het 'n merkbare invloed op slootligging, so ook inheemse woud en ruigte/bosland. Historiese grondgebruikanalise wys dat kultivering verantwoordelik is vir die begin en uitbreiding van slote by twee geselekteerde terreine. Die bevindinge bevestig dat faktore wat belangrik is in een area nie noodwendig belangrik is in 'n ander area nie weens die ruimtelike verskeidenheid. Die resultate kan egter verbeter word deur die gebruik en vergelyking van verdere statistiek, deur nuwe datastelle vir die studie te genereer en deur gedetailleerde historiese grondgebruik- en sloot-dinamika analise.

# MANWELEDZO

Muedzi wa mukumbululo ndi tshiṅwe tsha zwivhumbeo zwa ndeme zwa mukumbululo wa mavu nga ḽivhanga ḽa masiandoitwa a si avhuḓi kha ndozwo ya zwa vhulimi, nyengedzedzo ya u ḓadzwa ha Madamu nga muṱavha na u tshinyadzwa ha zwifhaṱwa zwi fanaho na dzibada, dziboroho, zwifhaṱo na phaiphi dza maḓi. Muedzi wa mukumbululo wo kunga ngudo dza Vho-Rasaintsi vhanzhi u mona na ḽifhasi, fhedziha, zwiṅwe zwa ndeme nga ha ngudo hedzi a zwi athu phaḓaladzwa. Tsenguluso dza ṱhoḓisiso dza muedzi wa mukumbululo fhano kha ḽa Afurika Tshipembe dzo itwaho kha ngudo ino dzi sumbedza uri zwivhangi a zwiathu u bviselwa khagala nga nḓila i fushaho na zwauri vhunzhi ha ngudo dza murahu dzo itwa kha mavunḓu a KwaZulu Natal na Kapa Vhubvaḓuvha. Tshipikwa tsha ngudo ino ndi u dodombedza, u vhambedza na u fhambanyisa zwivhangi zwa muedzi wa mukumbululo kha masia a zwa mupo na kushumisele kwa mavu, u katela na ḓivhazwakale ya kushumisele kwa mavu kha vhufaramaḓi (X12 and W55) ha milambo ya Komati na Usutu vunḓuni ḽa Mpumalanga.

Ngudo ino yo ḓi sendeka nga ṱhoḓisiso dza khomphyutha, zwi tshi katela u ita data nga ha nzulele ya shango sa kuṱuluwele, hune muelelo wa kuvhangana, kugodimele, tsumbo ya u ṋukala ha mavu na tsumbo ya mannḓa a kukumbele kwa zwidambwana u bva kha didzhithaḽa eḽevesheni modeḽe ibvaho kha dzikhonthuwa. Ngudo hei yo shumisavho na data ya zwivhangi yo itwaho nga vhaṅwevho zwo katela mavu, matombo, kukumbululele kwa mvula, na tsireledzo ya mavu nga zwimela. Miedzi ya mukumbululo yo didzhithaizwa ubva kha zwinepe zwa nga muyani zwire na rizoḽushini ya hafu ya mitha. Ḓivhazwakale ya kushumisele kwa mavu na u thomea ha miedzi nga musala uḽa yo gudwa zwi tshi bva kha zwinepe zwa nga muyani zwa kale kha miṅwe ya miedzi mihulwane mivhili yo khethiwaho. Tshileme tsha vhuvhangi tsho gudiwa nga u vhambedza vhudzhi ha zwipiḓa zwa miedzi kha tshipiḓa tshinwe na tshinwe tsha zwivhangi, nga u shumisa zonaḽa thulu ya sofuthuwe ya ArcGIS®. Mvelelo dza zonaḽa dzo senguluswa hu tshi khou shumiswa tshiṱaṱisiṱiki tshi no vhidzwa inifomesheni veḽu hu u itela u wana tshileme tsha kuvhangele kwa zwiṱuṱuwedzi.

Miedzi ya mukumbululo ina tshivhalo yo wanala kha vhufaramaḓi ha X12 (n = 5 397) ri tshi vhambedza na vhufaramaḓi ha W55 (n = 1 654). Tshiṱaṱisiṱiki tsha inifomesheni veḽu kha vhufaramaḓi ha X12 tshi sumbedza uri miedzi i vhangiwa nga mavu a rena utsa ha uya nga u

fhambanana ano wela kha dzigurupu dza oxidic, vertic, duplex, lithic na melanic. Mavu a dzigurupu hedzi o vhumbiwa a tshi bva kha matombo a ultramafic, malaṱwa a colluvium na alluvium na tombo ḽa ngwane ḽa miṅwahani ya Swazini. Zwipiḓa zwa nzulele ya shango zwino vhanga miedzi zwikatela fhethu hu songo ṱuluwaho uya kha fhethu ho ṱuluwaho lwa u linganela, ho godimaho, hune maḓi a elela o kuvhangana, hune mavu a na uṋukalela na hune zwidambwana zwi na mannḓa a u kumba kana u savha na mannḓa. Zwiṅwevho zwino ṱuṱuwedza miedzi ndi mvula ya kukumbululele kwa fhasi, ḓaka ḽa miri ya u vhavhelela ya Swazini, ḓaka ḽa u vhavhelela ḽa serpentine ya Barberton, u linganelela uya kha nṱha ha tsumbo dza u ḓala ha zwimela na fhethu ho limiwaho. Kha vhufaramaḓi ha W55, mukumbululo wa miedzi wo kwamesa mavu a Hutton o vhumbwaho nga mavutshakwane muṱavha, muṱavha na muṱavha wo kalulaho, o vhumbwaho zwitshi bva kha ngwane ya miṅwahani ya Randian. Nzulele ya shango ino ṱuṱuwedza miedzi i katela ho ṱuluwaho lwa u linganela uya kha u ṱuluwesa, fhethu hune maḓi a elela o kuvhangana, hune ho godima kana u ita tshivhanga, hune mavu a ya ṋukalela kana u sa ṋukalela na hune zwidambwana zwi elela zwi na mannḓa. Hune zwimela zwo ḓala lwo linganelelaho uya kha hune zwo ḓala ngamaanḓa hu ṱuṱuwedza miedzi u fana na ḓaka ḽa miri mihulwane na miṱuku. Ḓivhazwakale ya kushumisele kwa mavu i sumbedza uri vhulimi ho ṱuṱuwedza u thomea na u phaḓalala ha miedzi kha bulege mbili dzo khethwaho. Mawanwa haya a khwaṱhisedza ḽa uri zwiṱuṱuwedzi zwa miedzi zwo fhambana ri tshi ya nga u fhambana ha ku phaḓalele ha zwiṱuṱuwedzi kha bulege dzo fhambananaho. Fhedzi, mawanwa haya a nga khwiṋisedzea nga u shumisa na u vhambedza zwiṱaṱisiṱiki zwo fhambananaho, u shumisa data ntswa yo itelwaho ngudo dzenedzo na u sengulusa nga vhuḓalo ḓivhazwakale ya kushumisele kwa mavu na tshanduko kha miedzi.

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# CHAPTER 1: INTRODUCTION

## 1.1. Background to the research problem

Soil erosion has been an intriguing topic for decades amongst the scientific community such as geographers, soil, agricultural and environmental scientists. It is one of the most severe environmental problems threatening human populations across the globe, in particular for developing countries, and is the major causes of severe land degradation (Lal, 2001; Valentin *et al*., 2005; Le Roux *et al*., 2008; Jahantigh and Pessarakli, 2011). Of the main erosive agents, including water, wind, gravity and ice, water erosion in the form of sheet, rills and gullies has the biggest impact on soil degradation (Oldeman, 1993; Laker, 2004; Niemiec, 2009). In South Africa (SA), water erosion is more pronounced over northern parts of the Eastern Cape (EC), southern Free State (FS) and northern KwaZulu Natal (KZN) provinces (Le Roux *et al*., 2008; Mararakanye and Le Roux, 2012). Significant water erosion in other provinces such as Limpopo (LP), Western Cape (WC), Northern Cape (NC), North West (NW) and Mpumalanga (MP) was observed by Le Roux *et al*. (2008). Amongst the erosion forms, gullying is the most widespread (Sirviö and Rebeiro-Hargrave, 2004; Oakes, 2011), and is the focus of this study.

Gully erosion has both on-site and off-site effects such as top soil loss and sediment deposition respectively (Nazari Samani *et al*., 2009; Shit *et al*., 2013). A total loss of agricultural production land associated with gullying is documented worldwide (e.g. Oldeman, 1993; Marker and Sidorchuk, 2003; Casali *et al*., 2009; Kakembo *et al*., 2009; Desta and Adugna, 2012). Data collected in different parts of the world by Poesen *et al.* (2003) shows that soil loss by gully erosion represent up to 94% of total sediment yield by water erosion, which makes gullies the main source of sediments entering waterways (Hughes *et al*., 2001; Poesen, 2011). According to Vandekerckhove *et al.* (2000), gullies produce a considerable quantity of sediment, filling downstream reservoirs and exacerbating floods. In SA, a typical example of reservoir sedimentation associated with gullying is Welbedacht dam in the FS province. Welbedacht dam was constructed in 1973 and by the year 2002, the dam had lost approximately 90% of its storage capacity (De Villiers and Basson, 2007). Sedimentation of Welbedacht dam is attributed to severe gully erosion in the upper catchment of the Caledon River in Lesotho (Lindeque, 2011). Other impacts of gully erosion include, but are not limited to, damage to infrastructure such as roads, bridges, buildings and pipes (Nwilo *et al*., 2011). Gully erosion may cause lowering of ground water levels, impediment of access to land and pollution of water bodies (Valentin *et al*., 2005; Imasuen *et al*., 2011).

Gully erosion is a threshold phenomenon controlled by land use activities and biophysical factors such as soil, geology or parent material, rainfall and topography (Valentin *et al*., 2005; Le Roux *et al*., 2008; Svoray and Markovitch, 2009; Jakab *et al*., 2011). It occurs naturally, but is often accelerated by human activities such as improper cultivation methods or clearing of vegetation (Lal, 2001). For gullies to occur, threshold conditions must be exceeded, often related to the combined power of rainfall energy and overland flow versus the resistance of surface materials (Nazari Samani *et al*., 2009). The resistance of surface materials is controlled by the complex interaction of biophysical and land use factors governing the erosion process. It is imperative to understand that the importance of threshold conditions is different for different environmental conditions and gully initiating mechanisms (Nazari Samani *et al*., 2009). This can make gully erosion difficult to study and quantify due to the complexity of interaction processes (Valentin *et al*., 2005; Svoray and Markovitch, 2009).

## 1.2. Statement of the research problem

A recent review of gully erosion worldwide suggests that it has attracted the interest of many scientists in the last decade (Poesen, 2011). However, studies in SA addressing gully erosion directly presented in Chapter 2 shows that it has received little consideration and the majority of research was undertaken in the EC and KZN regions. The main problem is that, contributing factors that are important in one region are not necessarily the same in other regions due to the spatial and temporal variability of factors controlling erosion (Sonneveld *et al*., 2005; Nazari Samani *et al*., 2009). This poses a challenge to the decision makers since the development of policies and allocation of conservation resources demand understanding and prioritisation of the problem in the whole country (Vrieling *et al*., 2006). The current study seeks to quantify and makes a comparison of the contribution of various biophysical factors and land use activities (including historical use) on gully erosion from two tertiary catchments in the MP province with different gully densities. Previous soil erosion studies in the MP region (e.g. Walters, 1940; Marker and Evers, 1976; Ngetar, 2011) did not address the contributing factors of gully erosion sufficiently.

The majority of research in SA illustrated in Table 1.1 does not consider a substantial number of biophysical factors contributing to gully erosion and seldom include historical land use in the analysis, with a few exceptions (e.g. Kakembo and Rowntree, 2003; Vetter, 2007). Liggitt and Fincham (1989) and later Le Roux and Sumner (2012) considered the interplay of numerous gully erosion contributing factors but also omitted important variables. Liggitt and Fincham (1989) assessed the influence of geology, land use, vegetation cover, rainfall and slope on gullies, excluding soil in the analysis and other topographic variables such as upslope contributing area, curvature, Topographic Wetness Index (TWI) and Stream Power Index (SPI). Le Roux and Sumner (2012) assessed the influence of various topographic variables, geology, vegetation cover, land use, landtypes and soil (erodibility and depth) but could not consider rainfall in the analysis since it did not vary substantially, due to the relatively small size of the tertiary catchment (5 000km$^2$). Various other studies used the broad soil pattern of the landtypes data to describe the influence of soil on gullies (e.g. Watson and Ramokgopa, 1997; Watson, 2000; Le Roux and Sumner, 2012). The problem with landtypes data is that it does not give a spatial detail on the occurrence of soil components such as clay content, soil depth and soil form in a map unit (Land Type Survey Staff, 1984). This may lead to over estimation or under estimation of certain soil components.

**Table 1.1: Previously published gully contributing factor research in South Africa**

| **Authors (Year)** | **Factors Considered** | **Location** |
|---|---|---|
| Liggitt and Fincham (1989) | Geology type, slope percentage, land use, vegetation cover and rainfall | Northern KZN |
| Dardis and Beckedahl (1991) | Rock physical properties | EC and KZN |
| Watson and Ramokgopa (1997) | Land types | Northern KZN |
| Kakembo (2000) | Infrastructure (railway culverts) | West of Alice, EC |
| Rienks *et al*. (2000) | Soil physical and chemical properties | Central KZN |
| Watson (2000) | Land types | Northern KZN |
| Kakembo and Rowntree (2003) | Land use change history, rainfall and vegetation cover | Ngqushwa, EC |
| Sonneveld *et al*. (2005) | Soil physical and chemical properties and land use | Northern KZN |
| Keay-Bright and Boardman (2007) | Land use | Central Karoo, EC |
| Vetter (2007) | Geology, slope classes, land use and land use change or history | Herschel district, EC |
| Kakembo *et al*. (2009) | Topographic variables and land use | Ngqushwa, EC |
| Grellier *et al*. (2012) | Trees (vegetation) | Northern KZN |
| Le Roux and Sumner (2012) | Topographic variables, geology, vegetation cover, land use, land types and soil (erodibility and depth) | North of Mthatha, EC |

## 1.3. Aim and objectives of the study

The main aim of this study was to quantify, compare and contrast the influence of various biophysical and land use factors controlling gully erosion, including land use history in two tertiary catchments with different gully densities in the MP province. This was achieved by means of the following objectives:

- Mapping the most relevant topographic variables influencing gully erosion, including the slope, upslope contributing area, planform curvature, Topographic Wetness Index (TWI) and Stream Power Index (SPI);
- Mapping gully erosion features using high spatial resolution aerial photographs;
- Examining the contribution of historical land use changes on gully erosion; and
- Assessing and quantifying the influence of biophysical and land use factors on gully erosion.

## 1.4. Motivation of the study

This research has both practical and theoretical implications. The Department of Agriculture, Forestry and Fisheries (DAFF) recognised the lack of intervention to control and prevent soil erosion from policy perspectives, which led to the development of a proposed soil protection policy and strategy (Lindemann and Pretorius, 2005). Generally, soil conservation legislation in SA is well established (Watson, 1990), but according to Lindemann and Pretorius (2005) previous initiatives failed to address the depreciation of soil resources as evident from the increasing rate of soil loss. Lindemann and Pretorius (2005) recommended the initiation of a soil protection policy and strategy through the establishment of the Advisory Board for Soil Protection (ABSP). The board was to oversee and coordinate the work of different technical working groups and monitor the development and implementation of soil resources protection strategy and policy. The established technical working groups would mainly be responsible to identify and conduct relevant research, identify the control measures and develop policies and strategies to prevent soil degradation.

In support of the soil protection policy and strategy, a preliminary study to identify the problem areas was conducted by Le Roux *et al*. (2008) using the Revised Universal Soil Loss Equation (RUSLE) to estimate soil loss by water erosion. Originally, RUSLE and its predecessors were developed by the United States Department of Agriculture (USDA) from erosion plots and rainfall simulator, in order to estimate soil loss from hillslopes (Wischmeier and Smith, 1978). The RUSLE is designed to estimate soil loss associated with sheet and rill erosion, subsequently underestimating gully erosion (Van Zyl, 2007). In recognition of the problems associated with RUSLE, Mararakanye and Le Roux (2012) conducted a further study with the principal aim of determining the spatial extent and severity of gullies in SA. The process behind gully erosion initiation and development remained poorly understood, and it was recommended that the assessment of factors controlling gully erosion be considered. Conducting an assessment of gully contributing factors at national scale would require a large amount of data processing and runs a risk of underestimating local factors. The unavailability of good quality datasets at a national scale, such as aerial photographs and Digital Elevation Model (DEM) would pose challenges. Thus, it is imperative to limit the scope of the current study to a tertiary catchment level.

The results of this study will contribute to the knowledge base of gully erosion phenomena essential in the development of the appropriate prevention, control or rehabilitation measures (Beckedahl, 1996). It is worth recognising that successful soil conservation and rehabilitation measures depend upon a thorough understanding of the mechanisms of erosion processes as well as the consideration of biophysical and land use factors driving the process (Nasri *et al*., 2008, Shellberg *et al*., 2010; Chaplot *et al*., 2011; Nwilo *et al*., 2011; Le Roux and Sumner, 2012). The assessment of gully erosion contributing factors is important when modelling the erosion hazard of the area (Seitlheko, 2003; Ogbonna, 2012). The modelled vulnerable areas are particularly useful for area wide natural resource management or soil conservation planning advocated in the proposed initiation of soil protection strategy by DAFF (Lindemann and Pretorius, 2005). Studies have shown that modelling high-risk area is the core element of area-wide conservation planning and could successfully increase the conservation effectiveness across entire catchments and reduce erosion losses from sensitive areas (Meyer and Martinez-Casasnovas, 1999; Galzki *et al*., 2011; Jakab *et al*., 2011). Modelling vulnerable areas encourages the introduction of stricter land use and management policies from the relevant authorities.

## 1.5. Structure of the report

Chapter one gives an introductory remarks to the dissertation, including the background information to the research problem, a statement of the research problem, specific aim and objectives as well as motivation for the study. Chapter two provides a literature review focusing on the terminologies of gully erosion, mechanisms, contributing factors and modelling approaches available to predict the occurrence of gullies. A comprehensive review of gully erosion research in SA is also included in Chapter two. Chapter three provides a general description of the study area in terms of the location, climate, geology, soil, topography, vegetation and land use. The materials and methods used to conduct this study are described in Chapter four. These include a description of the sources of data used and methodologies for mapping topographic variables, gully erosion features and historical land use as well as the assessment and quantification of contributing factors. Chapter five provides a detailed description of the findings illustrated as Figures and Tables. An in-depth interpretation and evaluation of the results in comparison with previous findings is provided in Chapter six. Chapter seven presents the major conclusions drawn from the results and discussions as well as recommendations for future investigation.

# CHAPTER 2: LITERATURE REVIEW

This Chapter consists of two parts, a review of worldwide literature and a South African overview. The first part reviews gully erosion concepts, including the different classifications, followed by the description of mechanisms of erosion. Against this background, factors contributing to gully erosion are also described with both examples from South Africa and internationally. Although the modelling of gully erosion is outside the scope of the current research, it was deemed appropriate to give an overview of the existing gully erosion prediction approaches since this is useful when estimating the effects of environmental change (Poesen *et al*., 1998). The second part is a review of gully erosion in South Africa, focusing on its origin, soil loss rate and contributing factors.

## 2.1. Review of gully erosion worldwide

### 2.1.1. Concept of gully erosion

Gully erosion is defined as the process whereby runoff water concentrates in narrow flow paths, displacing soil or soft rock particles, resulting in incised channels larger and deeper than rills and usually carries water only during and immediately after heavy rainstorms (Poesen *et al*., 2003). Such incised channels are called gullies and bear many local names such as dongas, sluits, vocarocas, ramps and lavakas (Bull and Kirkby, 1997; Huggett, 2007). The names dongas or sluits are mainly used in SA (Rowntree, 2013). Gullies are morphologically defined by steep sidewalls and stepped channel slope with actively eroding head scarp which make them different from stream channels (Bradford and Piest, 1980; Poesen *et al*., 1996; Soufi, 2004). The words deep depressions, channels or ravines have also been used to describe gullies (Stocking and Murnaghan, 2000). Many criteria are used to distinguish gullies such as the nature, planform, position in the landscape and shape of a cross section (Poesen *et al*., 2002).

#### *2.1.1.1. Nature of a gully*

Gullies may be of an ephemeral or permanent nature. An ephemeral gully is often defined for agricultural land, implying small incised channels larger than rills, which can be refilled by normal tillage equipment, only to reform again in the same location even from a single rainfall event (Bull and Kirkby, 1997; Casali *et al*., 2000; Soil Science Society of America, 2001; Wilson *et al*., 2008; Kertész, 2009). Permanent or classical gullies are large and deep incised channels that cannot be easily destroyed by ordinary farm tillage equipment (SARCCUS, 1981; Bergsma *et al*., 1996; Poesen *et al*., 2003). Related to ephemeral gullies and permanent gullies is rills, which are intermittent erosion channels smaller than ephemeral gullies that are less likely to form in the same position once obliterated (Grissinger, 1996; Bull and Kirkby, 1997).

The rills, ephemeral and permanent gullies are usually differentiated by the size of a channel (Poesen *et al*., 2003). Grissinger (1996) acknowledged that distinguishing rill erosion, ephemeral and permanent gullies as well as first order streams can be challenging and subjective. The transition from rills to ephemeral and to permanent gullies is a continuum and any distinction of these classes is vague and to some extent subjective (Poesen *et al*., 2003). Bergsma *et al*. (1996) classified gullies (ephemeral and permanent) as any erosion channel with a depth of 0.3m to 30m. The size range used by the Soil Science Society of America (2001) is 0.5m to 30m deep. Vanwalleghem *et al*. (2003) define gully based on a minimum depth of 0.2m and minimum length of 15m. They regarded those channels less than or equal to 0.3m as ephemeral gullies and those greater than 0.3m as permanent gullies. Later, Vanwalleghem *et al*. (2005) defined two categories of ephemeral gullies, namely deep and shallow, by a depth equal to or more than 0.8m and less than 0.8m respectively. Hancock and Evans (2006) define gully channels ranging from 0.2m to 2.5m deep and 0.2m to 14m wide, with an average depth of 0.55m and width of 1.4m. Clearly, distinguishing gullies from the rills and ephemeral from permanent gullies based on the size of a channel has not yet been fully resolved and classification on this basis requires further clarification. As illustrated here, gullies of various dimensions have been observed in different landscapes with varied climatic conditions (e.g. Jahantigh and Pessarakli, 2011).

Poesen *et al*. (2002) recognised both river bank gullies and slope gullies forming badland areas. Bank gullies are caused by wearing away of the banks on the outer curves of streams or rivers associated with undercutting and slumping (SARCCUS, 1981) due to the concentration of water flow in rills, dead furrow or ephemeral gullies particularly where they cross the earth bank (Poesen *et al*., 1998; Poesen *et al*., 2003). Badlands are deeply dissected landforms of highly degraded relative relief and drainage density (Di Tommaso *et al*., 2009). Badlands are the worst stage of degradation by gullies and they are characterised by a high densities of uncontrolled progression of rilling, mass-wasting, piping and overland flow (Calvo-Cases and

Harvey, 1996; Liberti *et al*., 2009; Rowntree and Foster, 2012) often separated by short steep un-vegetated slopes (Boardman *et al*., 2003).

### *2.1.1.2. Plan form of a gully*

Gullies are also classified and defined by their plan form. Ireland *et al*. (1939) recognised six categories of gullies based on plan form such as linear, bulbous, dendritic, trellis, parallel and compound. Linear gullies are long and narrow, with a narrow head and few tributaries along the sides. They commonly occur along natural or man-made drainage lines. Bulbous gullies are broad and spatulate at the upper end, but may be linear in the downstream part. They are often incised upland and have a semicircular head with small tributaries or rills entering from the sides. Dendritic gullies have many branching tributaries with headward cutting that accentuates the dendritic character. Trellis gullies are characterised by tributary branches entering the main channel at approximately 90° angles. Parallel gullies are composed of two or more parallel tributaries which empty into the main gully (Ireland *et al*., 1939). Twidale (2004) observed deep parallel gullies believed to have developed as rills in the WC province of SA. Compound gullies are a combination of two or more of the above drainage patterns (Ireland *et al*., 1939). Generally, the classification of gullies in this manner follows drainage patterns, since gullies occur along natural drainage lines (Stocking and Murnaghan, 2000; Ehiorobo and Audu, 2012). Soufi (2004) observed most of the gullies in Iran that are formed around natural drainage lines including rivers and streams. Drainage patterns illustrated in Figure 2.1 are determined by the slope and the structural weakness of the rock properties (Twidale, 2004).

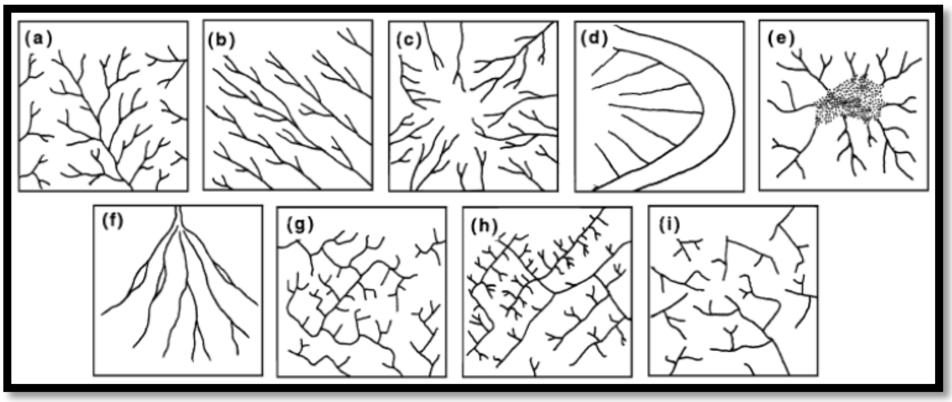

**Figure 2.1: Typical sketches of various drainage patterns (a) dendritic, (b) parallel, (c) radial, (d) centrifugal, (e) centripetal, (f) distributary, (g) angular, (h) trellis, (i) annular (source: Twidale, 2004)**

Ireland *et al*. (1939) classified the plan form of active gully heads as pointed, rounded, notched and digitate (Figure 2.2 B). In a pointed gully, channel deepens and broadens gradually and uniformly from the narrow pointed head that is usually shallow. Rounded gully heads are semicircular, usually with steep or vertical walls. A notched gully head is rounded, but with a sharp notch at the semicircle. Digitate comprises multiple heads arranged as fingers. Higgins *et al*. (1990) observed that most gullies formed by seepage erosion have rounded or digitate heads but sometimes are notched. Ireland *et al*. (1939) further classified gully heads based on their vertical profiles into four groups as inclined, vertical, cave and vegetated (Figure 2.2 A). Inclined gully heads comprise lower and higher heads within one soil horizon or soils with approximately uniform resistance across all horizons respectively. Vertical heads may be a temporary condition representing an inclined head. Cave is the most common type of head in deep gullies where soil horizons have different resistance to erosion. Vegetated is characterised by an overhanging root mat that keeps the flow of water away from its bank.

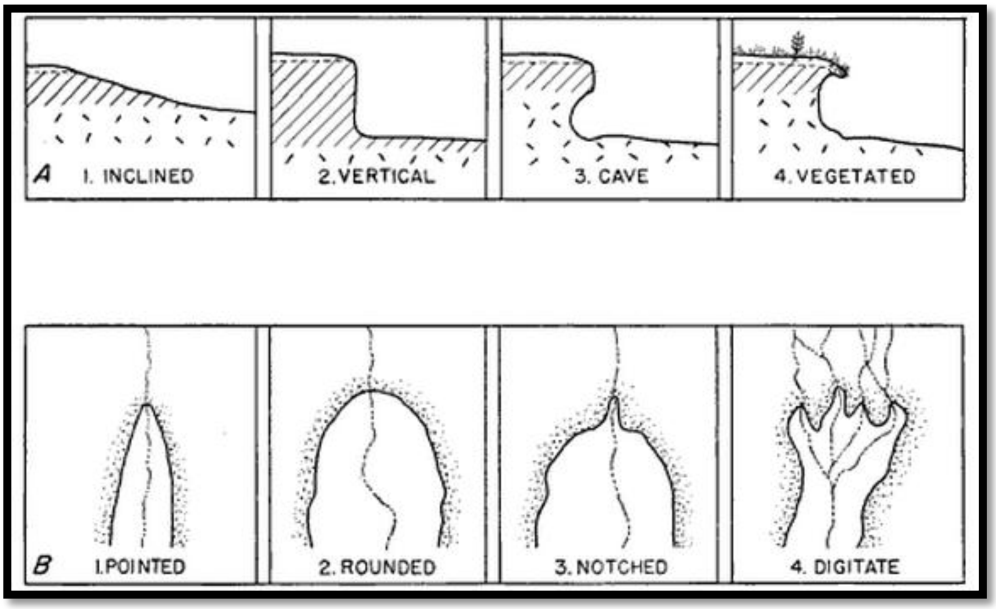

**Figure 2.2: Illustration of the characteristics of gully heads (A) vertical profiles and (B) plan views (source: Ireland *et al*., 1939)**

### *2.1.1.3. Position in the landscape*

Gullies have been classified based on their position in the landscape such as valley floor, valley side and valley head (e.g. Bradford and Piest, 1980; Harvey *et al*., 1985; Higgins *et al*., 1990; Poesen *et al*., 2002; Morgan, 2005) and each can be continuous or discontinuous (Higgins *et al*., 1990; Poesen *et al*., 2002). Valley floor gullies take the form of ephemeral gullies, developed in topographic swales in a landscape where runoff concentrates (Soufi, 2004; Morgan, 2005). They occur where the surrounding hillslopes are convexo-concave and land is used for arable farming where soils are freshly tilled and loose. Valley side gullies occur approximately at right angles to the main valley line where local concentrations of surface runoff cut the hillside, subsurface pipe collapse or local mass movements create a linear depression in the landscape. Once valley side gullies are formed, they grow upslope by headward retreat and downslope by the incision of a channel floor (Morgan, 2005). The origin and development of valley head gullies and valley side gullies is the same and both reflect the expansion of a drainage network (Higgins *et al*., 1990; Poesen *et al*., 2002). Valley head gullies differ with valley side gullies in their location and orientation in respect to the valley axis (Higgins *et al*., 1990).

Valley floor, valley side or valley head gullies are continuous when they are part of a drainage network and discontinuous when they are isolated from the drainage network (Poesen *et al*., 2002). Continuous gullies have a main channel and many mature or immature branches (Geyik, 1986; Desta and Adugna, 2012). They normally start in the upland area as rills that join to form the main gully on the valley floor. During formation, continuous gullies reach relatively greater depths which are maintained until the lowest reach above the gully mouth is attained (Heede, 1970). Discontinuous gullies are also known as independent gullies and may develop on a hillslope after for example a landslide. During their initiation, discontinuous gullies do not have a distinct connection with the main gully or stream channel. They are often scattered around the continuous gully systems or channels, but have also been observed where no continuous gully exists. Discontinuous gullies decrease in depth rapidly downstream, thus their bottom gradient is much gentler than the original valley floor. They begin with the headcut associated with the knick point along the flow path (Geyik, 1986; Desta and Adugna, 2012).

#### *2.1.1.4. Shape of a gully cross-section*

The morphology of gullies may be interpreted as the product of gully erosion initiation processes (Heede, 1970; Soufi, 2004). Various studies classified gullies based on the shape of their cross-sections such as the U-shaped, V-shaped and trapezoidal shaped (e.g. Geyik, 1986; Desta and Adugna, 2012) as shown in Figure 2.3. The shape explains the soil material from which the gully developed (Poesen *et al*., 2002. The U-shaped gullies develop where both topsoil and subsoil have the same resistance against erosion. Due to similar erodibility of topsoil and subsoil, nearly vertical walls are formed on each side of a gully. The V-shaped gullies develop where subsoil has more resistance against erosion than topsoil. Trapezoidal gullies are formed where the gully floor is made of more resistant material than the topsoil and subsoil, leading to greater erosion rate along the banks (Geyik, 1986; Desta and Adugna, 2012). Soufi (2004) associated the appearance of the V-shaped and U-shaped gullies to the main processes involved during its initiation, such as surface runoff and subsurface runoff respectively.

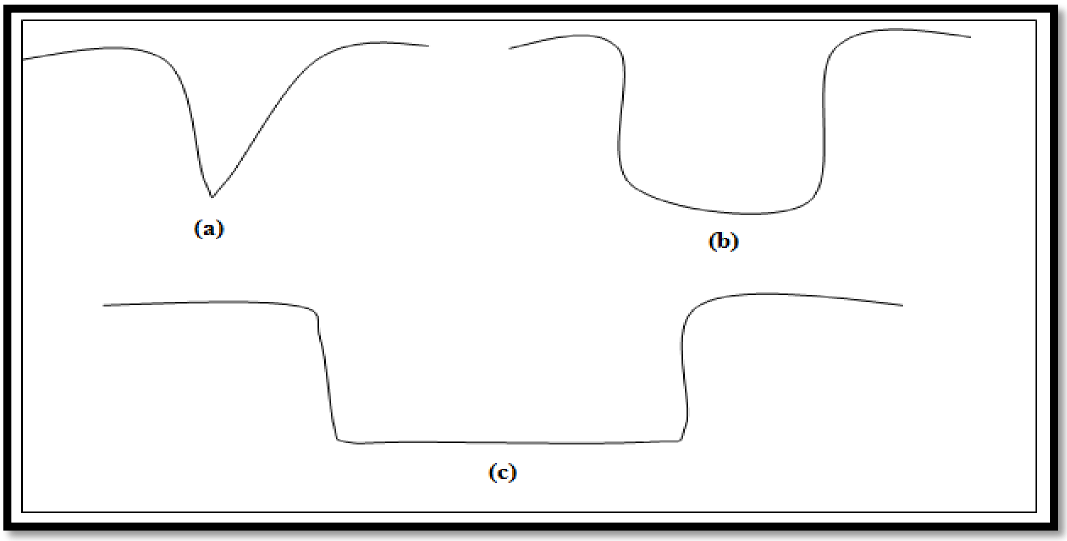

**Figure 2.3: Illustration of the cross section of gullies (a) V-shaped, (b) U-shaped and (c) trapezoidal shaped (adapted from Geyik, 1986)**

### 2.1.2. Mechanisms of gully erosion

As already mentioned, gully erosion is a complex phenomenon, often controlled by a combination of processes, making it difficult to describe its mechanism for development (Oygarden, 2003). The main processes involved during gully initiation include overland flow, expansion due to deepening and slumping of side walls of the rills (Watson, 1990), subsurface flow or piping (Poesen *et al*., 1996; Sjörs, 2001; Le Roux *et al*., 2006; Shit *et al*., 2013) and gully head retreat at the knick point (Bergsma *et al*., 1996; Oostwoud Wijdenes and Bryan, 2001; Poesen *et al*., 2003). These mechanisms are discussed below.

#### *2.1.2.1. Overland flow*

Gully erosion is primarily caused by overland flow processes (Shit *et al*., 2013). There are two recognised mechanisms of overland flow generation, namely Hortonian and saturation

(Bull and Kirkby, 1997; Huggett, 2007). Hortonian overland flow occurs when rainfall exceeds the infiltration rate and is more common on bare rock surfaces and deserts (Huggett, 2007). Saturation overland flow occurs during rainfall events on a saturated surface. While Hortonian overland flow extends to the catchment divide, saturation overland flow is usually confined to slope concavities and hollows (Bull and Kirkby, 1997).

According to Le Roux *et al*. (2006), erosion by saturation overland flow occurs when a persistent rain results in a saturated surface in such a way that water can no longer pass through the soil. The inherent resistance of the soil necessitates that certain critical condition be exceeded before saturation overland flow could cause soil erosion. This critical condition is normally described by the shear stress of the flow larger than the surface resistance (Bull and Kirkby, 1997; Svoray and Markovitch, 2009) and is influenced by the runoff intensity (Poesen *et al*., 1996; Howard, 1999). After the exceedance of the critical condition, soil particles then detach from the soil surface at a rate dependent on the shear velocity of the flow and the unit discharge. If the soil particles are small or are of low mass, they may move as suspended load, but if the particle sizes are larger or have higher mass, they may fall to the underlying surface bed and depending on the flow velocity, they move as bed load (Le Roux *et al*., 2006). The convergence or accumulation of overland flow into existing channels may cause gullies (Poesen *et al*., 1996; Strunk, 2003). Saturation overland flow is the dominant process during the initiation of ephemeral gully erosion (Poesen *et al*., 1996; Desta and Adugna, 2012).

#### *2.1.2.2. Rill expansion*

Gullies may also be established due to the deepening and slumping of a rill side walls through the shearing effect of concentrated overland flow (Pathak *et al*., 2006). Stocking and Murnaghan (2000) define rills as shallow linear channels usually aligned perpendicular to the slope and occur in a series of parallel erosion lines. Rills initiate when runoff water is channelled into natural depressions or along lineations caused by roads, culverts and tracks left by tillage equipment. A particular rill amongst a series of parallel rills may erode faster than others due to the localised variations in soil erodibility or slope roughness. As the principal rill develops, water flow is diverted laterally into it and in the process the neighbouring rills are overtopped and destroyed. A progressive increase in runoff associated with a wet spell or poor land use practises may deepen and widen the dominant rill to the extent that it is classified as a gully (see section 2.1.1). Cobban and Weaver (1993) observed gullies that formed when a series of parallel rills deepen downslope in the Tsolwana Game Reserve, former Ciskei. Most gullies in the Mfolozi catchment, KZN developed from rills expansion (Watson, 1990).

### *2.1.2.3. Gully head retreat and deepening*

Gully erosion, particularly a bank gully is initiated by knick points or small surface natural depressions or depressions caused by livestock tracks, furrows and ruts left by farm machineries (Bergsma *et al*., 1996; Svoray and Markovitch, 2009). The concentration of runoff or overland flow at the knick points or at the intersection with rivers or streams may cause waterfalls and plunge pools leading to undercutting and slumping, exposing a gully head. Subsequent to the formation of a gully head, the expansion or spread occurs rapidly through headward retreat and channel wall failures (Vandekerckhove *et al*., 2000; Oostwoud Wijdenes and Bryan, 2001; Poesen *et al*., 2003). Gully head retreat involves through-flow from the scarp and surface flow concentrated over the head of a scarp which scours a plunge pool at the base of the head. As the gully deepens, undercutting of the scarp leads to collapse (Watson, 1990). The gully expands and deepens until soil is completely removed from the ground or until bedrock is reached (Pathak *et al*., 2006; Le Roux *et al*., 2006; Nwilo *et al*., 2012). The failure of channel walls involves slumping due to flow saturation and undercutting of the base of the banks caused by scouring action of the water flow, leading to collapse (Watson, 1990). Scouring at the base of the scarp causes deepening of the channel.

### *2.1.2.4. Subsurface erosion or piping*

Gullies are also caused by subsurface flow or piping (Poesen *et al*., 1996; Le Roux *et al*., 2006; Kertész, 2009). Subsurface erosion is the process whereby soils are removed below the surface (Beckedahl, 1996) due to underground water channels (Henkel *et al*., 1938). Subsurface flow takes place under localised saturation flow conditions mainly in silt-clay materials containing cracks, fissures and discontinuities which promote the through-flow (Henkel *et al*., 1938; Beckedahl, 1977; Beckedahl *et al*., 1988; Beckedahl, 1996; Bull and Kirkby, 1997; Huggett, 2007). The gully formation process occurs when water reaches and super saturates the relatively slowly permeable subsoil, and moves soil particles laterally as seepage, thereby developing subsurface channels. Clay dispersions may occur along the flow lines and lead to the formation of tunnels (Henkel *et al*., 1938; Beckedahl, 1977; Beckedahl *et al*., 1988; Beckedahl, 1996). The movement of water through subsurface flow may be slow until the water breaks through the soil surface further downslope (Desta and Adugna, 2012).

The process is then advanced by steep hydraulic gradients in a soil of high infiltration capacity, but low intrinsic permeability, so that water does not move readily into subsurface matrix. Subsequently, water passes rapidly into the soil until reaching an impermeable layer where it moves along as subsurface erosion. Rapid flow results in headward erosion within soil and enlarges a pipe. When the ground surface subsides, pipe networks are exposed as gullies (Henkel *et al*., 1938; Beckedahl and De Villiers, 2000; Le Roux *et al*., 2006; Desta and Adugna, 2012). The progressive development of piped areas may lead to the development of non-piped badlands where surface or near surface erosion processes dominate (Vandekerckhove *et al*., 2000).

### 2.1.3. Factors contributing to gully erosion

All forms of water erosion processes are controlled by climatic characteristics, topography, geology, soil properties, vegetation, and land management or land use activities (Vrieling, 2006). Studies have shown that gully erosion is a threshold phenomenon influenced by a combination of factors rather than an individual factor (Kakembo *et al*., 2009; Van Zijl, 2010; Ehiorobo and Audu, 2012). These factors are discussed below.

#### *2.1.3.1. Climate characteristics*

The occurrence and distribution of soil erosion phenomena have often been associated with certain climatic regions of the world. The dry-land climate, for example, which consists of hyper-arid, arid, semi-arid and dry sub-humid experiences various forms and degrees of degradation, mainly soil erosion (Meadows and Hoffman, 2002). Studies have shown that semi-arid regions are often characterised by rapid gully erosion rates (e.g. Calvo-Cases and Harvey, 1996) due to the alternating climate characteristics which promote the development of cracks in soils and the slowdown of vegetation growth (Jahantigh and Pessarakli, 2011). Pathak *et al*. (2006) claimed that bare ground and flash floods characterise semi-arid regions and influence gully erosion in India and the African continent. The prolonged dry periods leave the ground bare for extended periods. Cracking of certain soils may occur during dry periods and when spells of heavy rainfall approach, various forms of soil erosion may be initiated. Soufi (2004) found that gullies are dominantly distributed in the semi-arid region of the Fars province in Iran compared to other regions. In spite of the contribution of temperature, which has not yet been fully resolved, the influence of climatic characteristics on soil erosion has been widely explained in terms of rainfall.

Rainfall is the driving force for all water erosion processes including the formation of gullies (Vanwalleghem *et al*., 2005). Thiemann *et al*. (2005) showed that the intensity of soil erosion depends on the erosivity of rainfall events and erosivity depends on the quantity, frequency and intensity of rainfall (Kakembo, 2000; Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Malik, 2006; Vetter, 2007; Le Roux *et al*., 2008; Alt *et al*., 2009; Kertész, 2009). Excessive rainfall causes greater runoff or overland flow due to the exceedance of infiltration capacity. According to Alt *et al*. (2009), intense or heavy fall of rain produces large volumes of fast flowing runoff that scours and carries soil into waterways. Similarly, the extended number of rainy days per month prevents evaporation and as a result, soil becomes saturated, promoting runoff. Casali *et al*. (1999) found that short but intense rainfall events and long but low intensity rainfall contributed to ephemeral gully erosion in southern Navarra, Spain. Notwithstanding that gully erosion is a threshold phenomenon influenced by a variety of factors, it is well-known that a single intense rainstorm may initiate a gully particularly when falling on a bare ground following a dry period (Vetter, 2007). Gair and Williams (1964) found a gully of 137m long, 46m wide and 8m deep in Canterbury, New Zealand, occurring within just four hours of a single intense rainstorm. Casali *et al*. (2000) observed the formation and reactivation of gullies during one intense winter rainfall event of short duration in southern Navarra, Spain.

#### *2.1.3.2. Bedrock or parent material*

Bedrock or parent material has a strong influence on gully erosion initiation (Liggitt and Fincham, 1989). The erodibility of soils is inherently determined by the parent material from which the soil has formed. When solid rock disintegrates due to weathering, minerals become the building blocks of soils (Huggett, 2007). The three broad categories of the parent rock materials in soils include igneous, sedimentary and metamorphic rocks (Carmichael, 2013). Table 2.1 illustrates the parent materials, including their characteristic minerals. According to Huggett (2007), igneous and metamorphic rocks are resistant to erosion. This claim was also found to be true by Vetter (2007) who observed severe gully erosion on soil overlying sedimentary rock formations such as Molteno and Elliot compared to lower levels of erosion on materials of igneous rock's origin such as dolerite, basalt and pyroclastic in the Herschel district, EC, SA.

**Table 2.1: Classification of rocks and characteristic minerals (source: Carmichael, 2013; Kudo, 2013; Schwab, 2013; Selverstone, 2013)**

| Classes | Rock type | Minerals |
|---|---|---|
| Igneous | Granite, Basalt, Andesite, Granodiorite, Dolerite, Syenite, Gabbro, Amphibolite, Eclogite, Dunite and Periodotite. | Felsic minerals (Quartz, Tridymite, Cristobalite, Feldspars (plagioclase and alkali feldspar), Feldspathoids (nepheline and leucite), Muscovite, and Corundum.<br>Mafic minerals (olivine, pyroxenes, amphiboles, and biotites). |
| Sedimentary | Shale, Sandstone, Mudstone or Claystone, Detrital rocks, Conglomerates (rounded clasts), Arenites (medium-grained), Quartzite, Siltstone, Loess (transported and deposited by wind). | Clay minerals (Kaolinite, Halloysite, Montmorillonite, Illite, Vermiculite, and Chlorite).<br>Authigenic minerals (Calcite, Halite, and Gypsum).<br>Detrital minerals (grains of quartz and feldspar). |
| Metamorphic | Gneiss, Schist, Slate, Hornfels, Marble Mylonites and cataclastites. | Pelitic, Calcareous, Felsic, and Mafic. Common minerals include Albite, Chlorite, Dolomite, Enstatite, Kaolinite, Magnesite, and Quartz. |

Minerals are the major chemical characteristic of rocks which contribute to the erodibility in soils, e.g. clay minerals, free iron (Fe), aluminium (Al) oxides, sodium and magnesium (Laker, 2004). Physical characteristics of rocks such as the resultant particle size also determine the erodibility of soil. Various rock types contain materials that are more vulnerable to aggressive energy of the rainfall and runoff. For example, soil derived from shale is susceptible to gully erosion due to its propensity for wetting and drying (Egboka and Okpoko, 1984). In SA, silt and mudstone of the Beaufort Series produce highly erodible soils due to the formation of fine textured dispersive soils compared to the dolerites which result in the formation of well structured clay soils (Le Roux *et al*., 2006). Igwe (2012) found that soil developed from weak unconsolidated sandy formations such as False-bedded sandstone, Coastal Plain sands, Nanka sands and the Bende-Ameki formations in the south-eastern Nigeria are more gullied than those derived from shale formations. Igwe (2012) contends that gullies in the False-bedded sandstone, Coastal Plain sands, Nanka sands and the Bende-Ameki rock formations represent the worst case in Sub-Saharan Africa.

Loose unconsolidated materials such as colluvium and alluvium have also been associated with gully erosion. Botha *et al*. (1994) found colluvium of thinly laminated sandy sediment with interbedded lensoid pebble gravel in the northern KZN and consider it to be deposited through sheet wash and ephemeral gully erosion. Rienks *et al*. (2000) found that the dispersive properties of the Masotcheni colluvium in northern KZN played a defining role in the development of the Dabekazi donga. Brooks *et al*. (2009) studied the distribution of alluvial gullies occurring in the alluvium in Australia. Gullies were favourable to alluvium deposits with silty or loamy duplex alkalinity soil at depth. Elsewhere, it was found that loose, friable and poorly cemented unconsolidated sands with thin shale layers greatly influenced the growth of gullies in Agulu-Nanka area, Nigeria (Egboka and Okpoko, 1984). The strength of sands and shale are affected by the saturation below the water table. Vetter (2007) found the presence of severe forms of erosion or gullies in alluvial soils in the EC province. Cobban and Weaver (1993) found that the alluvium within which gully system occur in EC consists mainly of fine to coarse reddish sand with less than 5% clay derived from sandstones and siltstones of the Beaufort Series, represented by the Burgersdorp and Katberg formations.

Gully erosion initiation and development is also linked to the tectonic induced compression or tensional forces which form fractures or cracks in rocks without causing actual tectonic induced movement or displacement (Valentin *et al*., 2005). The contribution to gully erosion by this mechanism has often been poorly understood. Fractures in rocks most often result in linear morphological features (e.g. linear valleys, ridgelines and slope breaks) along the intersection of the fracture plane and the land surface (Jordan *et al*., 2005; Rezaei Moghaddam and Saghafi, 2008). Fractures are the starting point of weathering processes because they have been structurally weakened. The resultant subsurface depressions concentrate through-flow, which accelerates the eluviations of soil particles, lowering the soil surface and as the surface flow concentrates gullies are formed (Valentin *et al*., 2005).

#### ***2.1.3.3. Soil properties***

The resistance of soil to gully erosion is influenced by most soil properties, making soil the most complex factor with high spatial and temporal variability that is not yet fully resolved (Knapen *et al*., 2007). Soil erodibility is influenced by aggregate stability and the ability of soils to generate runoff (Wischmeier and Mannering, 1969; Le Roux *et al*., 2006). Aggregate stability is the ability of soil aggregates to hold together even when subjected to various forms of stress and is an important soil property that affects the movement and storage of water, aeration, erosion, biological activity and the growth of crops (Amézketa *et al*., 2003). Soil aggregates are groups of particles of different sizes that bind each other under the influence of organic and inorganic materials (Amézketa, 1999). Structure depends, in part, on aggregate stability (Amézketa, 1999). Soils with weak structure are easily eroded due to the detachment of individual particles compared to soils whose particles are bound together in aggregates by organic matter, and Fe and Al oxides (Laker, 2004; Alt *et al.*, 2009; Igwe, 2012). High organic matter content helps to maintain good soil structure and requires greater runoff in order for the detachment of soil to occur (Wischmeier and Mannering, 1969).

Various factors influence aggregate stability, for example, sodium is regarded as the most dispersive cation in soil (Laker, 2004). High sodium (sodicity) in clay causes dispersion and cracking, which then promotes gully development through subsurface flow, piping or tunnelling. Sodicity is the measure of the relative preponderance of exchangeable sodium compared to other exchangeable cations such as calcium, magnesium, potassium, hydrogen and aluminium, measured by Sodium Absorption Ratio (SAR), Cation Exchange Capacity (CEC) and Exchangeable Sodium Percentage (ESP). While SAR measures the predominance of dissolved sodium in water compared to the amount of dissolved calcium and magnesium, ESP is a measure of the amount of sodium held in an exchangeable form on the soil’s cation exchange complex, expressed as a percentage of the total CEC (Van de Graaff and Patterson, 2001). High ESP values correlate with a high amount of sodium in soils.

Soils with ESP values higher than 6% are considered to have structural problems related to dispersion (Madikizela, 2000; Van de Graaff and Patterson, 2001). The ESP of 15% or greater is an indication that the soil is sodic (Madikizela, 2000; Seitlheko, 2003). Dispersive soils easily lose aggregation when water passes through (Alt *et al.*, 2009; Le Roux and Sumner, 2012). Studies have shown that ESP in excess of the threshold alone does not infer dispersibility of soil or imply that the soils are highly sodic and therefore susceptible to gully erosion. (e.g. Yaalon, 1987; Van de Graaff and Patterson, 2001). Van de Graaff and Patterson (2001) discouraged the use of ESP as a sole indicator of soil dispersibility and suggested the consideration of the associated clay mineralogy, Electrical Conductivity (EC) of soil solution, CEC and pH. Van de Graaff and Patterson (2001) reiterated that ESP is the measure of the dominance of sodium in the cation exchange complex of the soil, not the amount of sodium in the soil. Madikizela (2000) found gullies in soils with ESP values less than 7% and this supports Yaalon’s (1987) and Van de Graaff and Patterson’s (2001) contention. The dispersibility of duplex soils has been observed even at lower ESP values below the 6% threshold and lower SAR values (e.g. Beckedahl, 1996; Rienks *et al.*, 2000; Seitlheko, 2003).

Beckedahl and De Villiers (2000) and Sonneveld *et al.* (2005) found pipes occurring in soils with low ESP and SAR values. In duplex soils, a strong lateral flux over the less permeable B horizon could develop, followed by convergence of drainage lines into percolines, causing piping that may eventually result in the formation of gullies when the roof collapses (Rienks *et al*., 2000).

Clay is one of the aggregating factors in soils, but its effect on erodibility varies depending on the mineralogy (Amézketa, 1999). Smectitic soils are more erodible compared to stable soils with no smectite. Smectite, kaolinite and illite encourage the structural failure, sliding and mass movement of the soils and soil crusting. Smectite and illite readily form less stable aggregates due to the open lattice structure characterising these minerals and the greater swelling and shrinkage which occur on wetting and drying respectively (Igwe, 2012).

The influence of texture on the erodibility of soils is related to the particle size distribution. Soil texture is defined by Van de Graaff and Patterson (2001) as the varying proportions of sand, silt and clay in the soils. Fine textured clays have low erodibility because their particles are normally attached to each other and not easily separated by water forces. Coarse textured sand is not erodible because rainfall water infiltrates easily and thereby reducing runoff. Medium textured soils with high silt are normally erodible because their fine sand particles are easily detached and transported by rain water (Wischmeier and Mannering, 1969; Alt *et al*., 2009). Vandekerckhove *et al.* (2000) found that most of the bank gullies studied in southeast Spain are characterised by a fine textured soil belonging to the silt, silt loam, silty clay loam, loam and sandy loam classes. Nazari Samani *et al*. (2009) reported silty or fine textured sandy soils with bands of coarse sand as favourable to the development of gullies in Dareh-koreh watershed of Boushehr province, southwestern Iran.

#### *2.1.3.4. Topographic variables*

Various primary topographic variables influence the initiation and development of gullies (Kheir *et al*., 2007). Hilly or mountainous slopes have been described as the most favourable location for the development of gullies (e.g. Rienks *et al*., 2000; Valentin *et al*., 2005). Rienks *et al*. (2000) regard deep gullies as the defining geomorphic feature of the slopes of the central KZN province in SA. Hilly or mountainous regions are normally characterised by long and steep slopes that make them susceptible to gully erosion. Long and steep slopes favour high runoff quantity and velocity, thus, rills and gully initiation (Valentin *et al*., 2005;

Alt *et al*., 2009), but steep slopes can also produce lower runoff volumes compared to gentle slopes. The main cause of lower runoff on steep slopes is the lower crusting rate due to lower kinetic energy and a continuous erosion of the surface seal. A soil crust mainly develops on gentle slopes and as a result, generates high runoff. Contrary to Rienks *et al.* (2000) who regard steep slopes as favourable to gullies, several other studies in SA have shown that gullies favour the lower position of the slopes with gradients of 2˚, 5˚ and 8˚ or valley floors (Laker, 2004; Vetter, 2007; Kakembo *et al*., 2009; Le Roux and Sumner 2012). The regular occurrence of gullies in lower slope positions in SA has long been reported by Liggitt and Fincham (1989) though the authors acknowledged this as unexpected due to the conventional belief that erosion favours steep slopes.

Topography plays a role of concentrating water flow. The topography of a landscape is such that water accumulates in one or more natural waterways before reaching the main stream or river channel. Conventionally, erosion forms occurring along these natural courses were termed ephemeral gullies and recently the term has been extended to include erosion occurring along the man-made linear elements (Casali *et al*., 1999; Vanwalleghem *et al*., 2005). Vanwalleghem *et al.* (2005) observed most shallow ephemeral and large or deep gullies on valley side positions as opposed to the valley floor. In fact, all deep gullies observed by Vanwalleghem *et al.* (2005) were located on the valley side positions, emphasising the pivotal role played by linear landscape elements in concentrating water flow and thereby controlling the incision of deep gullies. Hancock and Evans (2006) found gullies in concentrated flow on hillslope and depositional main channel areas in the northern territory of Australia, confirming the favourability of linear landscapes to the gullies.

The role of other topographic variables, including slope curvature, has not been widely reported on. Curvature is the rate of change in slope which affects the convergence and divergence of water flow on the land surface and influences the acceleration and deceleration of water flow (Zevenbergen and Thorne, 1987). The two most frequently calculated forms of curvature include the profile and plan. Profile curvature is the curvature of the surface in the steepest down slope direction and describes the rate of change of slope along a profile, useful to highlight convex and concave slopes. Plan curvature is the curvature of a contour drawn through the central pixel and describes the rate of change of aspect in a plan across the surface and may be useful to define ridges, valleys, and slopes along the side of these features (Tarolli *et al*., 2012). Comparison of the average slope of the bank gully bed and the average slope of the soil surface by Vandekerckhove *et al.* (2000) showed the occurrence of bank gullies in the lower part of a concave slope profile, where the slope of the surface is flattening out. An overlay of gullied areas on slope curvature by Kakembo *et al*. (2009) also showed concave slope elements as favourable locations for the development of gullies.

### *2.1.3.5. Vegetation cover and type*

Vegetation cover is the fraction or percentage of the ground surface of the reference area covered by vegetation (Purevdorj *et al*., 1998; Schmidt *et al*., 2010). Vegetation cover and type play an important role in preventing soil erosion by protecting soil against agents of erosion (Vrieling, 2006). Soil erosion potential is increased if the soil has very little or no vegetation cover or residue (Soufi, 2002; Peng *et al.*, 2008). The canopies of vegetation intercept raindrops and reduce their kinetic energy, thereby acting as a soil surface barrier (Laker, 2004). According to Le Roux *et al*. (2006), raindrops produce a disruptive force and, when impacted on a bare or unprotected ground, detach the soil particles. Raindrops may also consolidate the soil, which results in the formation of a surface crust known to promote runoff. Laker (2004) indicated that a dense vegetation cover reduces the amount and velocity of runoff. Vegetation provides the organic matter which stabilises the structure of the soil. For vegetation type, grasses provide much better soil protection compared to the non-grass species due to greater basal cover and very fine root systems which bind the soil (Laker, 2004). Grellier *et al*. (2012) found a positive correlation between gully retreat rate and high acacia tree canopy area in the sub-humid grassland of KZN. The positive correlation was attributed to the hypothesis that high tree density is linked to overland and subsurface flows.

### *2.1.3.6. Land use factor*

Notwithstanding that gully erosion occurs naturally, the main trigger and driving force of gullies is human or land use activities (Geyik, 1986; Omuto *et al*., 2009). Land use contributes to gully erosion formation due to the associated reduction in vegetation cover and the development of channels/tracks/path where water flow concentrates. According to Geyik (1986) activities such as improper land use, forest and grass fires, overgrazing, mining, livestock and vehicle trails, urbanisation, road construction and destructive logging may initiate and accelerate gully erosion. Human activities that disregard conservation laws, intentionally and unintentionally, have been blamed for the severe soil degradation by gullies in Nigeria (Nwilo *et al*., 2012). The slash and burn or shifting cultivation practised in many developing countries on hillsides without applying conservation measures may cause gully formation due to loss of protective cover. Uncontrolled burning, by farmers near the end of dry season to encourage the germination of new shoots for livestock or burning new land for cultivation exposes the soil to runoff. Overgrazing decreases vegetation cover, leaving the soil exposed. Trampling effects of livestock compact the soil reducing the infiltration capacity. In underground mining areas, the cracks on the ground and soil creep promote gully erosion during rainy seasons. Gullies may form after road construction, if road cuts or the fill slope are not re-vegetated. Road construction, with inappropriate drainage facilities has been reported as the main land use activities contributing to gully formation in Nigeria (Ehiorobo and Audu, 2012). Gullies may also form on livestock and vehicle trails that run along hillsides because of compaction that reduces the water holding capacity. In forestry, logging with tractors downslope can lead to gully formation because of the runoff concentration along the trails. Gullies may also form where drainage pattern has been altered by urbanisation, more especially in illegal settlement which lacks infrastructure (Ehiorobo and Audu, 2012).

### 2.1.4. Prediction approaches

Models capable of predicting gully erosion are useful to estimate more accurately the effects of environmental change (rainfall regime, land use or land abandonment) on soil loss (Poesen *et al*., 1998). Studies modelling soil loss due to water erosion often consider interill (sheet) and rill erosion with little or no consideration of gully erosion (Capra *et al*., 2005). For example, the widely used USLE and its derivatives such as RUSLE was developed by the United States Department of Agriculture (USDA) from an extensive field based data of many years and small erosion plots using rainfall simulators to fill data gaps as needed. The USLE is designed to predict long-term average soil loss from runoff plots under specified crops and management (Wischmeier and Smith, 1978). Studies have shown that USLE cannot predict soil loss from gully erosion due to the complexity at which the phenomenon occurs, which is outside the scope of the model (Marker *et al*., 2001; Sidorchuk *et al*., 2003; Gordon *et al*., 2006; Van Zyl, 2007). Evidence from field based observations shows that sheet and rill erosion measured from runoff plots are not realistic indicators of a total catchment soil loss, thus there is a need for an appropriate model to predict gully erosion (Poesen *et al*., 2003). Few models exist and these are described below.

#### *2.1.4.1. Ephemeral Gully Erosion Model (EGEM)*

Ephemeral Gully Erosion Model (EGEM) was specifically developed to estimate gully width and soil loss by ephemeral gully erosion and incorporates rainfall for estimation of peak discharge and runoff volume (hydrology), and a combination of empirical relationships and physical process equation (erosion) (Woodward, 1999; Capra *et al*., 2005). Nachtergaele *et al*. (2001) tested EGEM in the Mediterranean environment by comparing the eroded volume of gullies measured on site to the model prediction. Though Nachtergaele *et al*. (2001) found a good correlation between predicted and measured gully volumes, the cross section relationship was not significant, and they concluded that the EGEM is not capable of predicting ephemeral gully erosion properly in the Mediterranean areas. Capra *et al*. (2005) applied a modified version of EGEM in Sicily, Italy by adjusting the hydrology components of the model, namely, the rain distribution type and causative rainfall. Despite these modifications, the results show agreement with Nachtergaele *et al*. (2001) findings, that the cross section and the width cannot be adequately predicted. The adaptations of a hydrological component improved the prediction of ephemeral gullies volume.

A revised version of the Ephemeral Gully Erosion Model (REGEM) was developed by Gordon *et al*. (2006) to address the challenges of EGEM and to be incorporated into Annualised Agricultural Non-Point Source (AnnAGNPS). REGEM simulates the development and upstream extension of an ephemeral gully within AnnAGNPS, based on a migrating headcut and discharge dependent gully dimensions in unsteady spatially varied runoff events. The model addresses transport and capacity limited flows, the routing of different particle size classes, and the potential for deposition and re-entrainment of sediment within the evolving or reactivated gully (Gordon *et al*., 2007). The REGEM is not yet widely tested for ephemeral gully erosion prediction. Both EGEM and REGEM are designed to model ephemeral gullies and require large amounts of input data, including the landscape position where the initiation of an ephemeral gully is expected (Gordon *et al*., 2007).

#### *2.1.4.2. Erosive Response Unit (ERU)*

Erosive Response Unit (ERU) is an area of land receiving more or less similar rainfall and temperatures and has similar characteristics in terms of land use, soil, geology and topography that all control erosion dynamics (Flugel *et al*., 1999; Marker *et al*., 2001). Marker *et al*. (2001) and Sidorchuk *et al*. (2003) applied successfully the concept of ERU to model various forms of erosion, including gullies in Mkomazi River catchment (KZN, SA) and the Mbuluzi River catchment (Swaziland). While ERU’s can identify areas affected by different forms of water erosion (Sidorchuk *et al*., 2003) and determine the susceptibility of a landscape to erosion (Marker *et al*., 2001), it can also be used in different models to obtain the estimation of soil loss from different types of soil erosion.

#### *2.1.4.3. Topographic indices or threshold*

A simple approach to predict gully heads in a landscape is the threshold concept which was long recognised and applied in earlier studies by amongst others Patton and Schumm (1975). Here, gullies are viewed as phenomena initiated by the exceedance of one or more threshold conditions. Topographic threshold for gully erosion initiation and development is widely understood in terms of the combination of slope gradient and upslope contributing area index (e.g. Vandekerckhove *et al*., 1999; 2000; Morgan and Mngomezulu, 2003; Valentin *et al*., 2005; Vanwalleghem *et al*., 2005; Hancock and Evans, 2006; Kheir *et al*., 2007). The combined effects of slope gradient and the upslope contributing area are normally used to predict gully head location (Poesen *et al*., 2003; Svoray and Markovitch, 2009). This index is based on the assumption that “in a landscape with a given climate and land use, there exists for a given slope gradient of the soil surface (S) a critical drainage area (A) necessary to produce sufficient runoff which will cause gully incision” (Poesen *et al*., 2003: p108) and the index is shown in equation 2.1. When the slope of a landscape steepens, the critical drainage area decreases and vice versa.

$$S = aA^b \tag{2.1}$$

where a and b are coefficients depending on the environmental characteristics (Poesen *et al*., 2003).

Other topographic indices such as Compound Topographic Index (CTI) or Topographic Wetness Index (TWI), Stream Power Index (SPI) and Sediment Transport Capacity Index (LS) have also been used to determine the threshold for the initiation of gullies. The TWI or CTI is a function of the upstream contributing area and the slope gradients of the landscape (Feng and Bajcsy, 2005) calculated using the formula indicated in equation 2.2. The TWI is used to describe the effects of topography on the location and size of saturated source areas of runoff generation (Wilson and Gallant, 2000). Le Roux and Sumner (2012) found out that high TWI values favours the development of gullies due to weak strength of soils particularly when wet. It was found by Le Roux and Sumner (2012) that high TWI values correspond well with high upslope contributing area values and represent zones of saturation with high surface soil water along drainage paths.

$$\mathrm{CTI} = \ln\left(\mathrm{A_s} / \tan \beta\right) \qquad (2.2)$$

where $A_s$ is the specific catchment area or upslope contributing area and β is the slope gradient in degrees (Tagil and Jennes, 2008).

The SPI was conventionally developed to estimate the erosive power of the terrain, such that areas with large stream power indices indicate high energy required to transport sediment and thus have a greater potential for erosion (Tagil and Jennes, 2008). The formula to compute SPI is shown in equation 2.3. Kakembo *et al*. (2009) regarded areas with high SPI values as potential areas for sediment removal and gully erosion formation. They used SPI to highlight the preferential topographic zone for gully formation and found that lower slope positions near drainage lines are prone to gullying. There were no gullies in upper slope positions and few were identified in high SPI values, in contrast with the theory that upper slopes generate high runoff.

$$\mathrm{SPI} = A_s \tan \beta \qquad (2.3)$$

where $A_s$ is specific contributing area and $\beta$ is local slope (Wilson and Gallant, 2000).

Related to the SPI is the LS factor which is also a power function of discharge and slope calculated as shown in equation 2.4. The LS is a slope length factor (Wilson and Gallant, 2000) which is defined by the distance from the point of origin of overland flow to where the slope gradient decreases or where a channel starts (Wischmeier and Smith, 1978). Similar to SPI, high LS values were conventionally interpreted as having the potential to generate high runoff (e.g. Wischmeier and Smith, 1978). Other studies found that gullies are dominant on gentle slope position (e.g. Kheir *et al*., 2007; Kakembo *et al*., 2009; Le Roux and Sumner, 2012). Gentle slopes correlate well with lower LS and lower SPI values.

$$\mathrm{LS} = (\lambda/72.6)^{m}\,(65.41 \sin^{2}\theta + 4.56 \sin\theta + 0.065) \qquad (2.4)$$

where $\lambda$ = slope length in feet; $\theta$ = angle of slope; and m = 0.5 if the percent slope is 5 or more, 0.4 on slopes of 3.5 to 4.5 percent, 0.3 on slopes of 1 to 3 percent, and 0.2 on uniform gradients of less than 1 percent (Wischmeier and Smith, 1978).

Realising the weak correlation between slope and critical drainage area at the initiation point of ephemeral gullies, Vandekerckhove *et al*. (1998) suggested the need for determining thresholds for gully erosion initiation using other environmental variables such as the soil factor. The incorporation of all environmental attributes in determining threshold conditions for gully initiation raises a prospect for successful gully location prediction. Threshold conditions for the initiation of gullies in terms of climatological, pedological, geological and even land use have not yet been fully established, but indices such as rainfall erosivity, soil erodibility and vegetation indices have been widely used in soil erosion modelling.

### *2.1.4.4. Rainfall erosivity*

Rainfall erosivity indices have been applied to estimate the ability of rainfall and runoff to cause soil detachment and transport. The concept of rainfall erosivity was first introduced in the 1940's (see Laflen and Moldenhauer, 2003) and gained popularity after its incorporation with other factors in the Universal Soil Loss Equation (USLE) in the 1970's by the United States Department of Agriculture (Wischmeier and Smith, 1978). Rainfall erosivity is defined in the USLE as the sum of individual storm erosion index values expressed as $EI_{30}$, where E is the total storm kinetic energy and $I_{30}$ is the maximum rainfall intensity in 30 minutes (Lu *et al*., 2001). To compute $EI_{30}$ continuous rainfall intensity data of at least 20 years are needed (Wischmeier and Smith, 1978). The storm $EI_{30}$ for a given month, e.g. January (j) is estimated as shown in equation 2.5. Monthly sums can be accumulated to calculate the mean annual average. The lack of long term rainfall intensity data as shown in various studies (e.g. Lu *et al*., 2001; Da Silva, 2004; Le Roux *et al*., 2006) prompted studies to estimate erosivity using daily rainfall amount. In SA, a rainfall erosivity map was derived from daily rainfall data by Le Roux *et al*. (2006) using the model developed by Yu and Rosewell (1996) in Australia. The choice of the Australian model was based on the climate similarity with SA where both countries receive winter rainfall in the southwest and summer rainfall with tropical influences over the northern parts (Le Roux *et al*., 2006).

$$EI_{30}(j)=\alpha\left[1+\eta\cos\left(2\pi f\, j-\omega\right)\right]\sum_{d=1}^{N} R_d^{\beta} \quad R_d>R_0 \qquad (2.5)$$

where $R_d$ is the daily rainfall amount, $R_0$ is the threshold rainfall amount to generate runoff (set to 12.7mm: Wischmeier and Smith, 1978) and N is the number of days with rainfall amount in excess of $R_0$ in the month. The first part of the equation is the sinusoidal function with a wavelength of twelve months ($f = 1/12$). The parameter $\omega$ is set at $\pi/6$, meaning that for a given amount of daily rainfall the corresponding rainfall erosivity is the highest in January when the temperature is the highest for most parts of the continent. $\alpha = 0.395\ [1 + 0.098 \exp(3.26\Psi/M)]$, $\Psi$ = average summer rainfall, M = average annual rainfall, $\beta = 1.49$ and $\eta = 0.29$ (Lu *et al*., 2001).

### *2.1.4.5. Soil erodibility*

Soil erodibility is the most complex property compared to other USLE indices. By definition, soil erodibility refers to the ability of the inherent properties of soil to influence erosion (Wischmeier and Smith, 1978) and accounts for soil properties response to soil loss during rainfall events (Le Roux *et al*., 2006). The erodibility of a particular soil was experimentally predetermined by Wischmeier and Smith (1978) from the rate of soil loss per erosion index unit as measured on a unit plot of 72.6ft (22.1m) long, with a uniform lengthwise slope of 9%, in a continuous fallow (free for at least 2 years), tilled up and down the slope. The primary soil properties considered when estimating the erodibility values are particle distribution, organic matter content, surface structure and profile permeability using the soil erodibility nomograph (Wischmeier and Smith, 1978). As an example, equation 2.6 solves the erodibility of soil containing less than 70% silt and very fine sand using the nomograph obtainable in Wischmeier and Smith (1978). In SA and many other parts of the world, the mentioned soil properties data are not available nationally or even locally in digital format. In the absence of soil property data, erodibility has to be estimated using other available soil physical and chemical data. Soil erodibility in SA was estimated using 1: 50 000 and 1:250 000 soil maps, rating the erodibility of individual soil series of the Binomial Soil Classification System. Soil erodibility values were then linked to corresponding soil series in the Land Type Inventories (Le Roux *et al*., 2006).

$$100\,K = 2.1\,M^{1.14}\left(10^{-4}\right)\left(12\text{-}a\right)+3.25\left(b\text{-}2\right)+2.5\,(c\text{-}3) \qquad (2.6)$$

where M = the particle-size parameter defined above, a = percent organic matter, b = the soil structure code used in soil classification and c = the profile-permeability class.

### *2.1.4.6. Vegetation indices*

While many methods for estimation of cover such as spectral mixture analysis and calibrated cover radiance relationships amongst others exist (Pickup *et al*., 1993), vegetation indices are commonly used. Vegetation cover is a good indicator of land management practise. Ground cover can be used to infer wind and water erosion risks (Purevdorj *et al*., 1998; Schmidt *et al*., 2010). Vegetation indices such as Normalised Difference Vegetation Indices (NDVI) and its derivatives have frequently been used to quantify vegetation cover (Röder *et al*., 2008). The NDVI is expressed using the ratio as shown in equation 2.7 and separates vegetative areas and bare ground. Taruvinga (2008) used vegetation indices such as NDVI, Soil Adjusted Vegetation Indices (SAVI) and Transformed Soil Adjusted Vegetation Indices (TSAVI) to map gullies in KZN, SA and found that NDVI produced better correlation with gullies compared to other indices. Le Roux and Sumner (2012) used TSAVI to estimate cover as one of the contributing factors of gully erosion in the EC province and found gullies in areas of low vegetation cover or low TSAVI values.

$$\mathrm{NDVI} = \frac{\mathrm{NIR\text{-}RED}}{\mathrm{NIR+RED}} \tag{2.7}$$

where NIR and RED are the amounts of near-infrared and red light bands reflectance, respectively. The formula is based on the premise that chlorophyll absorbs RED whereas the mesophyll leaf structure scatters NIR (Pettorelli *et al*., 2005).

In SA, Pretorius and Bezuidenhout (1994) developed a Bare Soil Index (BSI) to separate vegetation from bare ground in order to highlight land cover and soil erosion. BSI was developed from a Landsat satellite data by modifying the Transformed Vegetation Index (TVI) formula through substituting the NIR band with Mid-Infrared (MIR) band and Red (R) band with Green (G) band. MIR band normally has high soil reflectance values compared to low soil reflectance values of the G band. The BSI is calculated using the formula in equation 2.8 and was found very effective in separating vegetation from soil (Pretorius and Bezuidenhout, 1994).

$$\mathrm{BSI} = 100 \times \mathrm{sqrt}\left[\frac{\mathrm{MIR\text{-}G}}{\mathrm{MIR+G}}\right] \tag{2.8}$$

## 2.2. Gully erosion in South Africa

Gully erosion and its associated problems in South Africa (SA) have long been recognised. Research addressing gully erosion directly in SA mainly focuses on three aspects of a particular interest here, this includes: gully origin, soil loss rate and contributing factors.

### 2.2.1. Gully origin

Determining the origin and age of a gully is a contentious topic globally, even in countries with a long history of documentary records and data (Boardman, 2014). The debate on the origin of gullies in SA is centred on the geologic occurrence impelled by extreme climatic events and human pressure ascribed to the European settlements. Heine (1987) associated the development of gullies, surface wash, rill erosion and mass movement in Southern Africa to climate change during the Palaeolithic era. At the time, gullies had either been incised or refilled with land waste associated with wetting and drying. Foster *et al*. (2012) hypothesised that change in weather patterns, particularly flooding preceded by prolonged drought was the main trigger of gully erosion and badlands in the Karoo. They found low sedimentation rate during dry periods and an increase in sediment yield following high intensity rainfall to suggest that changes in weather patterns contributed to gully erosion. In a somewhat different approach, Cobban and Weaver (1993) consider the preferential occurrence of gullies in unconsolidated deep Quaternary sediments in the Tsolwana region of Ciskei as an indication that gullies are a natural component of the weathering succession. In an attempt to determine the age of the Quaternary sedimentary units elsewhere, Botha *et al*. (1994) applied the Infra Red Stimulated Luminescence (IRSL) dating technique in the northern KZN. The IRSL technique attests to the geomorphic cycles of gully cut and fill and palaeosol formation in the region during the past 135ka in the Masotcheni formation (Botha *et al*., 1994).

Marker and Evers (1976) blamed anthropogenic activities during the Iron Age for the formation of gullies near Lydenburg in MP province. They dated gully formation to approximately the year 1826 owing to the late Iron Age movement of livestock during village settlement and vegetation denudation as a result of the destruction of villages. Studies of land degradation in the Klein Seekoi River valley of the central Karoo in the EC regard the occurrence of gullies and badlands as a consequence of farming activities introduced by the European settlers (Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Keay-Bright and Boardman, 2007; Boardman 2014). Although the exact date of gully initiation was not revealed due to lack of long term data and evidence, analysis of historical aerial photographs shows that gullies were well established in 1945 (Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Rowntree and Foster, 2012), implying that the incision occurred earlier.

Foster *et al*. (2012) contend that it is unlikely that pre-colonial herders caused widespread irreversible destruction of the landscape, due to their nomadic lifestyle. Thus, logic suggests that the introduction of settled farming practises and development of communication networks of ox-wagon tracks associated with the European settlers are the main cause of degradation (badlands and gullies) in the Karoo (Keay-Bright and Boardman, 2007). Increased in stock numbers between 1850 and 1950 especially the introduction of sheep caused severe overgrazing, which may have resulted in gully formation (Boardman, 2014). It was speculated that the growth of livestock tracks networks, which were largely dependent on the availability of water and grazing, could have triggered the development of gullies due to runoff accumulation (Boardman *et al*., 2003; Keay-Bright and Boardman, 2006). These tracks were extensively utilised by cattle wagons during further developments of roads to Kimberly diamond mines during the 1870's which may have placed stress on vegetation, leading to degradation and gully initiation (Keay-Bright and Boardman, 2007).

Boardman (2014) investigated the relationship between vlei (wetland) deposits in the valley floors and gullies, insinuating that gullies postdate late Holocene development of vlei conditions. Boardman argued that the accumulations on vlei deposits presuppose a wet, poorly drained environment which could not have happened if gullies had increased. The much drier climate coupled with the use of wagons at the valley floors may have resulted in gully formation. Additional insight on gully origin in the Karoo was provided by Rowntree (2013) through the analysis of literature published in the Agricultural Journal of the Cape of Good Hope (AJCGH). Rowntree (2013) found that by the turn of the 19th century, literature revealed the widespread occurrence of gullies. The analysis of historical evidence suggests that gullies were initiated after the 1820's, and during 1860's, but gullies were certainly present during the 1870's. The 19th century was characterised by severe degradation in a form of badlands and gullies, ascribed to the disturbances of vegetation through livestock grazing and development of tracks (Keay-Bright and Boardman, 2006; Keay-Bright and Boardman, 2007; Boardman, 2014) as already discussed.

### 2.2.2. Gully erosion rates

Beckedahl and De Villiers (2000) estimated a soil loss rate of 14.2 t ha y$^{-1}$ and 5.6 t ha y$^{-1}$at KuLozulu and Qabata sites, EC respectively (Table 2.2). Soil loss estimate at the KuLozulu site were obtained from measurements of the diameter and depth of a pipe-gully systems caused by road culvert using a sequence of aerial photographs dating from 1984 to 1996. At Qabata, the rate was obtained using field measurements made in 1996 using prismatic compass and tape measure. According to Beckedahl and De Villiers (2000), the observed rate must be treated as preliminary until corroborated by further results.

**Table 2.2: Quantitative soil loss rates from gully erosion and the techniques used as quoted from their original source, excluding the extrapolated figures**

| Source | Techniques of measurement | Spatial scale | Soil Loss Rate |
|---|---|---|---|
| Beckedahl and De Villiers (2000) | Aerial photographs | Field scale | 14.2 t ha y$^{-1}$ |
| | Field measurements | | 5.6 t ha y$^{-1}$ |
| Boardman *et al.* (2003) | Rainfall simulation on grassland | Plot (0.5m x 1.0m) | 0.034 g m$^{-2}$ min$^{-1}$ |
| | Rainfall simulation on shrubland | | 0.085 g m$^{-2}$ min$^{-1}$ |
| | Rainfall simulation on degraded sites | | 0.203 g m$^{-2}$ min$^{-1}$ |
| Keay-Bright and Boardman (2009) | Stone Pedestals | Plot (350mm x 5mm) | 108 mm yr$^{-1}$ |
| | *Pteronia tricephala* | | 95 mm yr$^{-1}$ |
| | Erosion pins - interfluves | | 5.6 mm yr$^{-1}$ |
| | Erosion pins - sidewalls | | 16.7 mm yr$^{-1}$ |
| | Erosion pins - footslopes | | 4.7 mm yr$^{-1}$ |
| | Erosion pins - channels | | 2.6 mm yr$^{-1}$ |
| Chaplot *et al.* (2011) | Rainfall simulation - runoff | Plot (1m$^2$) | 450 g m$^{-2}$ h$^{-1}$ |
| | Rainfall simulation - splash | Plot (4m$^2$) | 176 g m$^{-2}$ h$^{-1}$ |
| | Rainfall simulation - fall of entire soil aggregate | Plot (1m$^2$) | 94 g m$^{-2}$ h$^{-1}$ |
| Grellier *et al.* (2012) | GIS | Sub-catchment (2.5km$^2$) | 200 Mg ha y$^{-1}$ |
| Rowntree and Foster (2012 | $^{210}$Pb and $^{137}$Cs dating, aerial photographs and mineral magnetic measurements | Sub- catchment (2.58km$^2$) | 654 t km$^{-2}$ yr$^{-1}$ |

Using field plots to estimate soil loss from gully erosion seems to be the most popular technique in SA. Boardman *et al.* (2003) used a rainfall simulator in 22 plots for an average of 30 minutes to investigate the effects of vegetation cover on runoff and erosion in the Karoo, EC. Three plots with a contrasting percentage of vegetation cover (grassland = 65.3%, shrubland = 30.6% and degraded land = 7.5%) were selected for further analysis. Estimates of sediment production on grassland, shrubland and the degraded plots were 0.034, 0.085 and

0.203 g $m^{-2}$ $min^{-1}$, respectively (Table 2.2), implying that a change to shrubby vegetation increases runoff and erosion. Chaplot *et al*. (2011) simulated rainfall for 45 minutes in order to quantify the contribution of splash detachment, sediment transport by runoff and fall of soil aggregates to potential gully bank retreat in a $10km^2$ watershed in KZN. Soil loss due to runoff corresponds to an erosion rate of 450 g $m^{-2}$ $h^{-1}$. Soil loss from the splash and fall of entire soil aggregate were 176 g $m^{-2}$ $h^{-1}$ per $m^2$ of gully bank and 94 g $m^{-2}$ $h^{-1}$ respectively (Table 2.2). The combined erosion rate was estimated at approximately 721 g $m^{-2}$ $h^{-1}$. An extrapolation to the whole bank gully of about $500m^2$ per hectare gave an erosion rate of 4.8 t ha $y^{-1}$.

Keay-Bright and Boardman (2009) installed pins in a grid pattern of 1m or 2m in 10 sites affected by badland erosion in the Karoo, EC. The depth of the pins was measured and re-measured at interfluves, footslope, channel and sidewall locations over four years. Annual mean soil loss estimates for the 10 sites was 5.6 mm $yr^{-1}$ for interfluves pins, 16.7 mm $yr^{-1}$ for sidewalls, 4.7 mm $yr^{-1}$ for footslopes, and 2.6 mm $yr^{-1}$ for channels (Table 2.2). Keay-Bright and Boardman (2009) also used stone pedestals and *Pteronia tricephala* shrub to measure erosion rates from the badlands. Mean soil loss from stone pedestals was 108mm, while the mean soil loss from *Pteronia tricephala* plants was 95mm (Table 2.2).

Grellier *et al*. (2012) applied GIS techniques for quantitative gully erosion rate measurements and monitoring by mapping gully density (length and area) and computing gully length, head area, retreat length and retreat area from 1945 to 2009 using aerial photographs in the upper part of Thukela River catchment in KZN. The analysis also included extraction of topographic variables such as average slope of each drainage area, local gully head slope, and Stream Power Index (SPI). They calculated volumetric retreat rate for each gully head by multiplying the measured retreat area with field measurements along transects where they measured the width and the depth every 20m along the longitudinal development of the gully. An estimated total retreat area during the period of assessment was 1 $530m^2$ $y^{-1}$, which gives a mean soil loss rate of 200 Mg ha $y^{-1}$ (Table 2.2).

Rowntree and Foster (2012) estimated sediment yield from a combination of $^{210}Pb$ and $^{137}Cs$ dating as well as the identification of sediment source using mineral magnetic measurements in the Karoo, EC. They found a mean yield of 654 t $km^{-2}$ $yr^{-1}$ (Table 2.2) and a peak of ~1 600 t $km^{-2}$ $yr^{-1}$ in a time span ranging from 1935 to 2007. Erosion pins were also used to estimate sediment yield, with the results suggesting an extremely active and high sediments yield from badlands erosion.

Although the techniques for estimation of soil loss from gully erosion differs and thus results not always comparable (e.g. Poesen *et al*., 2003), some of the rates quoted in Table 2.2 for SA are high compared to a soil loss tolerance of 10 t ha·$y^{-1}$ (Le Roux *et al*., 2008). This confirms that gully erosion in SA is occurring at an alarming rate. Various techniques for measurement were applied, including remote sensing (aerial photographs), Geographic Information System (GIS), erosion plots and field measurement (Table 2.2). The choice of a technique seems to have an influence on the size of the area investigated and hence the amount of soil loss. According to Poesen *et al*. (2003) the amount of soil loss through gullying depends on the size of the area investigated, where large area results in high sediment yield. This review shows that as the size of the area investigated increases from a plot size of 350mm x 5mm to a sub-catchment of 2.58$km^2$, soil loss rate increases from as minimal as 2.6 mm $yr^{-1}$ to an extremely high of 654 $km^{-2}$ $yr^{-1}$ (Table 2.2), thus confirming the Poesen *et al*. (2003) claim.

While some of the soil loss rates shown in Table 2.2 most probably underestimate gullying as a potential sediment source due to the small size of the area considered, it is important to indicate that several regions of SA are severely affected by gullies. The extensively gullied areas include the EC and KZN, whilst moderate to severely affected areas include the NC, FS, LP, MP, WC and NW (see Figure 2.4) (Mararakanye and Le Roux, 2012). At a catchment or field scale, severe gullies have also been observed (e.g. Taruvinga, 2008; Mararakanye and Nethengwe, 2012). Other studies have monitored the extent of gully erosion over time to show that gully erosion remains the source of sediments entering waterways. Kakembo (2000) observed dramatic incisions of stream channels in 1975 on an area where no gully erosion was observed in prior aerial photographs dated 1939, 1949 and 1963. A decrease in gullies and extent of degraded areas from aerial photographs at certain locations and at different timescale was observed, although some sites in the respective areas investigated and during a certain period, showed a slight increase (Garland and Broderick, 1992; Boardman *et al*., 2003; Keay-Bright and Boardman, 2006). Generally, studies have found that the rate, intensity and number of gullies are increasing at various spatial and temporal scales (e.g. Watson, 1996; Kakembo and Rowntree, 2003; Sonneveld *et al*., 2005; Vetter, 2007; Grellier *et al*., 2012). Vetter (2007) digitised gullies from aerial photographs dated 1969 to 1995 and implement change detection in order to determine the spatial change of gully erosion. The findings show that erosion over a 26 year period had increased in three sites by 7%, 3% and 2%. At one site, erosion decreased by 3%.

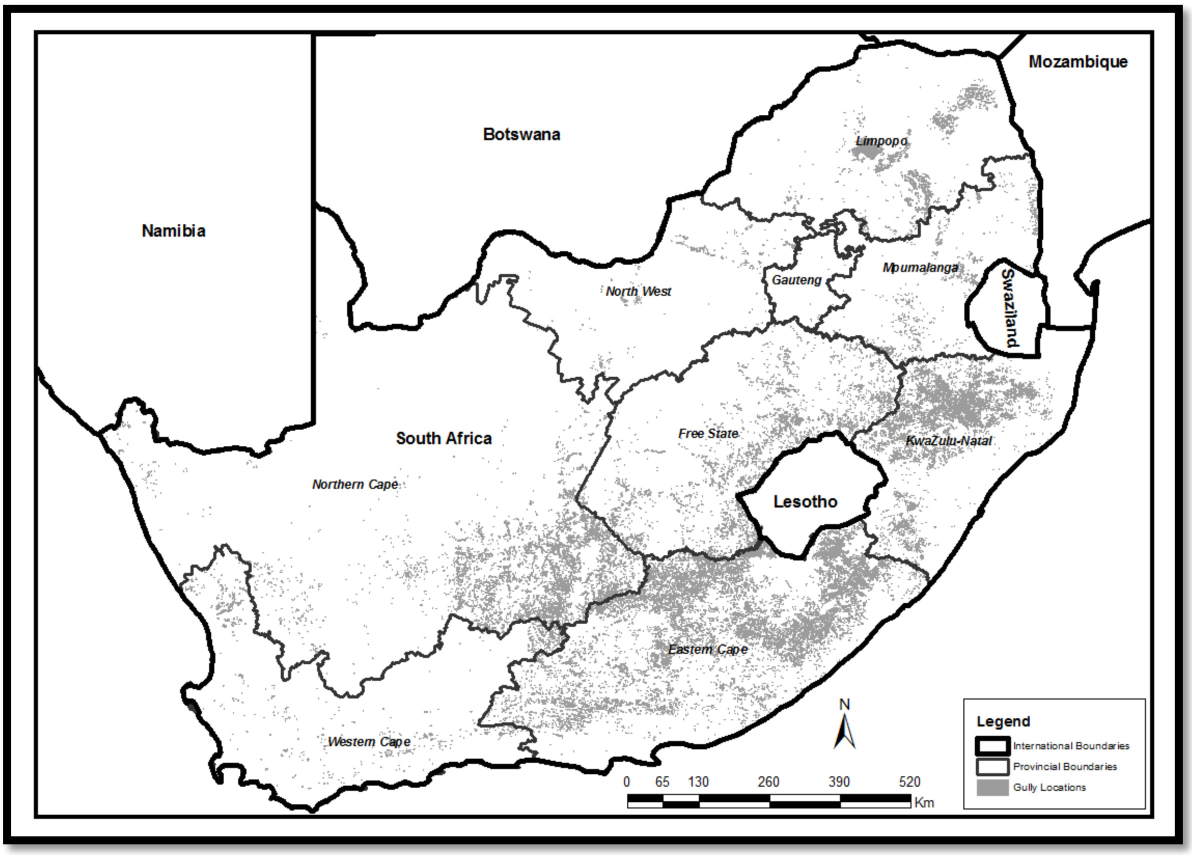

**Figure 2.4: Gully location map of South Africa (source: Mararakanye and Le Roux, 2012)**

### 2.2.3. Dominant contributing factors

The following section gives a detailed summary of gully erosion factors important in SA. It is recognised that other factors are interrelated and therefore warrant groupings such as the lithological and pedological factors as well as land use and vegetation cover.

#### *2.2.3.1. Lithological and pedological factors*

In a SA context, studies have shown that the proportion of gullies on sedimentary rocks such as mudstones, sandstone, siltstone and shale as well as unconsolidated alluvium and colluvium constantly supersede those of igneous and metamorphic rocks (e.g. Beckedahl, 1977; Liggitt and Fincham, 1989; Dardis and Beckedahl, 1991; Cobban and Weaver, 1993; Watson and Ramokgopa, 1996; Watson and Ramokgopa, 1997; Beckedahl and De Villiers;

2000; Watson, 2000; Vetter, 2007; Le Roux and Sumner; 2012). Cobban and Weaver (1993) found a network of gullies confined to fan-shaped deposits of alluvium situated at the base of hillslopes in the Tsolwana Game reserve, Ciskei. The alluvium was comprised of fine to coarse reddish sand, with less than 5% clay. Sandy texture of the alluvium was found to be derived from the coarse grained sandstones and siltstones of the Beaufort Series, represented by the Burgersdorp and Katberg Formations. Botha *et al*. (1994) and later Rienks *et al*. (2000) studied gullies developed from the unconsolidated colluvial sequence, mapped as the Masotcheni Formation while Beckedahl and De Villiers (2000) observed piping developed into a 0.5m to 8m thick stratified colluvium above weathered mudstone. The most important characteristic feature of most of the mentioned sedimentary rocks and the unconsolidated materials is that they give rise to unstable duplex soils (Rienks *et al*., 2000; Laker, 2004; Le Roux and Sumner; 2012).

Duplex soils are dispersive and easily lose aggregation, making them prone to gullying particularly through tunnelling (Rienks *et al*., 2000; Laker, 2004; Le Roux and Sumner; 2012). The clay mineralogy and sodium content of soils often measured by the ESP, SAR, EC, and CEC are used to determine the shrinkage and cracking of the clays as well as dispersibility which makes them prone to piping (Beckedahl *et al*., 1988; Beckedahl, 1996; Beckedahl and De Villiers, 2000; Madikizela, 2000; Rienks *et al*., 2000; Sonneveld *et al*., 2005). Conventionally, it has often been misinterpreted that the soil with high ESP or SAR values indicate that the soil is highly sodic and therefore highly erodible (Yaalon, 1987). Recently, most studies found that gullies may occur in soil with very low ESP and SAR values (e.g. Beckedahl and De Villiers, 2000; Madikizela, 2000; Sonneveld *et al*., 2005). The particle size distribution of soil such as sandy, silty and clayey materials has also been found to be favourable to gully erosion due to their collapsible grain structure (Beckedahl, 1977; Beckedahl and De Villiers, 2000; Keay-Bright and Boardman, 2009; Chaplot *et al*., 2011).

#### *2.2.3.2. Topographic factor*

It is often accepted in SA that gully erosion predominates on lower slope positions (Liggitt and Fincham, 1989; Cobban and Weaver, 1993; Beckedahl, 1996; Beckedahl and De Villiers, 2000; Sonneveld *et al*., 2005; Vetter, 2007; Kakembo *et al*., 2009; Le Roux and Sumner, 2012; Manjoro *et al*., 2012) as opposed to some findings elsewhere where steep slopes are favourable to the development of gullies (e.g. Valentin *et al*., 2005; Alt *et al*., 2009). The reason why lower slopes are favourable to gullies is that the unconsolidated alluvium and colluvium materials which are often composed of unstable duplex soils are mainly found on lower slopes (Liggitt and Fincham, 1989; Cobban and Weaver, 1993; Manjoro *et al*., 2012) in SA. For example, Manjoro *et al*. (2012) found that the gullied and badland areas in the Mgwalana catchment, EC are located mainly on concave readily erodible colluvial deposits on lower slopes.

Little is known about the role of other topographic variables on gully erosion initiation in SA, but, Kakembo *et al*. (2009) introduced the concept of thresholds, through investigation of the relationship between gullies and several variables such as slope angle, position, configuration and SPI. They found that the topographic zone for gully initiation is the concave lower hillslope elements, with slope angle of 5°–9° and SPI values of 2 to 6 near drainage lines. Le Roux and Sumner (2012) investigated several topographic variables influencing continuous and discontinuous gullies such as slope degrees, upslope contributing areas (AS), Topographic Wetness Index (TWI) and Sediment Transport Capacity Index (LS). They found continuous gullies are more prominent on gentle slopes less than 10° whereas discontinuous gullies are prominent on steep slopes. The higher AS and TWI values correlated well with gullies but large proportions of gullies were found in areas with low LS values.

#### *2.2.3.3. Land use and vegetation cover*

It is widely acknowledged that soil erosion is a natural phenomenon, initiated and accelerated by land use activities. The blame is often on agriculture in a form of overgrazing due to the associated vegetation disturbances and thus increase rates of gully erosion (Liggitt and Fincham, 1989; Watson, 1996; Watson and Ramokgopa, 1997; Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Keay-Bright and Boardman, 2007; Vetter, 2007; Foster *et al*., 2012; Le Roux and Sumner, 2012). Evidence shows that overstocking, particularly associated with sheep farming introduced by the European settlers as already discussed, contributed to widespread overgrazing during the mid 19th and 20th centuries (Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Keay-Bright and Boardman, 2007; Foster *et al*., 2012; Rowntree, 2013; Boardman 2014). The denudation of vegetation associated with overgrazing and those exacerbated by periodic drought was found to be the most likely trigger of gully erosion (Marker and Evers, 1976; Watson, 1996; Watson and Ramokgopa, 1997; Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Vetter, 2007; Foster *et al*., 2012).

Numerous other studies associated gully erosion with land abandonment (Marker and Evers, 1976; Kakembo, 2000; Kakembo and Rowntree, 2003; Sonneveld *et al*., 2005; Vetter, 2007; Kakembo *et al*., 2009; Foster *et al*., 2012). Whether the land was abandoned due to widespread gully erosion or if the initiation of gullies occurred after the land was abandoned remains speculative. Kakembo and Rowntree (2003) as well as Vetter (2007) shed some light. In an attempt to establish the relationship between land use in a form of grazing, cultivation and land abandonment in a communal land of the EC province, Kakembo and Rowntree (2003) examined a series of aerial photographs dating from 1938 to 1988. The predominance of gully erosion on abandoned cultivation fields was discernible throughout the study period. Different possible explanations were obtained. First, it was suggested that the loss of land productivity consequent to sheet erosion may have caused low yielding fields to be abandoned. Second, the extended drought in the 1940's and 1970's may have caused the abandonment directly or these spells may have hindered the resumption of cultivation using ox-drawn ploughs even during the short rainy spells. Last, the increase in pension payment may have resulted in a shift from dependency on cultivation to the grant, encouraging land abandonment. Vetter (2007) considers land abandonment in Herschel district, EC province as a direct consequence of the betterment planning policy in which homesteads and arable land were abandoned and since used for grazing. It was postulated that the lack of vegetation cover in the first few years since the land was abandoned, render all the land vulnerable to gully erosion. Kakembo *et al*. (2009) found that abandoned lands were associated with the replacement of indigenous perennial vegetation species by arid condition shrubs, impairment of soil biophysical properties and gully erosion. Foster *et al*. (2012) found small gully systems in contour terraces extended upslope to areas of former cultivation, confirming the vulnerability of land abandonment to gully erosion.

Infrastructural development, such as the construction of roads, railways and associated structures has also been found to influence gully erosion (e.g. Watson; 1996; Beckedahl and De Villiers, 2000; Kakembo, 2000; Madikizela, 2000; Boardman *et al*., 2003; Ngetar, 2011). Beckedahl and De Villiers (2000) observed piping that resulted in localised badlands downslope of a road culvert. The examination of aerial photographs shows that piping developed subsequent to the construction of a tar road. Kakembo (2000) investigated the incision caused by runoff concentration from a series of railway culverts constructed on natural drainage lines. The non-erosive conveyance structures of the concrete culverts concentrate water flow at increased velocity and discharge, leading to gully erosion.

Interviews with local communities by Madikizela (2000) revealed that the compactions associated with machinery and off-road vehicles are the contributor to gully erosion. Boardman *et al*. (2003) shows that the wagon tracks along the Seekoei River are the most likely contributor to gully development, particularly during the 1870s when they were utilised extensively on opening up of the Kimberley diamond mine.

#### *2.2.3.4. Rainfall factor*

Rainfall is the main driver for all water erosion features worldwide that acts as a source of energy in the detachment and transportation of soil particles (Read, 2002; Vanwalleghem *et al*., 2005). Watson (2000) ranked rainfall and vegetation cover as the principal contributor to badland erosion in northern KZN. Some studies recognised the impact of rainfall in gully erosion formation, particularly when preceded by a dry spell (Watson, 1996; Keay-Bright and Boardman, 2006; Vetter, 2007). The ability of rainfall to cause gully erosion depends on its quantity, frequency and intensity (Kakembo, 2000; Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Vetter, 2007). Numerous studies used the annual rainfall amount as the surrogate to rainfall quantity, frequency and intensity. Liggitt and Fincham (1989) found greater gully erosion rates (13,5% of grid squares affected) in areas where rainfall was less than 900mm per annum compared to lower erosion (2% of grid squares) in areas receiving more than 900mm of rain in northern KZN. Similarly, Botha *et al*. (1994) found a strong association between areas receiving 600mm to 800mm of summer dominated rainfall with gullies within colluvial deposits in the same geographical region. Additional analysis in the same area by Watson and Ramokgopa (1997) revealed that catchments susceptible to gully erosion have erosive rainfall, ranging from 550mm to 560mm. Kakembo (2000) contends that monthly rainfall peaks are usually better indicators of episodes of intense rainfall than annual totals. Kakembo (2000) observed the stream channel incisions in the 1975 aerial photograph sequence that occurred subsequent to the recorded extreme rainfall events between 1970 and 1975. According to Vetter (2007), a single intense rainfall event may have a devastating effect on soil erosion, particularly when falling on a bare ground following a dry period. The direct field observations of rain storms by Boardman *et al*. (2003) indicate that rainfall events of 10mm or greater may give rise to Hortonian overland flow while Chaplot *et al*. (2011) estimated an erosion rate of 4.8 t ha $y^{-1}$ from a rainfall simulator at an intensity of 60 mm $h^{-1}$ for 45 minutes as already mentioned.

### 2.2.4. Research trends

An analysis of historical literature from the Agricultural Journal of the Cape of Good Hope (AJCGH) by Rowntree (2013) showed that gully erosion in SA has a long scientific observation history dating back to the late 19th century. The majority of studies reported on the growing concern of deterioration of veld conditions consequent to overgrazing. Subsequent soil erosion research in SA is believed to have been triggered by the release of the Drought Investigation Commission (DIC) report (Liggitt and Fincham, 1989) during the early 1920's which concluded that human induced soil erosion is the main cause of desertification in most parts of the country (Liggitt and Fincham, 1989; Cooper, 1996; Pile, 1996). Liggitt and Fincham (1989) recognised that the majority of soil erosion assessments conducted following the release of the DIC report did not comprehensively include gully erosion. Since the late 1980's, gully erosion research was conducted at regular intervals, gradually increasing during the year 2000 and in 2012 (Figure 2.5). The beginning of the regular and rising research trend coincided with the advent of remote sensing and GIS technology for assessment. According to Macdevette *et al*. (1999), GIS in SA has a short history dating back no further than 1980's. Although remote sensing technology in a form of aerial photographs dates as far as the 1937 (Garland and Broderick, 1992), its application in soil erosion research was often limited. Earlier studies relied mainly on field observations and laboratory analysis (Henkel *et al*., 1938; Marker and Evers, 1976; Beckedahl, 1977).

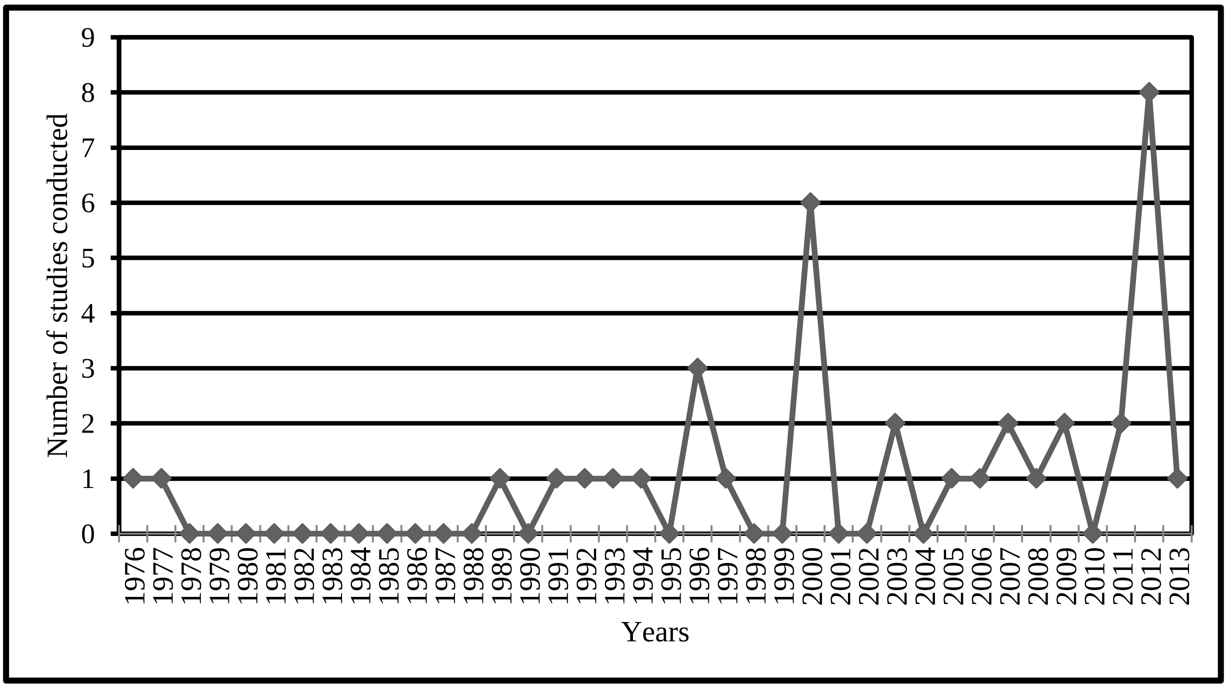

**Figure 2.5: Temporal trends in gully erosion research since 1976**

Much of the published work on gully erosion in SA concentrates on the degradation of the Karoo region in the EC province (e.g. Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Keay-Bright and Boardman, 2007; Keay-Bright and Boardman, 2009; Rowntree, 2013; Boardman 2014) and Mfolozi catchment in the northern KZN province (e.g. Liggitt and Fincham, 1989; Botha *et al*., 1994; Watson, 1996; Watson and Ramokgopa, 1996; Watson and Ramokgopa, 1997; Rienks *et al*., 2000; Watson, 2000). Figure 2.6 illustrates the concentration of gully erosion research in the EC and KZN. The concentration of research works in these two provinces could be attributed to the severe intensity of gully erosion as already indicated. According to Mararakanye and Le Roux (2012), the mentioned provinces ranked the highest including NC in terms of proportion of the areas affected by gullies. Nevertheless, the severity of gully erosion in other provinces cannot be underestimated, particularly when prioritising soil conservation. Specifically, provinces such as the MP and GP contain greater proportions of the land suitable for cultivation (Schoeman *et al*., 2002) and thus require protection against any form of degradation such as soil erosion.

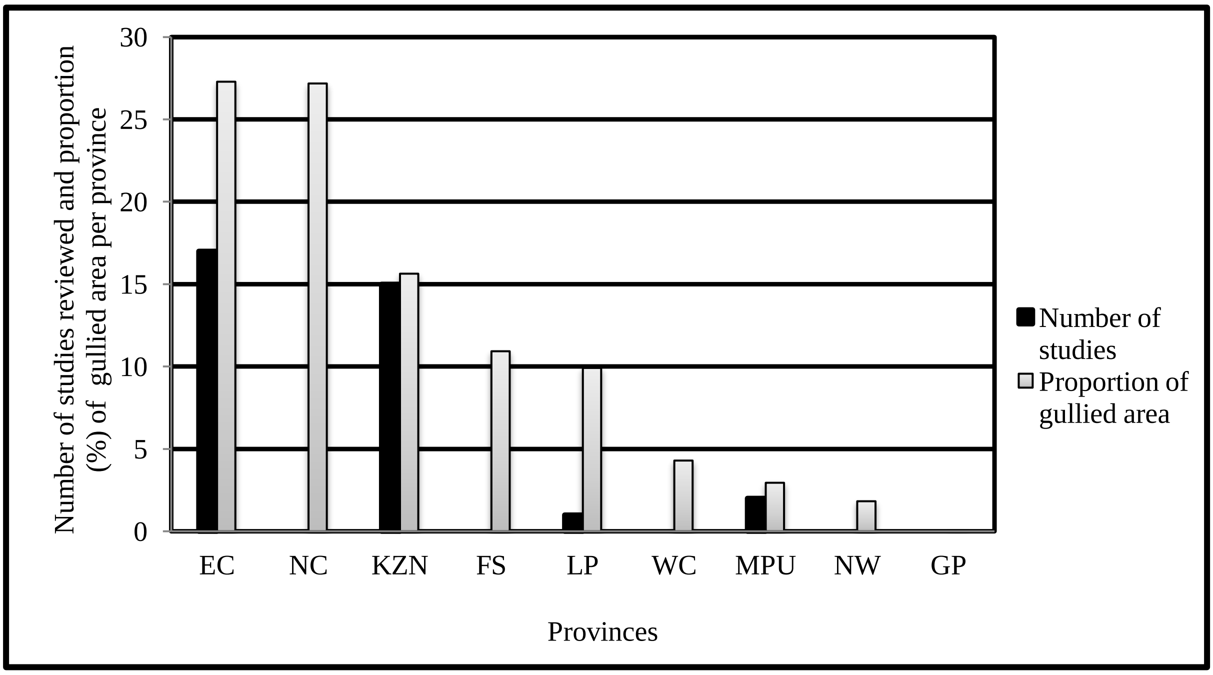

**Figure 2.6: Number of reviewed gully erosion studies by province (n = 35) excluding those crossing one or more provincial borders, versus the proportion of the total gullies per province (source: Mararakanye and Le Roux, 2012)**

Most of the gully erosion assessment in SA tended to concentrate on smaller geographical areas and the only reference addressing gully erosion at national scale is Mararakanye and Le

Roux (2012). Studies have shown that while erosion control measures are normally implemented at the field scale, the allocation of scarce conservation resources and development of policies and regulations requires erosion assessment at the regional or national scale (Vrieling, 2006; Le Roux *et al*., 2007). Various assessment techniques such as field observations, plot studies and laboratory analyses applied in SA are suitable for small areas and their results cannot be directly extrapolated to monitor erosion on a larger geographical region (Sivapalan, 2003). The main drawback of the small area assessment is the lack of heterogeneity of the landscape properties which are often higher at regional or national level (Boix-Fayos *et al*., 2006). For example, Le Roux and Sumner (2012) found that rainfall in their factor assessment in a tertiary catchment did not vary substantially, leading to its exclusion in further analyses. While remote sensing and GIS offer greater possibilities for national scale assessments, the approaches such as digitising often adopted in most studies is labour intensive and thus is less utilised effectively. Boardman (2006) observed that the rate of erosion is scale dependent and illustrated an overestimation in the rate of soil losses from rills and gullies with an increase in the size of the area where erosion is being estimated. Scale transitions should thus be approached with caution.

### 2.2.5. Gaps in current knowledge

Despite the notable progress made in gully erosion research in SA, there are issues or questions of international importance that have been inadequately addressed or not dealt with completely. According to Poesen *et al*. (2003) and Poesen (2011), the following issues or research questions are priorities for gully erosion control and prevention, and have been partially or not yet addressed in SA. First, the critical thresholds for the initiation, development and infilling of gullies in terms of the combination of both environmental and land use factors requires further investigations. Several studies highlighted variables that are prone to gullying without quantifying the potential influence of these variables to gully erosion processes (e.g. Liggitt and Fincham, 1989; Watson and Ramokgopa, 1997; Le Roux and Sumner, 2012) thus failing to predict the threshold conditions for gully initiation. Kakembo *et al*. (2009) highlighted the topographic threshold for gully erosion initiation by studying the slope configuration, positions, slope angle and SPI variables, but acknowledged the need to determine the threshold in terms of the combination of other factors. Second, there is a lack of modelling or prediction techniques for gully erosion risk areas. Bull and Kirkby (1997) suggested that modelling should be able to provide an approach to understand channel head location by using simple relationships that can be predicted theoretically.

Currently, there is no standardised model for prediction of gully erosion internationally, an assessment made in preceding gully erosion research reviews (Poesen *et al*., 2003; Poesen, 2011). Third, while the cause of gully erosion may arguably be well elucidated, the response in a form of the appropriate techniques for prevention and control requires further investigation. According to Boardman (2014), prevention and control are the practical implications of the debate on gully erosion and as already explained depend on the understanding of the mechanisms of erosion processes as well as the consideration of biophysical and land use factors driving the process (Nasri *et al*., 2008, Shellberg *et al*., 2010; Chaplot *et al*., 2011; Nwilo *et al*., 2011; Le Roux and Sumner, 2012).

## 2.3. Summary

From this literature review, it is clear that gully erosion in SA has not been extensively researched and the majority of international key priority research areas are yet to be studied. It is impossible to address all issues highlighted in this review simultaneously. Thus, the aim of the current study was to extend the existing knowledge on biophysical and land use factors contributing to gullies to two tertiary catchments in the MP province by assessing numerous factors and quantifying their influence since this was not previously dealt with sufficiently. The main objectives included examining the role of historical land use on gully erosion occurrence, mapping of topographic variables, mapping of gullies and assessing and quantifying the dominant factor. This is a desktop based research involving the use of Geographic Information System (GIS) and the statistical analysis. The details are presented in the subsequent Chapters, but first, the environmental setting within which this research was conducted is described.

# CHAPTER 3: DESCRIPTION OF THE STUDY AREA

This Chapter describes the environmental (climate, geology, soil, vegetation and topography) and land use setting within which the study area occurs. Particular attention is given to those factors that are likely to have an effect on gully occurrence. The land tenure systems in the two tertiary catchments are described and compared. A brief historical land use of the whole geographical region of Mpumalanga province as reported in the literature is presented, but first, the location of the study area including its areal extent is described.

## 3.1. Location

This study is conducted in the South African part of two tertiary catchments located on the central-eastern Mpumalanga and the west side of Swaziland (Figure 3.1). First is the middle Komati River catchment, upstream of its confluence with the Crocodile River in Mozambique and is coded X12 by the Department of Water and Sanitation (DWS). Second is the upper Usutu River catchment, upstream of its confluence with Pongola River and is coded W55 by the DWS. Tributaries that flow in catchment X12 include Seekoeispruit, Teespruit, Sandspruit and Mlondozi. In catchment W55, the main drainage systems include the Umpuluzi, Swartwater and Metula Rivers. The two catchments are located adjacent to each other at approximate longitudes 30° 06′ 40″ E and 31° 07′ 40″ E as well as latitudes 26° 31′ 34″ S and 25° 52′ 56″ S. Catchment X12 covers a large part of the Chief Albert Luthuli municipality and minor parts of the Umjindi and Msukaligwa local municipalities. Catchment W55 includes large sections of both Chief Albert Luthuli and Msukaligwa local municipalities. It is estimated that the total size of the two tertiary catchments, which include parts of Swaziland, is 4 429km$^2$ with X12 occupying a relatively large area of 2 559km$^2$ and W55 an approximate area of 1 870km$^2$. Previous gully erosion mapping by Mararakanye and Le Roux (2012) showed the presence of high gully density in tertiary catchment X12 compared to catchment W55. This variation presents an opportunity to compare and contrast the significant differences in factor dominance between the two tertiary catchments.

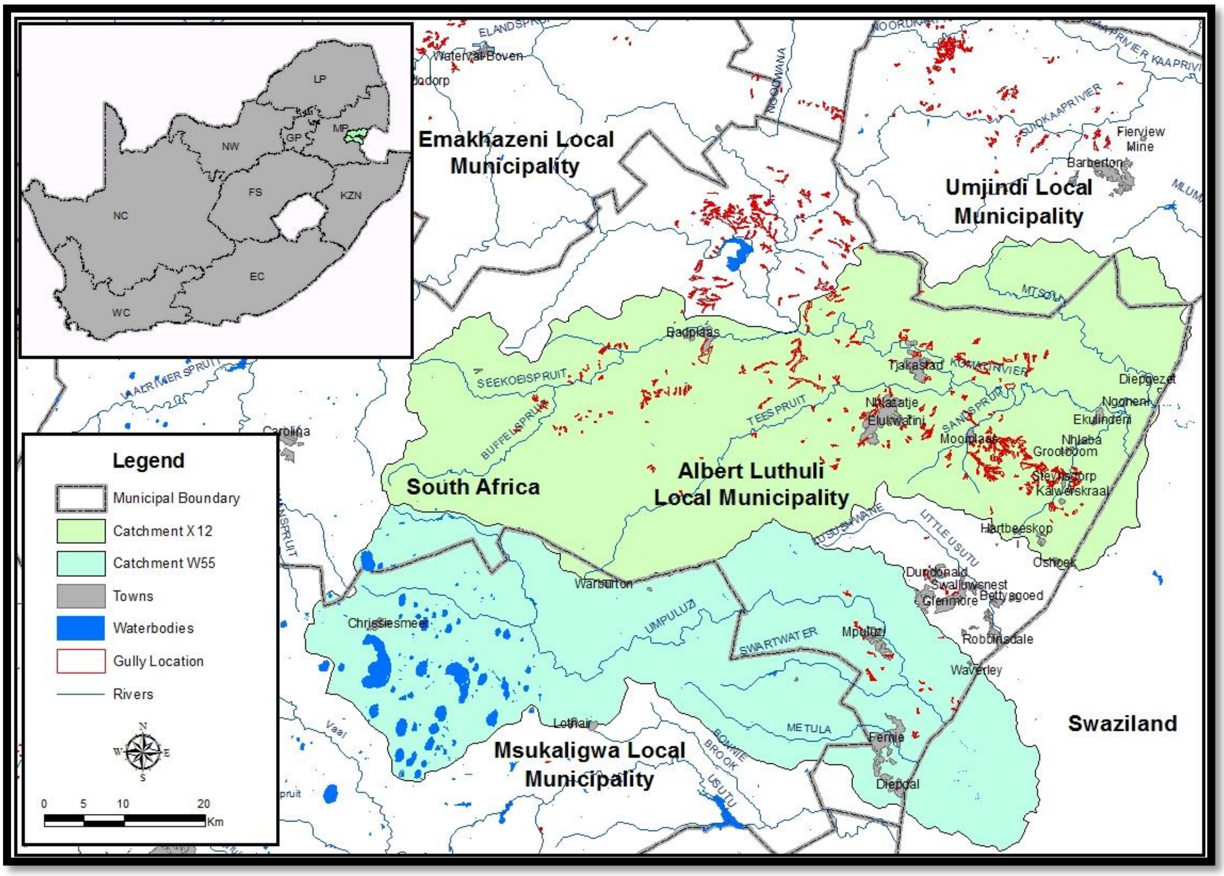

Figure 3.1: Location of the two tertiary catchments including gully location map of Mararakanye and Le Roux (2012)

## 3.2. Climate

Approximately 60% of SA falls within an arid climate zone while the majority of the remaining 40% falls in temperate zone (Schulze, 2010). The two tertiary catchments are located within a temperate climate zone. More than two-thirds of tertiary catchments X12 and W55 are located in a long dry winter and cool summer zone. Rainfall is highly seasonal, comprising the summer rainfall region of SA where the majority is received from September to December (Schulze, 2010). Mean annual rainfall ranges from 600mm to 1 200mm in tertiary catchment X12, with the majority in excess of 800mm (Figure 3.2). In contrast with tertiary catchment X12, rainfall in catchment W55 ranges from 600mm to 1 000mm with the majority below 800mm (Figure 3.2). The seasonality of rainfall makes the study area vulnerable to various forms of erosion due to a contrasting climate impact on vegetation between various seasons and the occurrence of drought (Boardman *et al*., 2010).

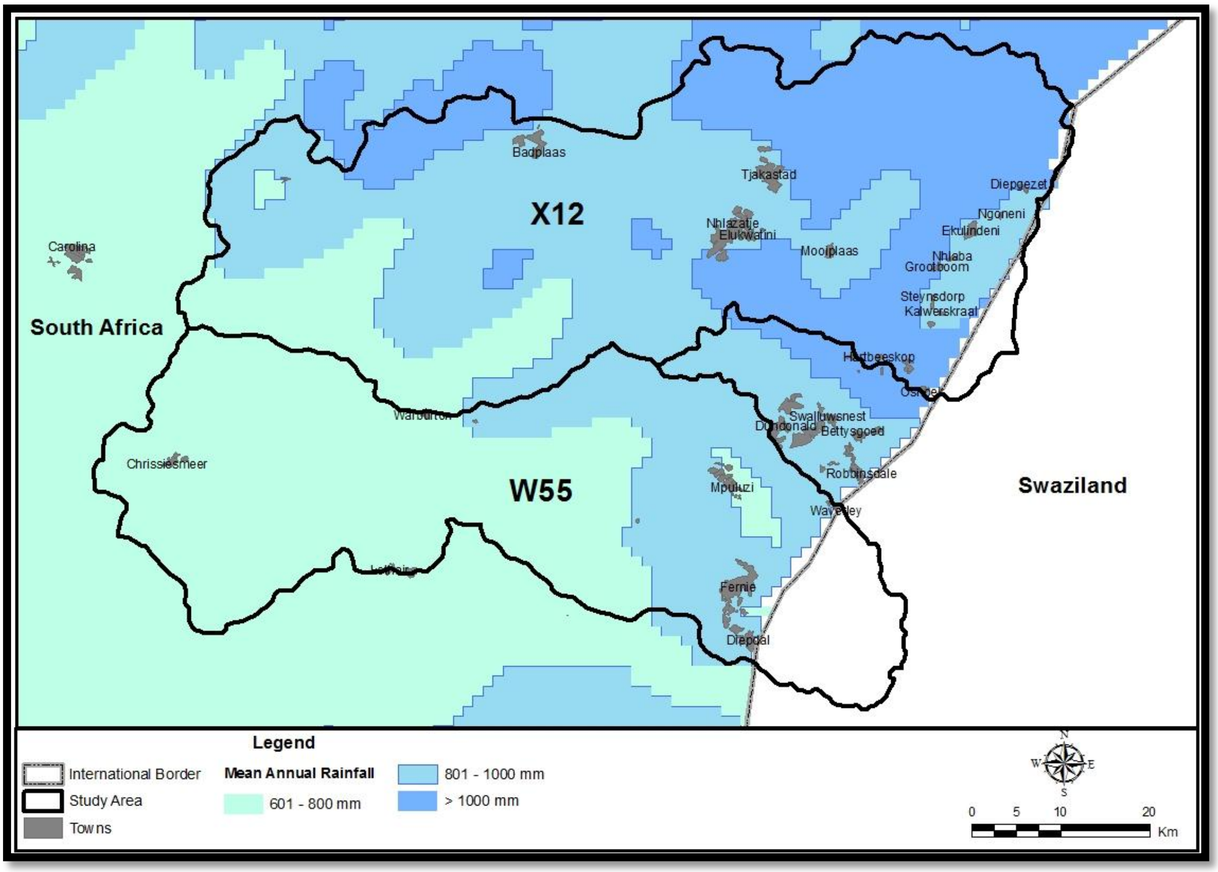

**Figure 3.2: Mean annual rainfall map of the study area (Schulze, 2010)**

## 3.3. Geology

The geology of the two tertiary catchments is shown on a 1:1 000 000 simplified geological map of SA (Figure 3.3). It is found within the ancient crustal block volcanic Kaapvaal Craton on the north eastern part of SA, and is the keystone upon which the geological formations in the country have evolved. The Craton is made up largely of the Archaen tonalitic and trondhjemitic gneisses and granitoids, along with lesser volumes of metamorphosed volcano-sedimentary rocks known as the greenstone belts (Wilson, 1998). Several lithostratigraphic units occur, which include the granites, tonalite and granitoids rocks of the Archean granitic crust (Meinhardskraal), the Pretoria and Chuniespoort group of the Transvaal super-group, and the greenstone belt of the Barberton super-group which comprises the Zwartkoppie, Kromberg, Hooggenoeg, Komati, Theespruit and Sandspruit formations. The Barberton super-group contain some of the oldest rocks exposed on earth and is well-known economically as the most significant gold producing greenstone belt in SA (Wilson, 1998). In the study area, the Barberton super-group is located in catchment X12, whilst the Meinhardskraal and the Transvaal super-group occur in both catchments X12 and W55. Only a sliver of the Transvaal super-group stretches to catchment W55. A considerable proportion of catchment W55 and a sliver in catchment X12 consist of the Karoo super-group. The Karoo super-group comprises of the younger sedimentary depositions dominated by clayey and silty sedimentary rocks such as Dwyka, Ecca, Adelaide, Tarkastad and Clarens groups. It is the Vryheid formation of the Ecca group which stretches into the study area and primarily consists of grey micaceous shale, course grained sandstone and subordinate grit and coal beds found mainly at the basin margin (Johnson, 1976; Turner, 2000).

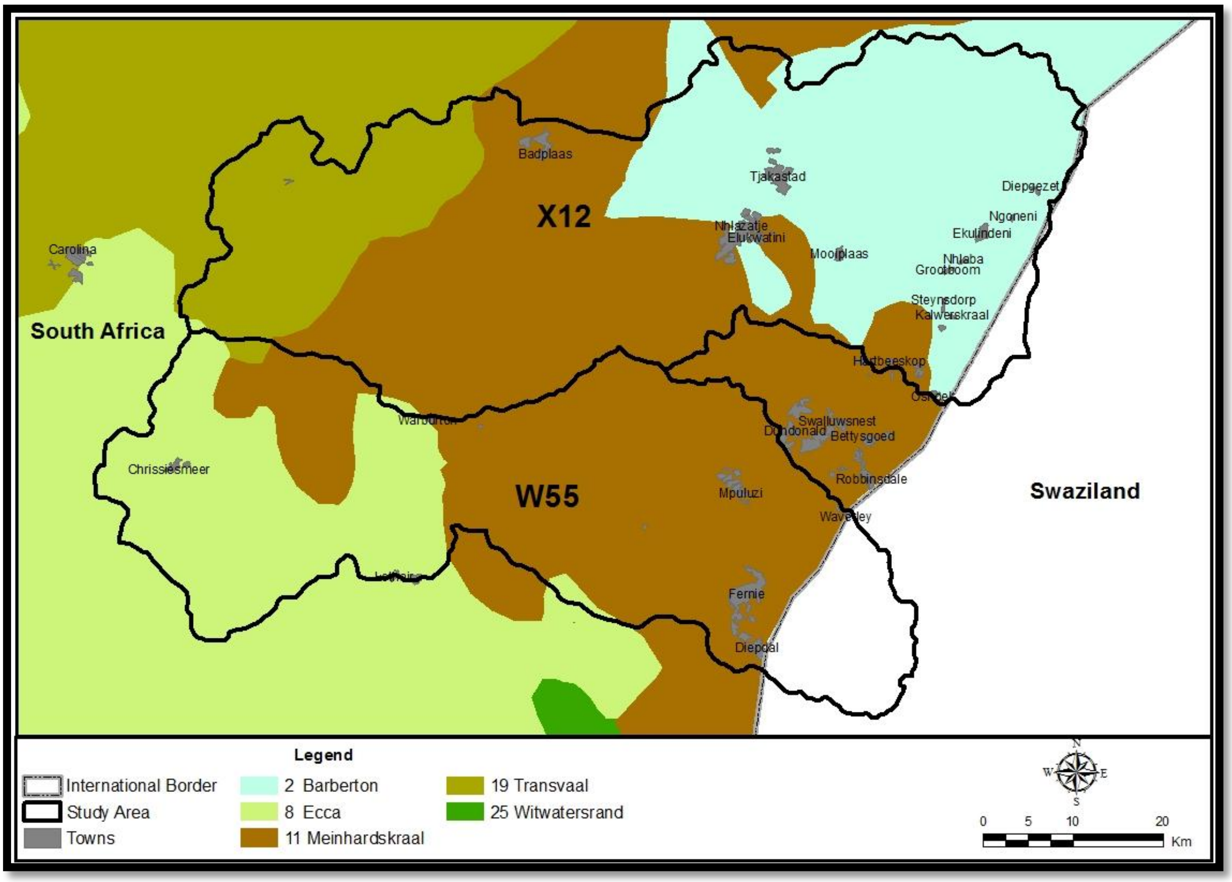

**Figure 3.3: The 1: 1 000 000 simplified geological map of the study area (Wilson, 1998)**

## 3.4. Soils

The spatial distribution of soil forms and characteristics (depth and clay content) in the two tertiary catchments are shown in Figures 3.4, 3.5 and 3.6. Figure 3.4 shows that both tertiary catchments X12 and W55 are dominated by high agricultural potential Hutton (Hu) soil form which is mainly very deep (Figure 3.6), very sandy to sandy and loam textured (Figure 3.5). It is evident from Figure 3.4 that the soils within the two tertiary catchments vary. The main distinctive characteristic between the two areas is the considerable occurrence of the association of Hutton (Hu), Avalon (Av), Clovelly (Cv), Glencoe (Gc) soil forms in tertiary catchment W55 which is only distinguishable in a small area upstream of catchment X12. The mentioned association is mainly characterised by medium deep soils (Figure 3.6) with a sandy loam texture (Figure 3.5). In tertiary catchment X12, the association of Hu (30%), Shortlands (Sd) (30%) and Glenrosa (Gs), Cartref (Cf), Estcourt (Es) as well as Es, Gs, Cf also predominate but are not observed in catchment W55 (Figure 3.4). The Es is a duplex soil that is often considered highly erodible (e.g. Beckedahl, 1996; Rienks *et al*., 2000; Seitlheko, 2003; Le Roux and Sumner, 2012). The clay content of Gs, Cf, Es and Es, Gs, Cf soil form associations' classes in tertiary catchment X12 vary from very sandy, sandy, loamy sandy and loam (Figure 3.5) and are mainly medium shallow soils (Figure 3.6).

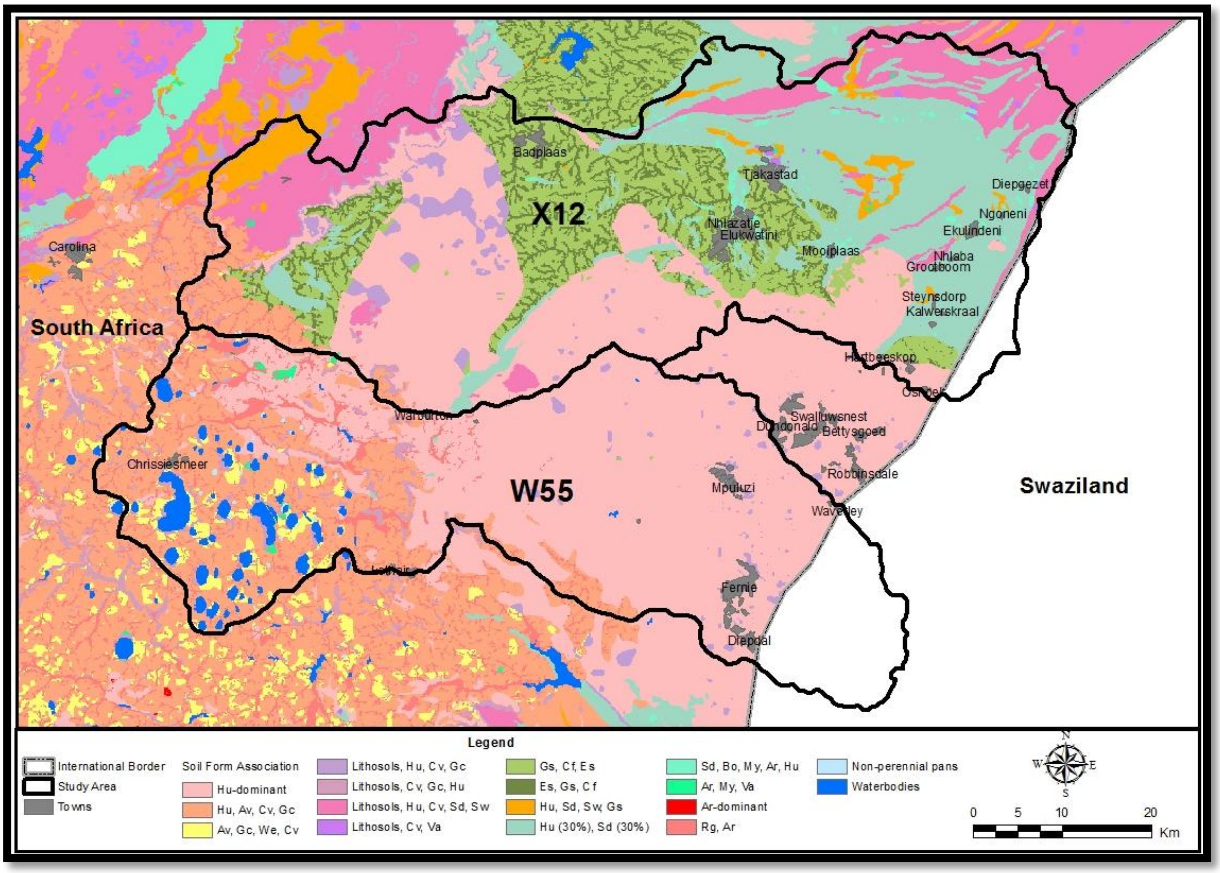

**Figure 3.4: Soil form association map of the study area (Van den Berg, 2000)**

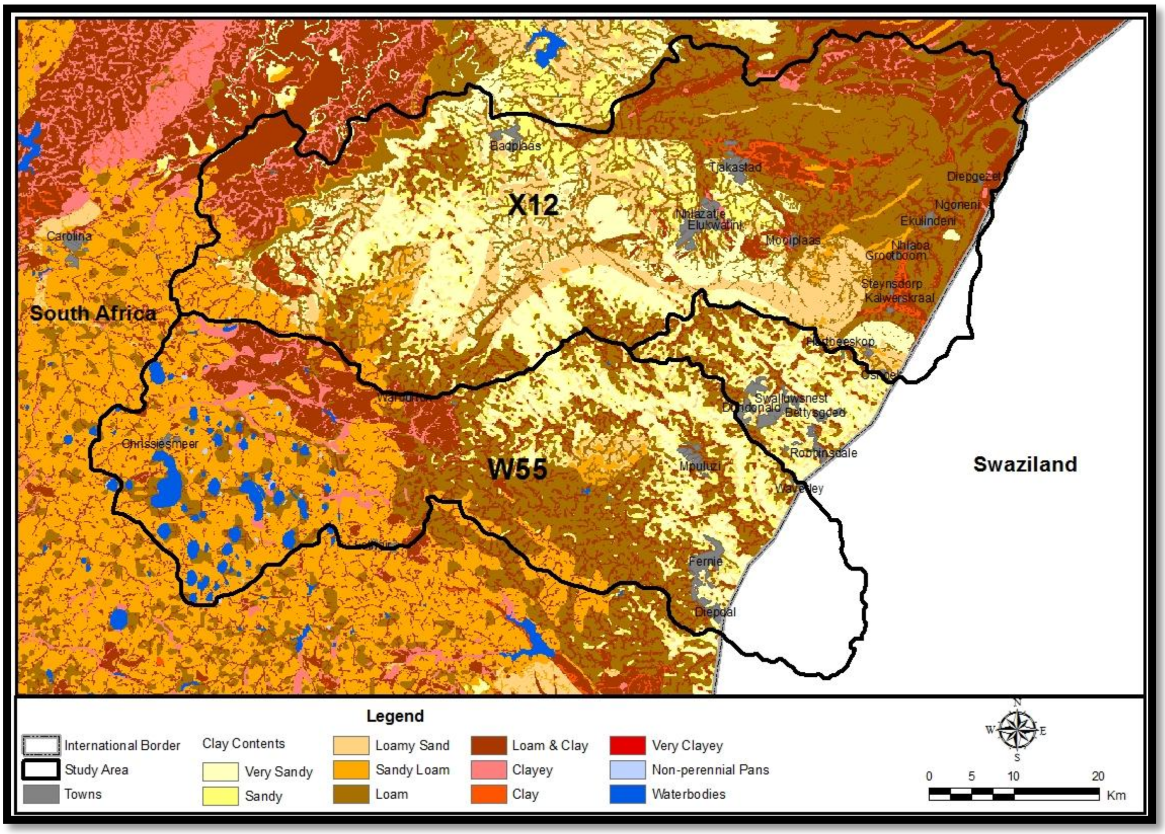

Figure 3.5: Clay contents map of the study area (Van den Berg, 2000)

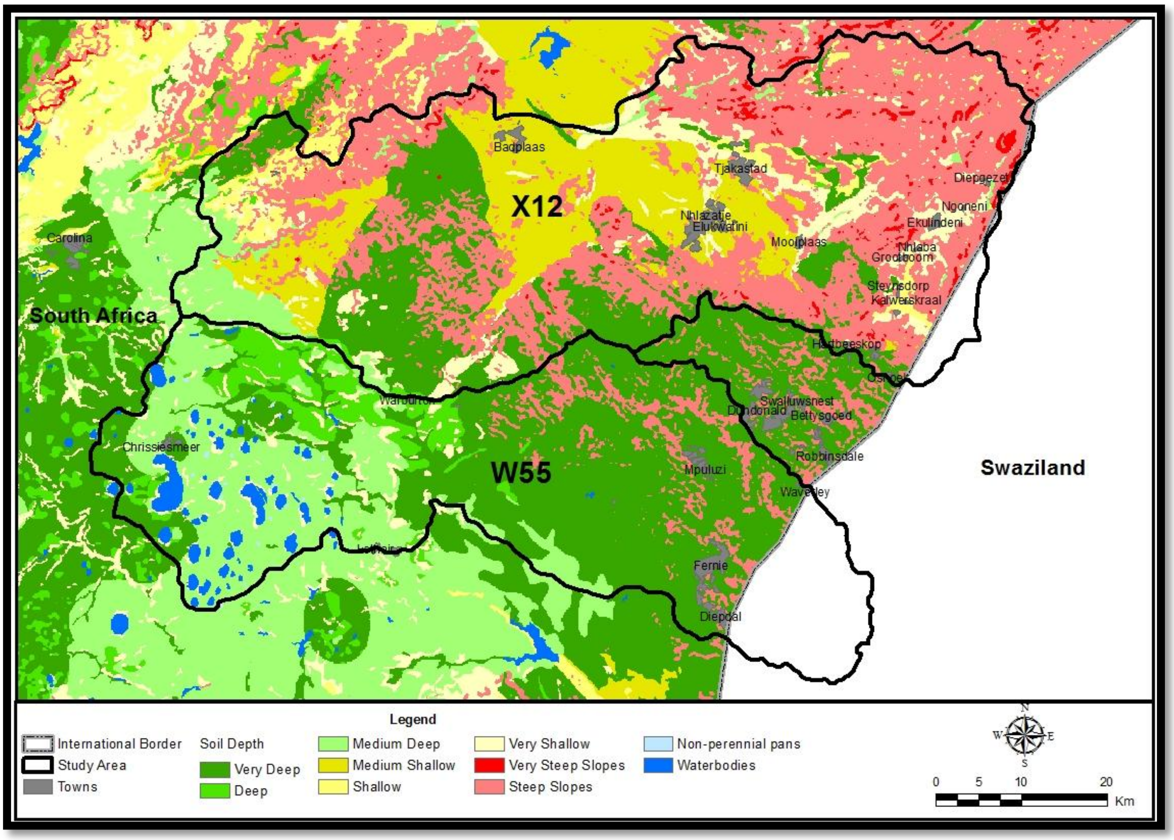

Figure 3.6: Soil depth map of the study area (Van den Berg, 2000)

## 3.5. Topography

The topography of the two tertiary catchments is illustrated by the elevation or altitude map in Figure 3.7. Elevation largely influences climate, for example, high altitudes are the major cause of lower temperatures and high rainfall in windward facing slopes (Schulze, 2010). A plateau covers a large part of SA (Clark *et al*., 2011) including the central to western parts of MP. The topography of the two tertiary catchments is highly variable, ranging from as low as 700m above sea level in catchment X12 to 2 320m above sea level in catchment W55. High and low elevation areas are separated by the Great Escarpment, though the division is indistinct in the study area. Highland areas are particularly dominant on the western half of catchment W55 whereas elevation drops steadily towards the east, closer to the border of Swaziland. Catchment X12 is primarily dominated by relatively low elevation values stretching towards the narrow strip of low lying land on the Mozambique coastal border. High elevation values in catchment X12 are prevalent on the far west and the southern edge of the catchment (Figure 3.7).

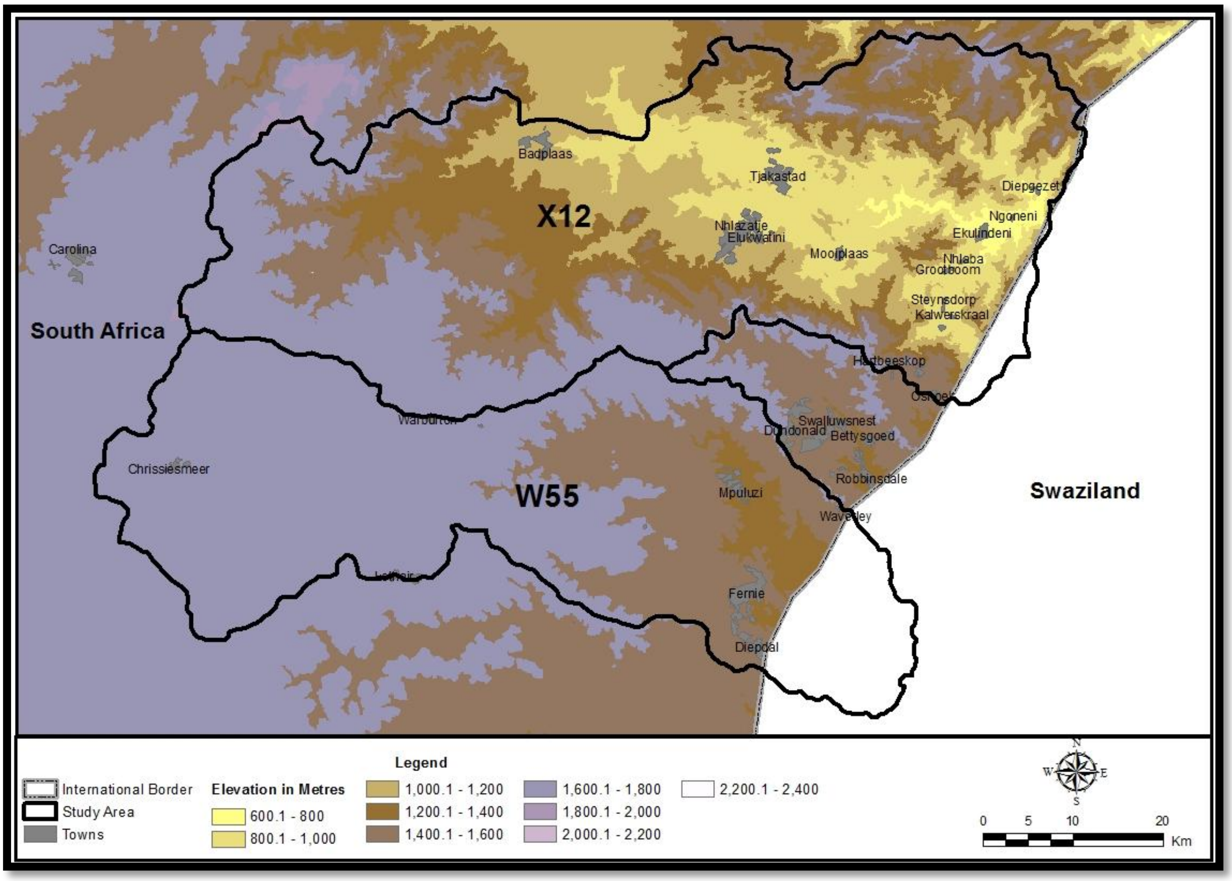

Figure 3.7: Elevation map of the study area (Schulze, 2010)

### 3.6. Vegetation

The vegetation types of the two tertiary catchments are shown on a map developed by Mucina and Rutherford (2006) in Figure 3.8. The study area fall within the grassland biome of MP province, comprising mainly the Highveld region. Savanna biome in the Lowveld region covers approximately one-third of the area. Highveld vegetation region is located in the plateau areas characterised by high elevation values compared to the relatively low elevation values in the Lowveld region. Lowveld vegetation region occupies large part of the eastern half of catchment X12. Grassland occurs in the western half of catchment X12 including the rest of catchment W55. Natural vegetation in the Lowveld region varies, consisting of the Swaziland Sour Bushveld, Barberton Serpentine Sourveld, Barberton Montane Grassland and Northern Mistbelt forest. Natural vegetation in the Highveld region consists of the Eastern Highveld Grassland and KaNgwane Montane Grassland (Figure 3.8). Commercial plantations of the Eucalyptus and Pine trees have transformed the natural vegetation of some parts of the study area.

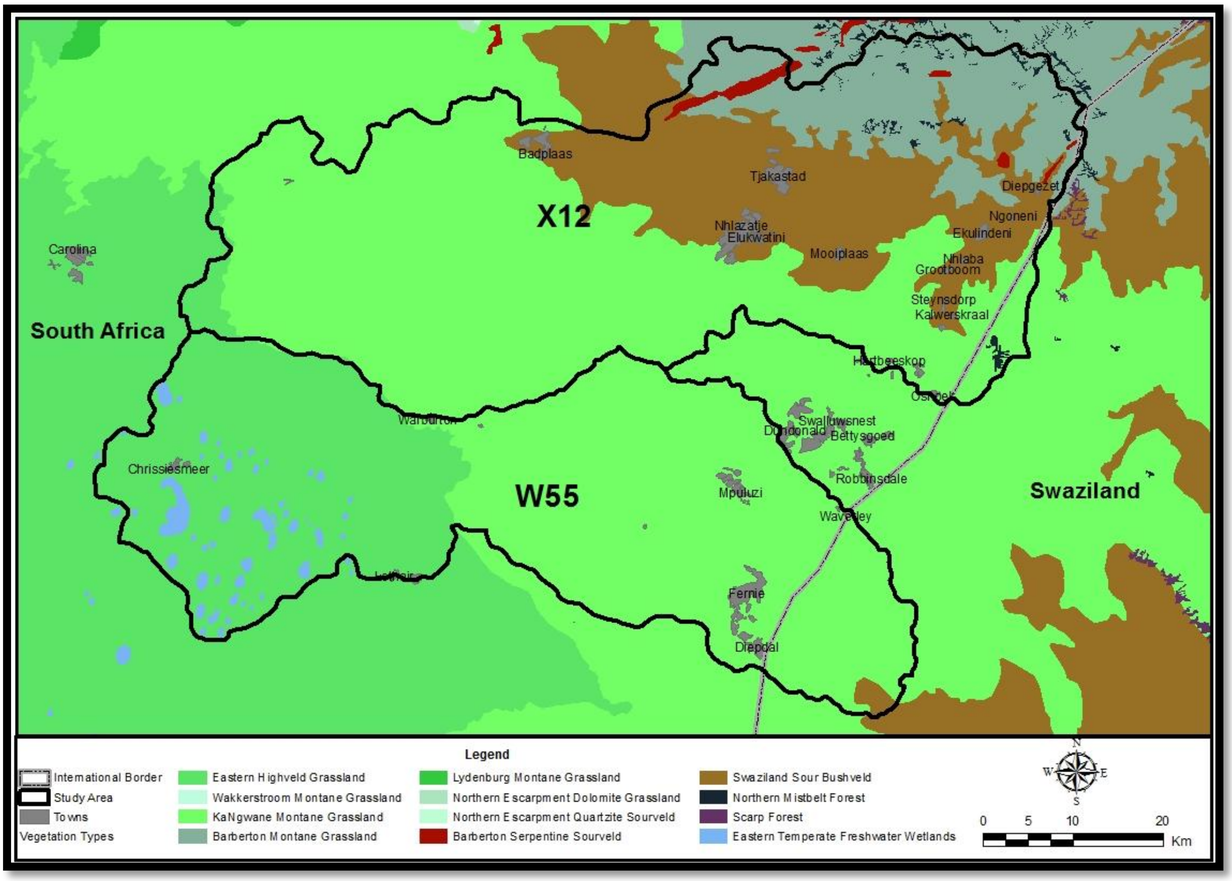

Figure 3.8: Vegetation map of the study area (Mucina and Rutherford, 2006)

### 3.7. Land use

The study area is predominantly rural in nature with agriculture and forest plantation the dominant land use activities (Table 3.1). There are a wide variety of agricultural activities such as subsistence or small scale farming and low to medium scale commercial cultivation mainly in the western side of catchment W55. Numerous concentrations of settlements occur throughout the study area which includes the following formal areas: Badplaas, Ekulindeni, Elukwatini, Nhlazatshe, Oshoek (Catchment X12), Chrissiesmeer, Empuluzi, Fernie and Diepdale (catchment W55). These areas encompass the former homeland of KaNgwane along the border of Swaziland on the eastern side of both tertiary catchments where small scale subsistence farming activities dominate. The former homelands in SA are well-known for severe forms of land degradation often due to the communal land use systems (Kakembo, 1997). In particular, the communal land use system is characterised by community residences, subsistence farming and community grazing (Ngetar, 2011). Land in the central to western side of the study area is privately owned.

**Table 3.1: Comparisons of the proportion of land use or land cover classes between catchment X12 and W55**

| **Land Use and Land Cover Classes** | **Proportion of Land Cover Class in X12 (%)** | **Proportion of Land Cover Class in W55 (%)** |
|---|---|---|
| Indigenous Forests | 0.40 | 0.02 |
| Thicket & Bushland | 11.31 | 0.72 |
| Grassland | 60.57 | 54.04 |
| Forest Plantations | 16.90 | 25.82 |
| Dams / Lakes | 0.06 | 3.64 |
| Wetland | 0.00 | 0.09 |
| Bare Rock & Soil | 0.66 | 0.68 |
| Degraded: Grassland | 2.60 | 1.07 |
| Cultivated Land | 4.99 | 12.61 |
| Degraded: Erosion | 1.06 | 0.06 |
| Urban | 1.39 | 1.25 |

The details on land use history of the area are sketchy, but, farming by the European settlers and the original inhabitants in the former Transvaal region was reported as early as the 19th century (De Villiers, 1896). According to De Villiers (1896), the farming community in the former eastern Transvaal region (Mpumalanga province) was small in the late 19th century and was dominated by sheep, cattle and horse breeding. White farmers mainly used the area for winter grazing of livestock and as private labour reserves, whilst the natives retained large herds of cattle, which enabled them to perform marriage alliances (Macmillan, 1989). The discovery of gold in the mid 19th century in the surrounding Barberton area also shaped the historical land use activities of the study area, which resulted in the development of tracks and footpaths (De Villiers, 1896; Macmillan, 1989). The development of forestry, sugar, citrus production, coal mining and railway is dated after the World War II in the 1940's and forms the major historical land use around the study area (Macmillan, 1989).

## 3.8. Summary

Although the two tertiary catchments are located adjacent to each other and have similar climatic or geologic history, the occurrence of biophysical and land use factors varies. This variation presents an opportunity to compare factors likely to be the cause of gully erosion between the two tertiary catchments, bearing in mind the contrasting gully densities reported by Mararakanye and Le Roux (2012). The next Chapter describes the materials and methodologies followed to assess the contribution of each biophysical and land use factor on gully erosion.

# CHAPTER 4: MATERIALS AND METHODS

A desktop-based research approach was followed to quantify the dominant gully erosion contributing factors. This includes mapping of gully erosion features, mapping historical land use and gully dynamics, acquisition of the existing contributing factors data, extraction of the topographic variables and assessment of the dominant contributing factors using Geographic Information Systems (GIS) and Information Value (InfVal) statistical method. Resources and materials (e.g. external data and software) were obtained and accessed with permission from the Department of Agriculture, Rural Development, Land and Environmental Affairs (DARDLEA) GIS section.

## 4.1. Overview of the existing contributing factor data

### 4.1.1. Soil data

Soil datasets derived for DARDLEA by the Agricultural Research Council – Institute for Soil, Climate and Water (ARC-ISCW) from the 12 199 soil sampling points of the landtype survey were used (Van den Berg, 2000). The landtype data provides a seamless national coverage of units of land with homogenous terrain form, soil pattern and macro-climate. However, the landtype data provides the percentage occupation of soil components (e.g. clay content, soil depth and soil form) in a memoir without providing the spatial detail of the soil occurring in a particular map unit (Land Type Survey Staff, 1984). The main purpose of deriving the new soil datasets by Van den Berg (2000) for DARDLEA was to enhance the spatial detail of the landtype datasets developed by the Land Type Survey Staff (1984) through spatially representation of each soil component within a landtype map unit. The mentioned soil data utilised in this study, which includes the clay content, soil depth and soil form association represent the percentage of soil attributes in a given map unit. It was developed through the correlation of the landtype survey sampling points with other available or derived spatial datasets which include geology, soil colour (derived from the bare soil colour visible on Landsat TM imagery), terrain unit, altitude, slope and rainfall. Although the results of fieldwork by Van den Berg (2000) shows that soil in certain areas is accurate at farm scale, he recommended that the datasets be utilised at 1:150 000 scale. The spatial distribution of each soil component (soil form, clay content and soil depth) is illustrated in Chapter 3 (see Figure 3.4, 3.5 and 3.6 respectively).

### 4.1.2. Geology data

Detailed geological characteristics of the two tertiary catchments were obtained from the scanned 1:250 000 image format geochronologic and lithostratigraphic map of SA published by the Council for Geoscience (2007). The scanned map provides more detailed information on the geological formations compared to the 1:1 000 000 simplified geological map version of SA (Wilson, 1998) but a scanned image format map could not be analysed with other spatial datasets in a GIS environment. Thus, in order to enable the integration and analysis with other spatial datasets, the scanned map was converted to a digital format by tracing the boundary of each geological formation using on-screen digitising tools in ArcMap™. Figure 4.1 shows the spatial distribution of the digitised geology super-group polygons. The attributes of the output vector format dataset were captured for each polygon and the map was later converted to a raster format. Notwithstanding the errors associated with the conversion from vector to raster format, the distortions were deemed insignificant due to the relatively broader scale of the original dataset. The cell size of 10m used was chosen to minimise distortions associated with vector to raster conversion.

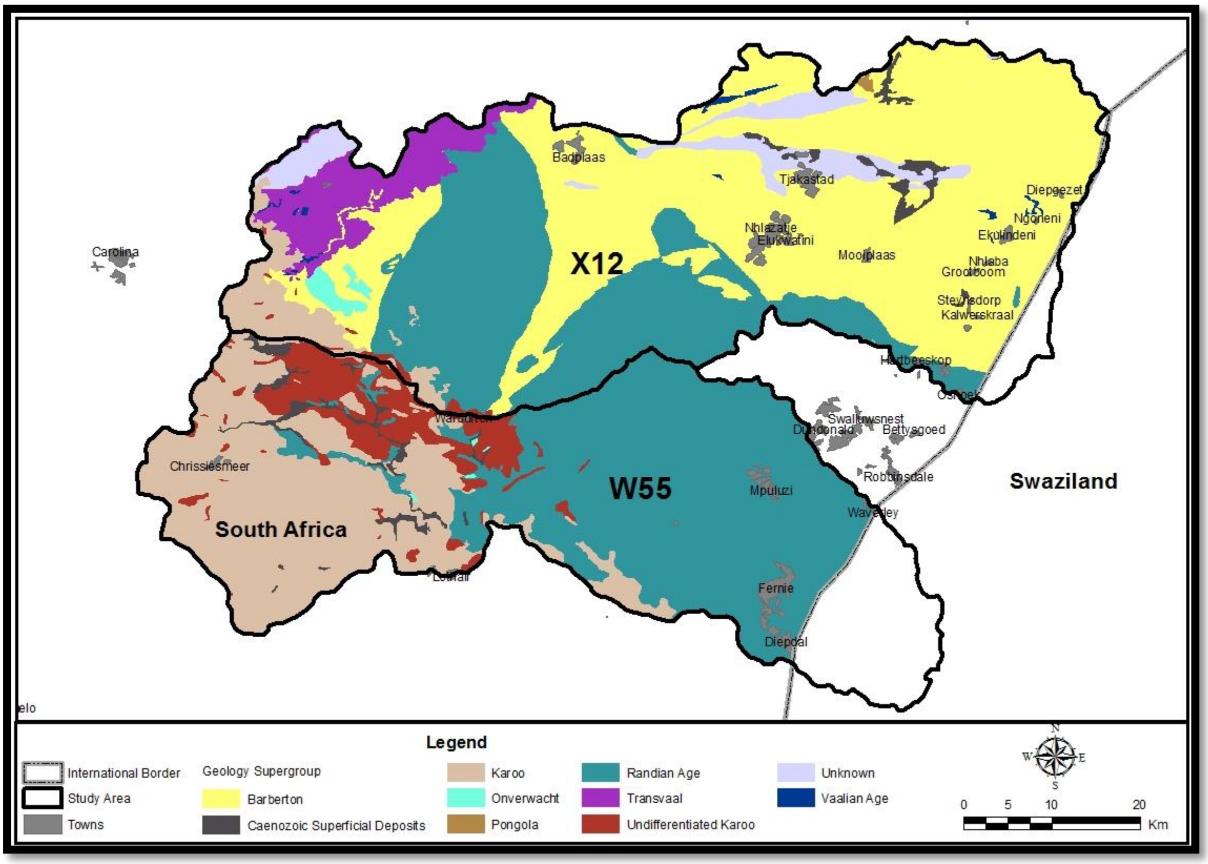

**Figure 4.1: The 1: 250 000 geology super-groups of the study area (Council for Geoscience, 2007)**

### 4.1.3. Vegetation type and cover data

The vegetation data utilised here (see Figure 3.8 in Chapter 3) is derived from the most recent national vegetation map of SA containing the vegetation types, the bioregions and biomes. It is important to acknowledge here that the Acocks veld type map (Acocks, 1988) has been the most frequently used spatial datasets by ecologists and other natural resource scientists for some time (see Vetter *et al*., 2006). The Acocks veld type map has relatively few vegetation types and has not been updated. Despite the value of the map, a need was identified for an up to date appraisal of detailed vegetation types called the vegetation map (VEGMAP) of SA (Mucina and Rutherford, 2006). The VEGMAP project was initiated through collaborations by various organisations, coordinated by the South African National Biodiversity Institute (SANBI). It contains 435 vegetation types in SA, Lesotho and Swaziland, consisting of 34 Azonal, 119 Fynbos, 87 Savanna, 72 Grassland, 63 Succulent Karoo, 15 desert, 14 Nama Karoo, 14 Albany Thicket, 12 Forest and 5 Indian Ocean coastal belt vegetation types (Mucina and Rutherford, 2006). Due to the detailed nature of this spatial dataset, it is more appropriate for use in the current study compared to the Acocks veld type map.

Long-term annual average Normalised Difference Vegetation Index (NDVI) map calculated by the ARC-ISCW for the period 1985 to 2003 (Wessels *et al*., 2004) was used as an indicator for vegetation cover (see Figure 4.2). NDVI map is a composite image of annual maximum NDVI values, averaged for the 17-year period for which data were available from the National Oceanic and Atmospheric Administration - Advanced Very High Resolution Radiometer (NOAA - AVHRR) satellite imagery. The NOAA – AVHRR is a polar orbiting satellite which orbits the earth at an altitude of approximately 820km and has a large spatial coverage of 2 400km x 3 000km with a coarse spatial resolution of 1.1km x 1.1km operated on a 5 spectral bands (2 visible, 1 Near-Infrared and 2 Thermal). NDVI is used to describe the amount of vegetation present (vegetation density or cover) and is computed as follows (see Wessels *et al*., 2004):

$$\mathrm{NDVI} = \left(\mathrm{IR\text{-}R}\right) \div (\mathrm{IR+R}) \qquad (4.1)$$

where IR is the Infrared band and R is the red band. The NOAA – AVHRR channel 2 (Near-Infrared band) and channel 1 (Red band) are used as a substitute to the general NDVI formula.

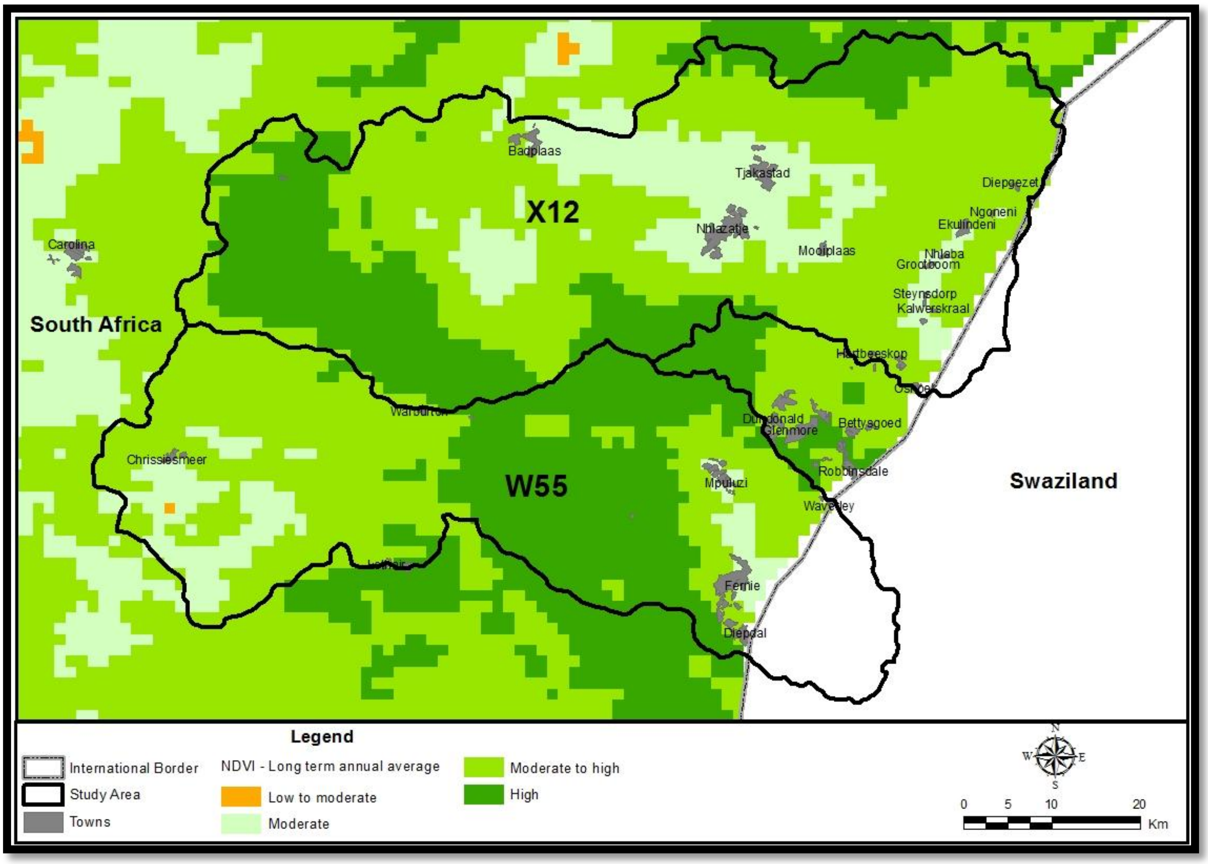

**Figure 4.2: Long-term annual average (1985 to 2003) Normalised Difference Vegetation Index (NDVI) map of the study area (Wessels *et al*., 2004)**

### 4.1.4. Rainfall erosivity data

The rainfall erosivity map utilised in this study (see Figure 4.3) was developed by Le Roux *et al*. (2008) for sheet and rill erosion prediction using the Revised Universal Soil Loss Equation (RUSLE). Rainfall erosivity data was estimated using the improvement of the RUSLE model by Yu and Rosewell (1996) for the Australian condition which considers rainfall seasonality of the region and time of the year to estimate erosive potential. Le Roux *et al*. (2008) applied this model because it proved to predict the R-factor accurately in the Australian climatic environment perceived to be similar to SA. This recent spatial dataset was chosen because it was developed for erosion estimation purposes and considers various rainfall variables unlike the available annual rainfall mean. An example for estimating the total storm kinetic energy (E) on maximum 30 minutes rainfall intensity ($I_{30}$) during a specific month (j) was illustrated in Equation 2.5, Chapter two.

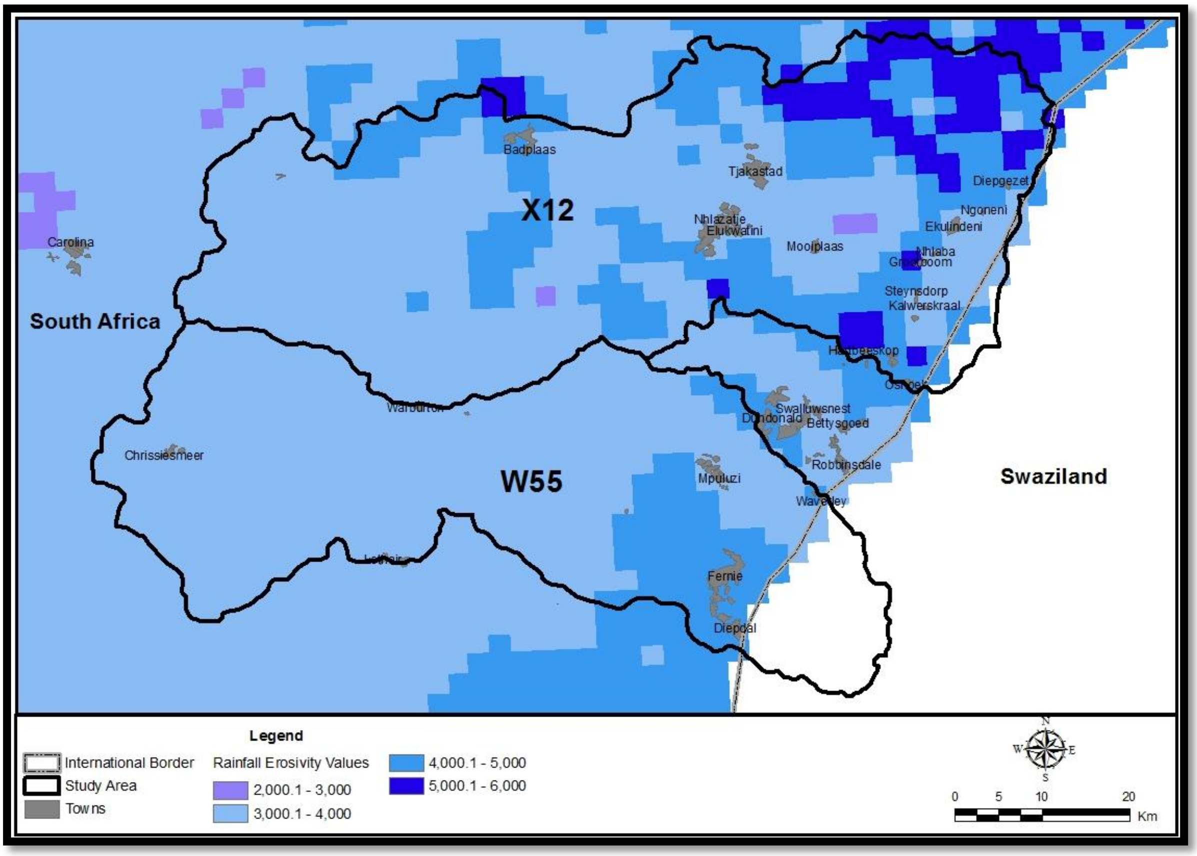

Figure 4.3: Rainfall erosivity map of the study area (Le Roux *et al*., 2008)

### 4.1.5. Land cover data

In the absence of reliable land use dataset in MP, this study resolved to use the land cover data illustrated in Figure 4.4. Such data has been used in other studies in SA (e.g. Le Roux and Sumner, 2012) because it shows broad land use classes. Land cover database of Mpumalanga developed in-house by DARDLEA through substituting some land cover classes of the National Land Cover (2000) database with the best available spatial datasets was used to give an overview of the current land use. National land cover 2000 database was derived from Landsat TM imagery with a grid cell resolution of 30m (National Land Cover, 2000) and was updated using other recent databases such as the field crop boundaries (Fourie, 2009) and gully erosion features (Mararakanye and Le Roux, 2012). Field crop boundaries were digitised from SPOT 5 satellite imagery in ArcMap™ at a scale of 1:10 000 (Fourie, 2009). Similarly, gully erosion features were digitised in ArcMap™ from the background SPOT 5 satellite imagery at a scale of 1:10 000 by Mararakanye and Le Roux (2012).

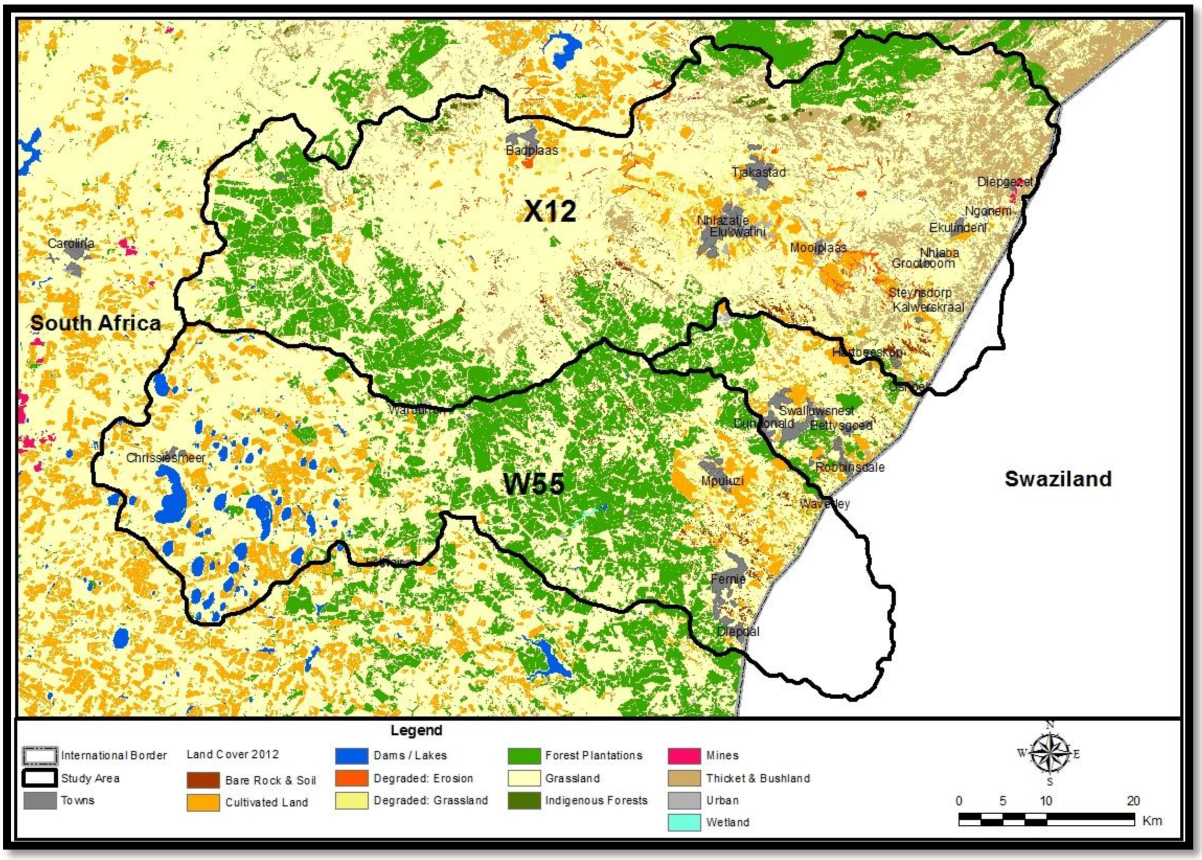

**Figure 4.4: Land cover map of the study area (National Land Cover, 2000; Fourie, 2009; Mararakanye and Le Roux, 2012)**

## 4.2. Mapping of the topographic variables

A grid based Digital Elevation Model (DEM) is the most convenient method for representation of the continuously varying topographic surface that is frequently used in terrain analysis (Thompson *et al*., 2001). A DEM is obtained from digitised contours or photogrammetricaly. In this study, 5m vertical interval contours digitised by the Chief Directorate: National Geospatial Information (CD: NGI) of the Department of Rural Development and Land Reform (DRDLR) from the 1:10 000 orthophoto map series and spot heights (Vorster, 2003) were used to interpolate a DEM. It is worthy to mention that the 5m contours utilised here do not provide a full coverage for the whole country or MP province, however, a better representation for the two tertiary catchments was obtained. Contours with a lower vertical interval (e.g. 5m) produce better DEM than contours with a higher (e.g. 20m) vertical interval (Van Niekerk, 2012). The existing Australian National University Digital Elevation Model (ANUDEM) algorithm available in ArcGIS® Topo to Raster surface interpolation tool (see Van Niekerk, 2012) was used to interpolate contours at 10m cell size. Ten metre grid cells were chosen in order to ease computer processing time. To ensure the production of hydrologically correct DEM, drainage enforcement was imposed to remove all the sinks encountered during interpolation.

Following the acquisition and interpolation of the 5m contours to a gridded DEM surface, several topographic variables, including slope, upslope contributing area, planform curvature, Topographic Wetness Index (TWI) and Stream Power Index (SPI) were extracted. Slope and upslope contributing area were extracted using the multi flow directional (MFD) D-Infinity algorithm (Tarboton, 1997). Compared to the existing single flow direction (SFD) algorithm in ArcGIS® spatial analyst, MFD was preferred due to its ability to route flow from one cell to one or multiple surrounding cells (Haas, 2010). The SFD routes flow from one grid cell to only one of its eight neighbours and as a result, it does not give a proper representation of the real landscape where flow will likely converge and/or diverge at various places and times (Tarboton and Mohammed, 2013). Figure 4.5 gives an illustrative example of the results from SFD (deterministic eight-node) flow routing compared to the MFD (D-Infinity) approach (see Tarboton, 1997). The D-Infinity flow algorithm was implemented from the Terrain Analysis Using Digital Elevation Models (TauDEM) tool developed as an add-on extension for Hydrologic Terrain Analysis in ArcGIS® 10 by the Utah State University (USU) (Tarboton and Mohammed, 2013). For the planform curvature, the algorithm of Zevenbergen and Thorne (1987) implemented directly from the ArcGIS® spatial analyst tool was used to measure the convergence and divergence of water flow. Planform curvature is calculated on a cell by cell basis using a 3 x 3 window (Tagil and Jennes, 2008).

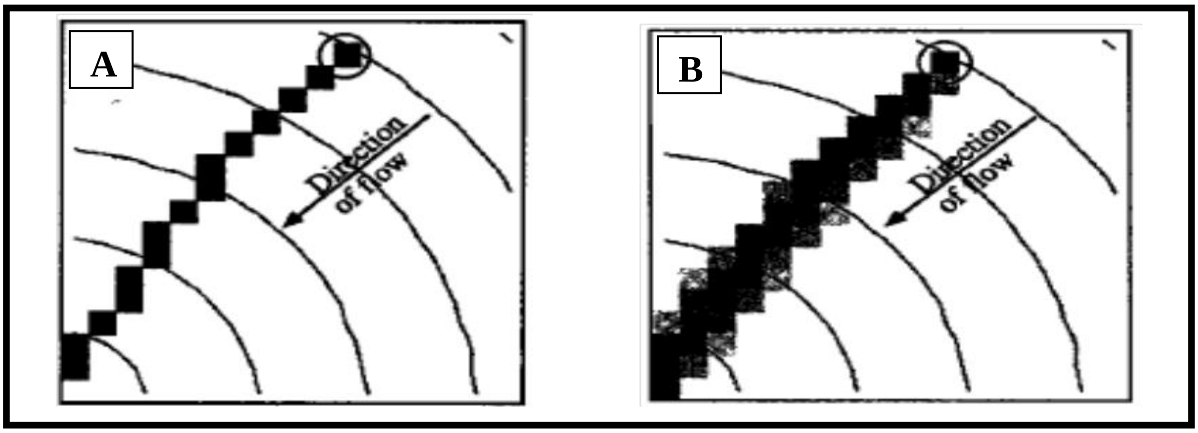

**Figure 4.5: An illustrative example of the difference between (A) SFD (deterministic eight-node) usually implemented in ArcGIS® spatial analyst and (B) TauDEM MFD (D-Infinity) outputs (source: Tarboton, 1997)**

The TWI and SPI are the secondary topographic derivatives calculated as a function of slope and the upslope contributing area which are both not directly supported in TauDEM or ArcGIS® spatial analyst tools implementation. Their calculations were carried out in ArcGIS® raster calculator based on the formula described in Wilson and Gallant (2000) as shown in Equation 4.2 and 4.3. Where $A_s$ is the upslope contributing area ($m^2$) and $\beta$ is the slope gradient in degrees. Since TauDEM D-Infinity slope calculation algorithm expresses the results as the actual slope (vertical distance change or rise / horizontal distance change or run), it was necessary to convert to degrees before calculation of the secondary variables. TWI predicts zone of saturation where $A_s$ is large (typically in converging segments of landscapes) and $\beta$ is small (at the base of concave slopes where the slope gradient is reduced), normally encountered along drainage paths and in zones of water concentration in landscapes. SPI measures the erosive power of flowing water based on the assumption that discharge is proportional to specific catchment area (Wilson and Gallant, 2000).

$$\mathrm{TWI} = \ln\left(A_s/\tan\beta\right) \qquad (4.2)$$

$$\mathrm{SPI} = A_s \tan\beta \qquad (4.3)$$

## 4.3. Mapping of gullies and historical land use

### 4.3.1. Overview of the aerial photographs utilised

The aerial photographs utilised here include the orthorectified digital imagery produced since 2008 by the Chief Directorate: National Geospatial Information (CD: NGI) of the Department of Rural Development and Land Reform (DRDLR). The imagery has a nominal ground sample distance (GSD) of 0.5m and was acquired using the Intergraph Digital Mapping Camera (DMC). GSD is the size of one pixel on the ground commonly referred to as spatial resolution. It is influenced by the flying height and the focal length of the camera. The Intergraph DMC used has a 4-band multispectral capability that allows capturing of panchromatic (greyscale), true colour (RGB) and colour infrared (CIR) images in a single flight (Duncan and Smit, 2013). Aerial photographs were obtained already orthorectified to minimise the distortions caused by displacements of terrain variations, the earth curvature and the varying scale from the centre of the image to the outer edge. They are available in a 1:10 000 reference sheets composed of mosaiced image scenes. In addition, historical non-georeferenced analogue vertical aerial photographs taken from aircraft at a photo-scale varying between 1:20 000 to 1:50 000 and flown at a height of approximately 4 570m above ground level by the CD: NGI, then known as Trig Survey were used. Vertical aerial photographs provide an historical record of the country and were flown since the 1930's (Vorster, 2003).

### 4.3.2. Gully location mapping

Gullies referred to in this study are defined as linear erosion features characterised by actively eroding steep sloping and poorly vegetated banks with incised channels large enough to be visually detectable in a computer using high spatial resolution (0.5m) aerial photographs. A rule set by Tobler (1988) is that the minimum size of features visually detectable from the imagery (satellite and aerial photographs) is twice the spatial resolution of the imagery in question, on a mapping scale determined by multiplying the detectable size of an object by 1 000. Gullies were mapped in this study for correlation with biophysical and land use factors in order to quantify the influence of dominant factors, thus only the location and spatial extent or severity are understood. Gully erosion mapping commonly follows a remote sensing and GIS based approach which includes the automatic or semi-automatic classification and the traditional digitising techniques respectively (Taruvinga, 2008). Although the automatic or semi-automatic classification technique has not been widely tested, some studies found low map accuracy due to the heterogeneous nature of gullies which is considered the main drawback in distinguishing them from the surroundings (e.g. Taruvinga, 2008; Mararakanye and Nethengwe, 2012; Mararakanye and Le Roux, 2012).

In order to ensure a high accurate product, gully erosion mapping in this study was based on traditional visual interpretation (see Taruvinga, 2008) of 0.5m spatial resolution aerial photographs followed by the delineation of the outer boundary in Esri® ArcMap™ software at a scale of 1:1 000. The visual interpretation was made easier due to known characteristics of gullies which include their occurrence along drainage lines and un-vegetated steep banks. Figure 4.6 illustrates an example of a digitised gully characterised by active banks and a stabilised floor amid cultivated land. The mapping technique was shown to be useful in producing high accuracy results at the country (SA) level by Mararakanye and Le Roux (2012). They digitised gullies using a background panchromatic sharpened SPOT 5 images at 2.5m resolution merged with 10m multispectral bands imagery to produce a 5m resolution image. Thus, the resultant spatial resolution of the SPOT 5 imagery could not enable the detection of smaller discontinuous gullies less than 10m of width and length using Tobler (1988)'s rule discussed above. The smallest gully observable on a 0.5m spatial resolution aerial photograph using Tobler (1988)'s rule is 1m, which is tenfold better than the 10m observable on a merged SPOT 5 satellite imagery (see Mararakanye and Le Roux, 2012).

For quality assurance, reconnaissance field observations were conducted within both tertiary catchments X12 and W55 in order to confirm the existence of the mapped gullies. Field observations were aimed at verifying the occurrence of gullies and no further information was collected. A traverse route was created in a desktop subjectively based on accessibility and the proximity to mapped gullies. Field coordinates of gullies were collected using a Garmin Global Positioning System (GPS) and later compared with gullies on the map. A total of 73 sample points representing the observed gullies on the field were collected and later uploaded in ArcMap™ for accuracy assessment. The location of sample points and associated attribute information is illustrated in Appendix A. Comparison of field data and the gully map showed no errors of commission since all the features mapped as gullies were indeed confirmed as gullies from the sample points. However, errors of omission were identified. The seven smaller gullies that were not initially included in the mapped features were observed in the field, implying 9% of errors of omission. Only four of the seven omitted gullies were distinctively visible on the aerial photographs and were later included in the final gully location map. The other three could not be easily identified on the aerial photographs due to their relatively small size and were subsequently excluded in the final map preparation.

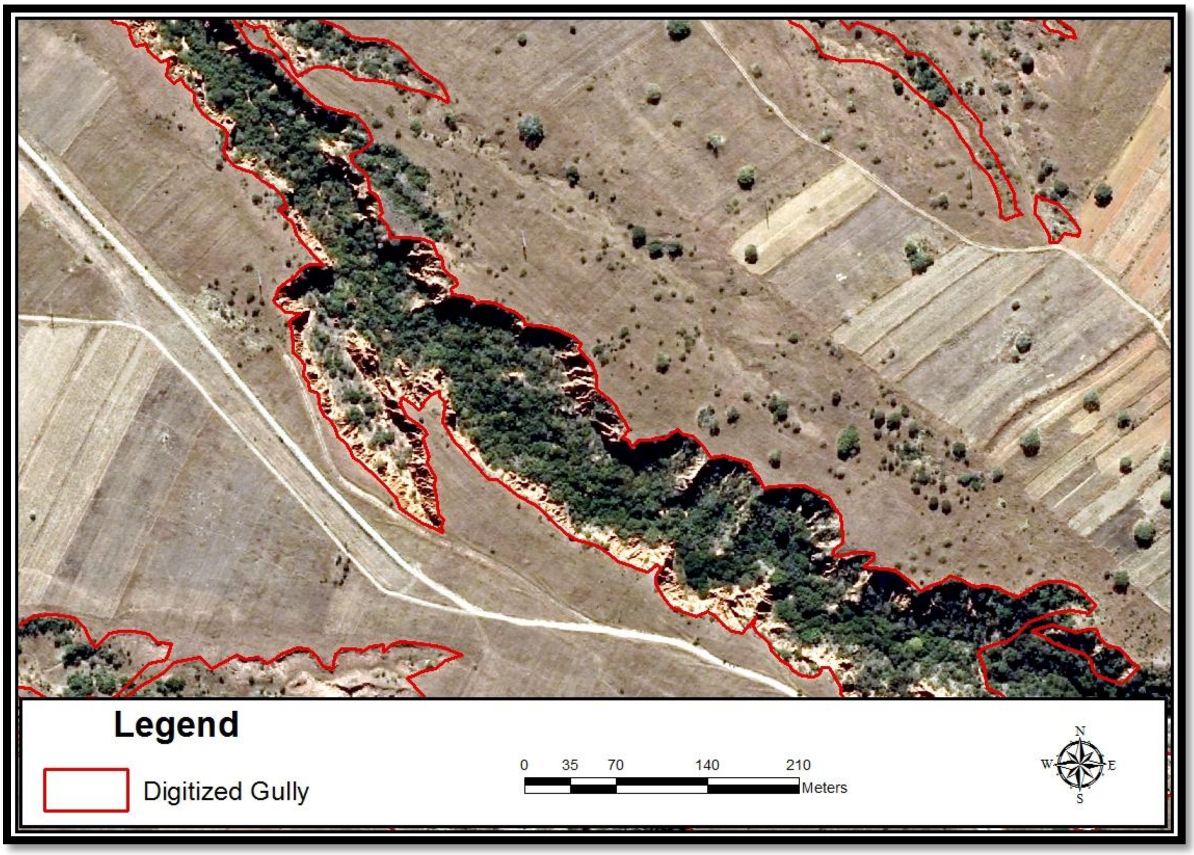

**Figure 4.6: Example of a digitised gully near Mooiplaas village characterised by active banks and stabilised gully floor**

### 4.3.3. Historical land use mapping and gully dynamics

Historical land use mapping was undertaken in order to examine the relationship between land use change and gully expansion and stabilisation. Given the scope of the current study, it would be impossible to examine the entire historical aerial photographs of the study area. Thus, it was decided to select two relatively active and large continuous gully systems for detailed analysis (Figure 4.7A and B). The first gully system is located in the middle reaches of tertiary catchment X12 and is approximately 98ha. The second gully system is located in the lower reaches of tertiary catchment W55 and is approximately 11ha. Priority for selection was given to gully systems occurring on an earlier date aerial photographs available for the two tertiary catchments (i.e. 1936 and 1950). Subsequent to gully systems selection, it was decided to create a buffer of 1km around all gully systems. Within the vicinity of the selected buffered gully systems, smaller discontinuous gullies exist that postdate the earliest aerial photograph, thus providing the opportunity to study their timing.

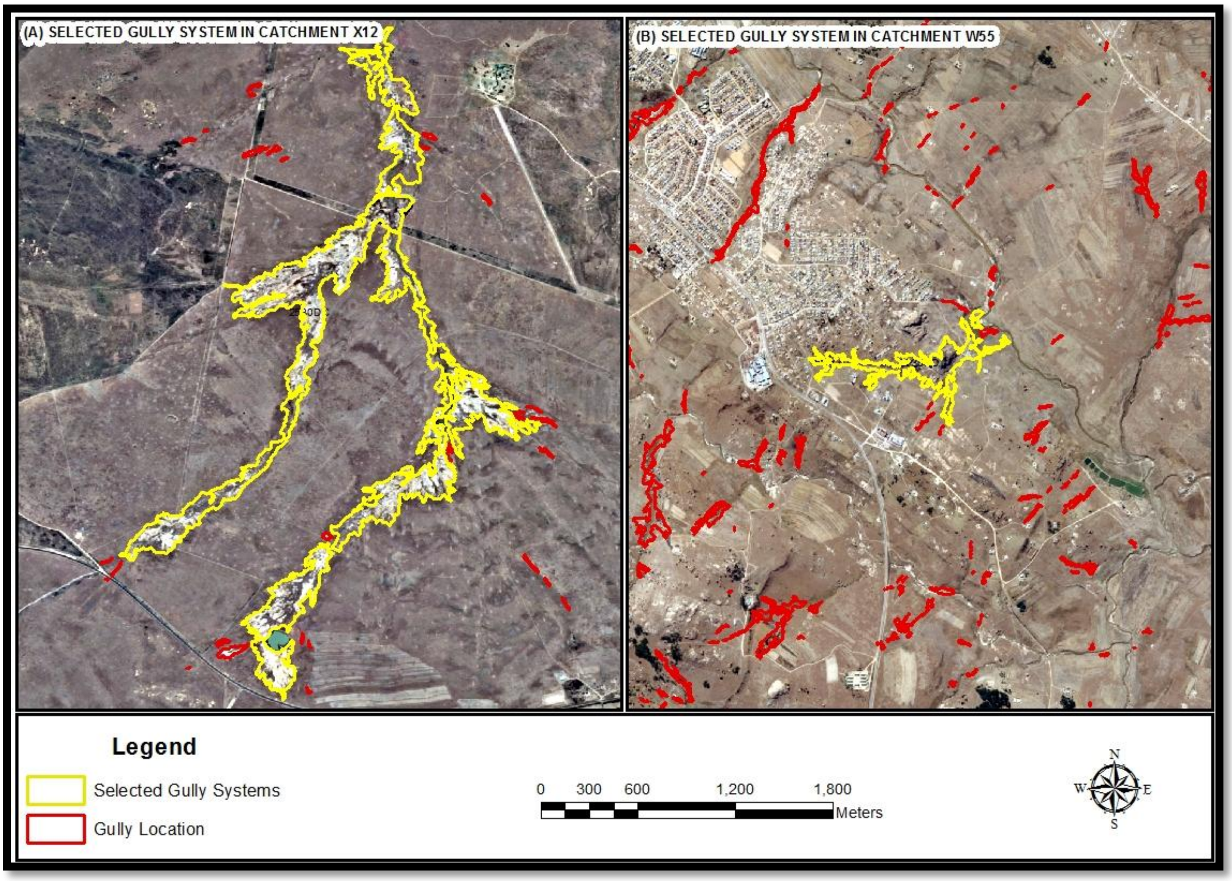

**Figure 4.7: (A) Selected gully system in catchment X12 and (B) gully system in catchment W55 for land use change and gully dynamics assessment**

Various sequential historical aerial photographs encompassing the buffered gully systems were identified as illustrated in Table 4.1. Historical photographs were georeferenced in ArcMap™ using identifiable land features discernible in the photographs and the reference digital aerial photographs. Notwithstanding the distortions on the historical aerial photographs caused by variations in ground relief, curvature of the camera lens and the tilt of the aircraft (see Read, 2002), no negative influence on the mapping of land use features and subsequent analysis was anticipated. Following georeferencing, the main land use activities such as cultivated fields, plantations and settlement areas were digitised for each year indicated in Table 4.1. The evidence of gully initiation, extension and stabilisation were recorded. Generally, change detection analysis would be the preferred technique to monitor land use and gully dynamics. Due to errors in digitised land use data associated with the difference in scale or spatial resolution of the selected aerial photographs (see Table 4.1), georeferencing accuracy and other distortions of the aerial photographs, a change detection approach would have provided unreliable results. Therefore, quantitative observation of the changes in land use activities and gullies were documented with caution.

**Table 4.1: Metadata of the selected sequential historical aerial photographs for tertiary catchments X12 and W55**

| Tertiary Catchment | Job No. | Strip No. | Photo No. | Acquisition Date | Scale |
|---|---|---|---|---|---|
| X12 | 110 | 045 | 28665 | 1936 (Month unknown) | 1:20 000 |
| | 110 | 045 | 28667 | 1936 (Month unknown) | 1:20 000 |
| | 110 | 046 | 28696 | 1936 (Month unknown) | 1:20 000 |
| | 110 | 046 | 28698 | 1936 (Month unknown) | 1:20 000 |
| | 110 | 048 | 28748 | 1936 (Month unknown) | 1:20 000 |
| | 110 | 048 | 28750 | 1936 (Month unknown) | 1:20 000 |
| | 469 | 004 | 09175 | August 1962 | 1:36 000 |
| | 469 | 005 | 08800 | August 1962 | 1:36 000 |
| | 469 | 005 | 08802 | August 1962 | 1:36 000 |
| | 875 | 009 | 00043 | 24 August 1984 | 1:50 000 |
| W55 | 244 | 003 | 00377 | August 1950 | 1:30 000 |
| | 789 | 008 | 00847 | 08 June 1977 | 1:30 000 |
| | 821 | 005 | 06932 | 05 June 1979 | 1:50 000 |

### 4.4. Assessment of the contributing factors

Assessment of the influence of various contributing factors of gully erosion was based on the implementation of the bivariate statistical Information Value (InfVal) method frequently applied in landslide hazard assessment (e.g. Van Westen, 1993; Rautela and Lakhera, 2000; Zezere, 2002). Recently, the InfVal weighting approach was implemented in the gully erosion susceptibility assessment (e.g. Conforti *et al.*, 2011; Lucà *et al.*, 2011). The InfVal approach is a statistical analysis based on the observed relationships between each contributing factor and the density of observed gullies (Lucà *et al.*, 2011). The relationships between contributing factors and gullies were quantitatively determined using the zonal approach in GIS. Following Le Roux and Sumner (2012), the zonal statistics tool in ArcGIS® spatial analyst extension was used to determine the proportion of gullies in each contributing factor class. In contrast with Le Roux and Sumner (2012), zonal statistics as a table function was used since it gives more statistical output such as sum, mean and standard deviation compared to the tabulate area function. It is worth mentioning here that in order for ArcGIS® zonal functions to work properly, the input class and zone layers must be rasters. If the input class or zone data is a vector polygon, a conversion to raster is applied internally and this may cause inconsistency of the compared variables and unexpected results due to the lack of control of vector to raster conversion. It was deemed necessary to convert all datasets to a raster format and resample to a cell size of 10m x 10m for consistency and easier computer processing purposes. All datasets were projected to Africa Albers Equal Area Conic projection since the current study seeks to preserve the area property. A detailed process workflow is included as Appendix B.

Subsequent to determining the proportion of gullies per contributing factors class, the InfVal weight was calculated using the formula as shown in Equation 4.4. The InfVal define weight value as the natural logarithm of the gully density class divided by the area of gully density over the entire study area (Conforti *et al.*, 2011). Thus, the sum or count results of zonal statistics were used as input in the InfVal equation.

$$\mathrm{Wi} = \ln \frac{\mathrm{DensClass}}{\mathrm{DensMap}} = \ln \frac{\mathrm{NpixSi}/\mathrm{NpixNi}}{\sum \mathrm{NpixSi}/\sum \mathrm{NpixNi}} \qquad (4.4)$$

where Wi is the weighting value of the class i, DensClass is the density of gullies in class i, DensMap is the density of gullies in the whole tertiary catchment, NpixSi is the number of pixels that contain gullies in class i; NpixNi is the number of pixels within class i; ΣNpixSi is the total number of pixels that contain gullies in the whole tertiary catchment; and ΣNpixNi is the total number of pixels of the whole tertiary catchment. A positive value of InfVal weight implies a strong or significant influence on gully, whereas a negative value indicates a weak influence on gully occurrence (Conforti *et al.*, 2011; Lucà *et al.*, 2011).

## 4.5. Summary

Secondary datasets described in this Chapter come from different sources and their scale of intended use varies. Their spatial details make them suitable for use at tertiary catchment scale. The methodology adopted here involved mapping and statistical analysis which resulted in a series of maps and tables presented in the next Chapter.

# CHAPTER 5: RESULTS

This Chapter presents the findings as per the objectives and methodologies described in Chapter 1 and 4 respectively, drawing into the discussion the comparison between tertiary catchments W55 and X12. First is the distribution of topographic variables in a form of maps and a table, highlighting the critical class values with potential for gully erosion development. Second is the gully location map and distribution in a form of simple statistical table. Third is the historical land use and gully erosion dynamics in a form of maps and tables. Fourth is the correlation statistics between the mapped gullies and various contributing factors, highlighting the most dominant and most influential variables.

## 5.1. Distribution of topographic variables

### 5.1.1. Slope gradient distribution

Figure 5.1 displays the slope gradient in degrees calculated using the D-Infinity flow routing algorithm introduced by Tarboton (1997). The slope steepness in the two tertiary catchments ranges from 0° to approximately 62°. There is a significant difference in the distribution of slope values between the two tertiary catchments. For a more meaningful interpretation, the slope gradient results were classified into nine slope steepness classes modified from Food and Agriculture Organisation (2006). Table 5.1 shows the proportion of each slope steepness class in hectares per tertiary catchment. The slopes in tertiary catchment X12 are highly variable with moderate to steep slopes more pronounced on the eastern side. Tertiary catchment W55 is dominated by gently sloping to sloping land observable mainly on the western side. Steep slopes have been identified as unfavourable to gully erosion development in SA conditions compared to gentle and lower slopes (e.g. Kakembo *et al.*, 2009), whilst studies elsewhere in the world regard it as favourable for the development of gullies (e.g. Valentin *et al.*, 2005). The correlation between gullies and the slope classes is assessed in section 5.4.

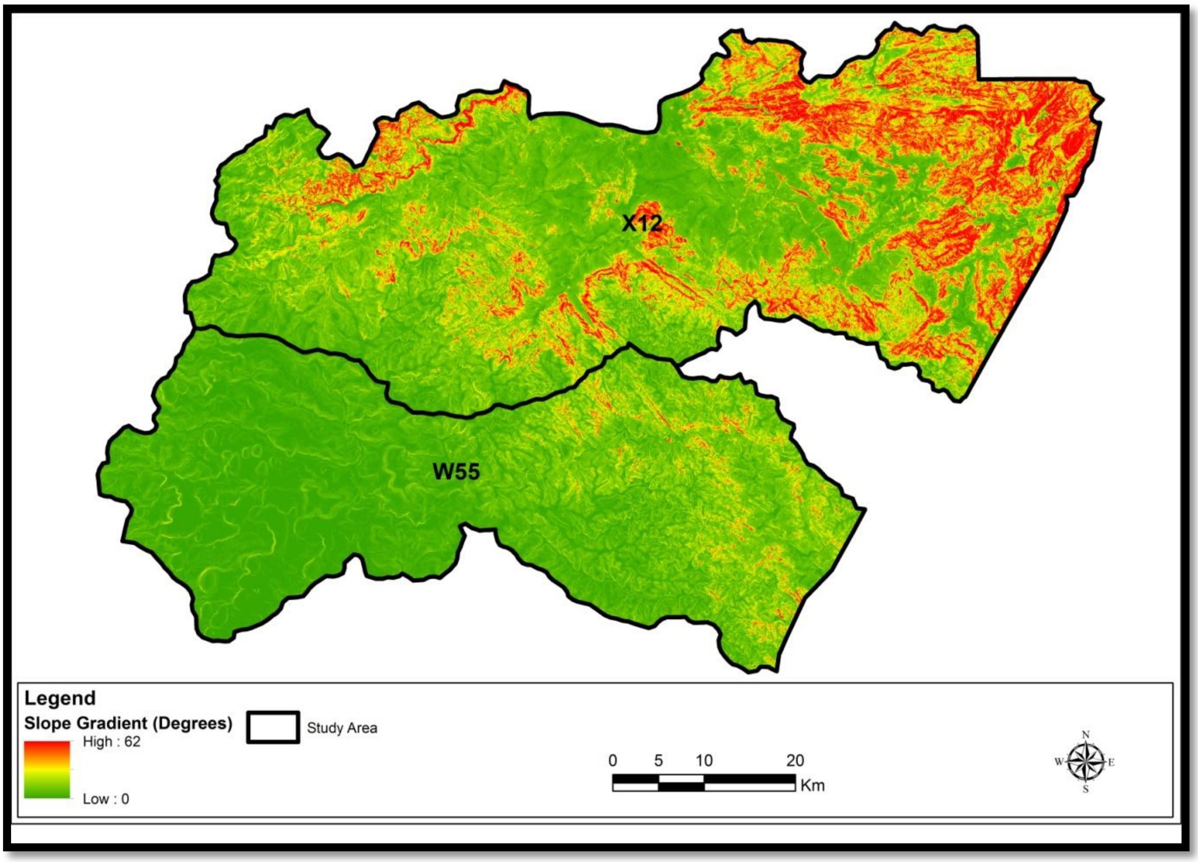

Figure 5.1: Slope gradient map in degrees for catchments X12 and W55

Table 5.1: Distribution of slope classes in tertiary catchments X12 and W55

| | Tertiary catchment X12 results | | Tertiary catchment W55 results | |
|---|---|---|---|---|
| **Slope Classes** | **Area (ha)** | **Percentage of the total area** | **Area (ha)** | **Percentage of the total area** |
| Flat or level | 372.6 | 0.2 | 4344.4 | 2.6 |
| Nearly level to very gentle sloping | 3286.1 | 1.3 | 24194.8 | 14.6 |
| Gently sloping | 15105.8 | 6.1 | 41564.0 | 25.0 |
| Sloping | 46362.8 | 18.7 | 42747.5 | 25.7 |
| Strongly sloping | 43202.9 | 17.5 | 24979.8 | 15.0 |
| Moderately steep | 58360.5 | 23.6 | 23164.8 | 13.9 |
| Steep | 58869.5 | 23.8 | 4811.9 | 2.9 |
| Very steep | 21289.6 | 8.6 | 333.2 | 0.2 |
| Extremely steep | 452.2 | 0.2 | 0.4 | 0.0 |

### 5.1.2. Upslope contributing area distribution

Figure 5.2 shows a logarithmic scale of the upslope contributing area results calculated using Tarboton (1997) D-infinity algorithm. The values of the upslope contributing area were originally given as catchment area measured in m$^2$. For simplicity, the logarithm values of the original upslope contributing area were calculated. The higher logarithm values represented by shades of dark blue or values greater than seven, represents a significant area with potential for gully erosion development where flow concentrates into stream channels. Higher values have a greater catchment area of approximately 1 000m$^2$ and above (figure obtained from the original contributing area calculations which is not shown here). Previous studies (e.g. Le Roux and Sumner, 2012) found a strong correlation between gullies and catchment area greater than 200m$^2$. The appearances of darker shades of blue upslope of catchment W55 (western side) highlight wetlands and pans (not shown in Figure 5.2) characterising the majority of the upslope area of catchment W55.

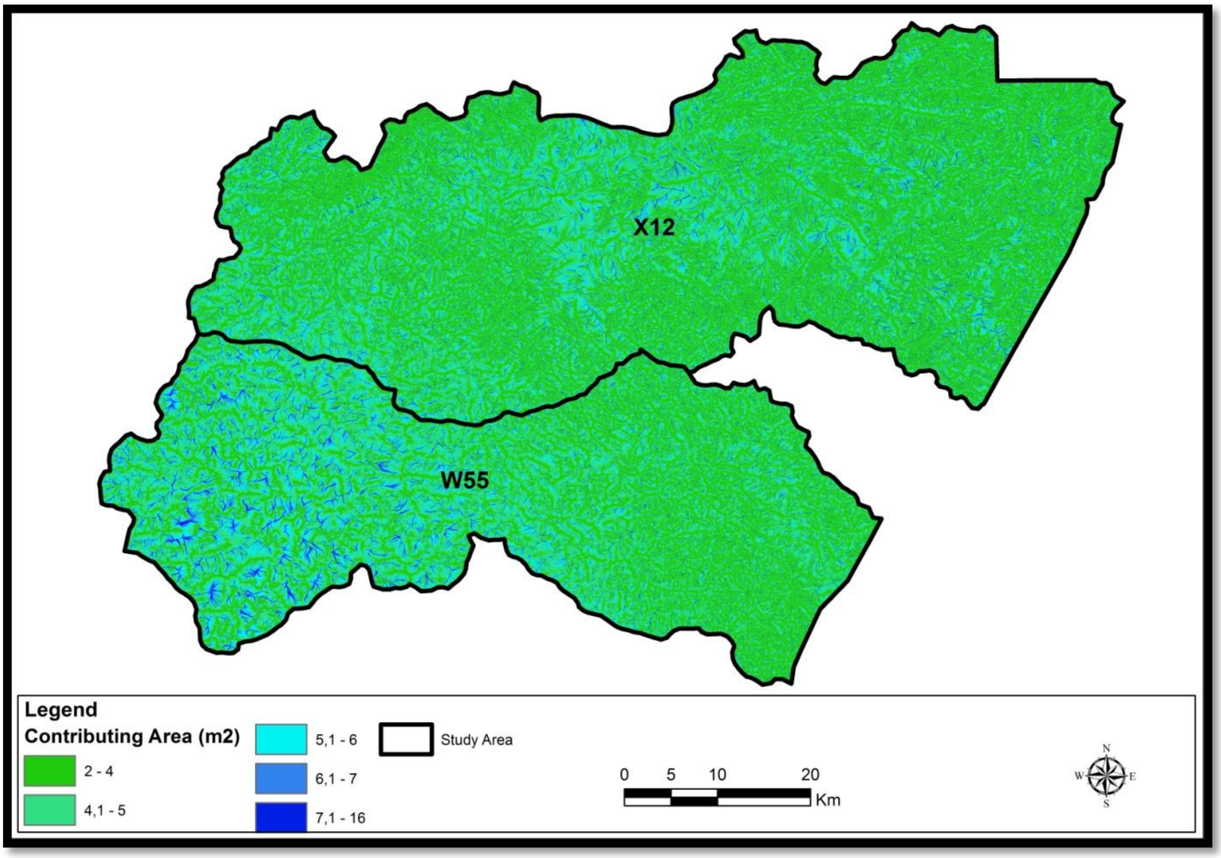

**Figure 5.2: A logarithm scale upslope contributing area (m$^2$) for tertiary catchments X12 and W55**

### 5.1.3. Planform curvature distribution

Figure 5.3 displays the planform curvature distribution map. The values of the computed planform curvature range from approximately -16 to 7 as shown in Figure 5.3. A negative planform curvature value represents the upwardly concave surface where there is high potential for gully erosion development due to the convergence of water flow (Tagil and

Jenness, 2008). A value of near zero represents a flat surface whilst positive curvatures represent upwardly convex slope such as ridges, hills and mountains. Flat and convex surfaces are less favourable to gully erosion development (Tagil and Jenness, 2008). The distribution of concave surfaces is widespread in tertiary catchment X12 and less in W55 due to the dominance of ridges, hills and mountains in the former and flat areas in the latter.

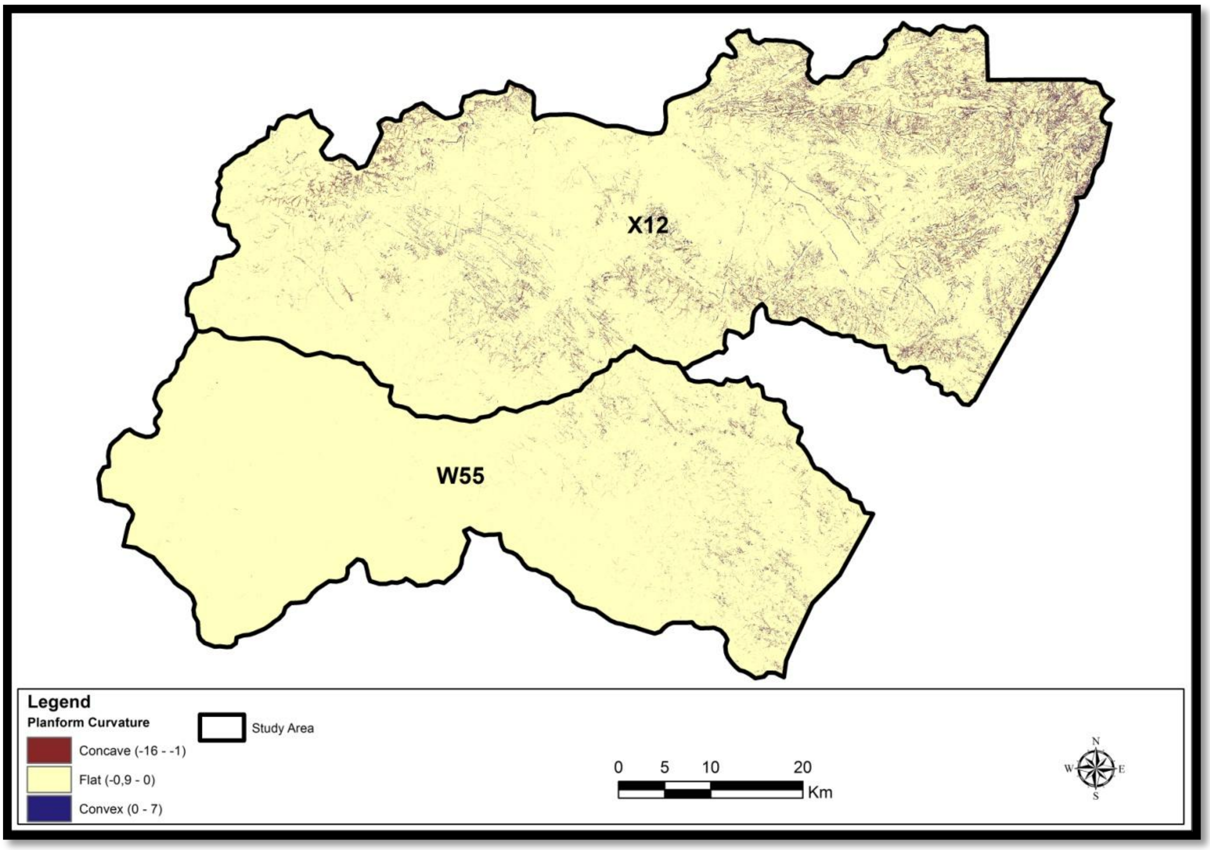

**Figure 5.3: Planform curvature map for tertiary catchments X12 and W55**

### 5.1.4. Topographic Wetness Index (TWI) distribution

Figure 5.4 illustrates TWI results calculated using the formula of Wilson and Gallant (2000) as already discussed in Chapter 4. The value of the calculated TWI ranges from approximately 2 to 28 within the study area. High TWI values correspond well with high upslope contributing area values and represent zones of saturation where there is abundant soil moisture (Wilson and Gallant, 2000). Previous studies have shown that areas of high TWI values have greater potential for gully erosion development particularly since the soil easily loses strength when wet (e.g. Le Roux and Sumner, 2012). High TWI values are easily distinguishable in Figure 5.4 by their darker shade of blue. In the region upslope of tertiary catchment W55 where there are many wetlands, pans and along channels, TWI is high. This is associated with the ability of the waterbodies and water channels to retain soil moisture compared to the surroundings.

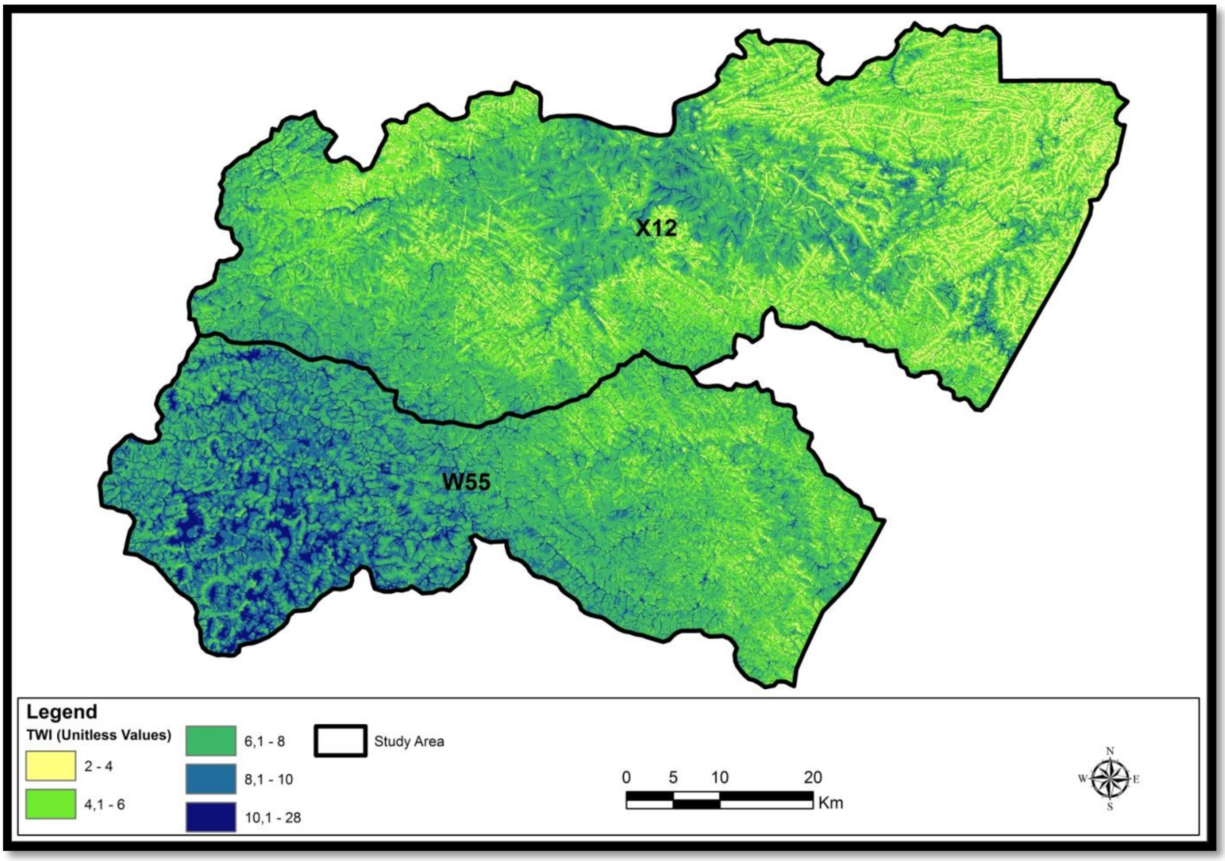

**Figure 5.4: Topographic Wetness Index map for tertiary catchments X12 and W55**

### 5.1.5. Stream Power Index (SPI) distribution

Figure 5.5 displays the logarithmic results of SPI calculated using the formula suggested by Wilson and Gallant (2000). The logarithmic SPI values in the study area range from -10 to 13 represented by a reddish-brown to dark blue colour ramp. The SPI values indicate the erosive power of the terrain such that higher values produce an increased velocity of water flow and thus increase the potential for erosion (Tagil and Jenness, 2008). High SPI values (light to dark blue colour in Figure 5.5), were previously identified as favourable to the development of gullies due to great runoff potential (e.g. Kakembo *et al.*, 2009) and they dominate throughout tertiary catchment X12. In tertiary catchment W55, high SPI values are in a majority downslope within the catchment.

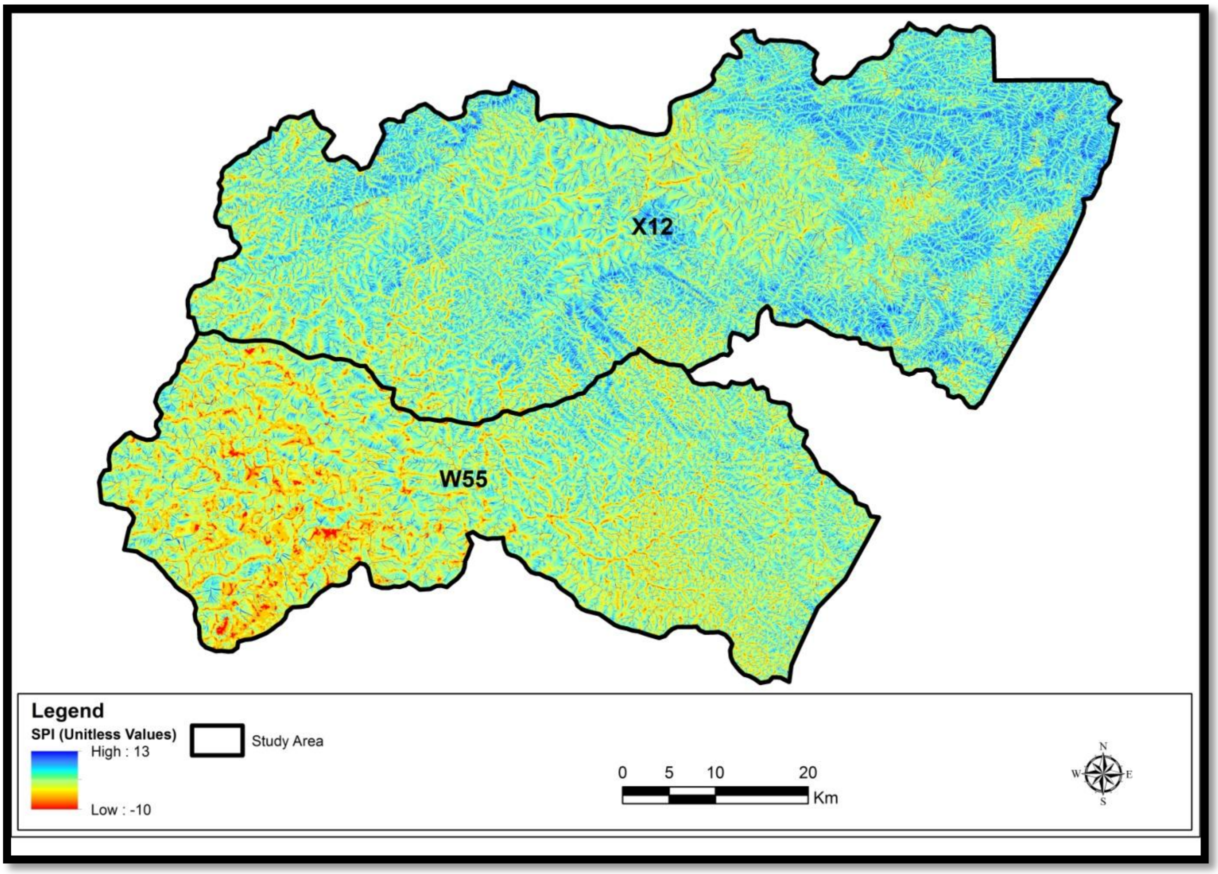

Figure 5.5: Stream Power Index map for tertiary catchments X12 and W55

## 5.2. Gully location mapping results

Table 5.2 shows the extent of the area affected by gullies in tertiary catchments X12 and W55. The spatial distribution of gullies within the catchments is displayed in Figure 5.6. The results shown here reaffirm the assertion made in Chapter 3.1 that catchment X12 has a relatively high gully density compared to catchment W55. Although gullies mapped here were not classified for the entire catchments, visual observation shows a greater proportion of smaller discontinuous gullies in X12. The gullies mapped range in size from approximately 4m$^2$ to 74ha (not illustrated here) and affect an area of approximately 1 834ha (18.34km$^2$) of the total tertiary catchment surfaces. Table 5.2 shows that 0.6% of catchment X12 is affected by gullies compared to 0.2% in catchment W55. Figure 5.6 illustrates that gullies are widespread throughout catchment X12, while in catchment W55, they predominate on the eastern side along the border with Swaziland.

**Table 5.2: Summary statistics of gullies detected and digitised in South African portions of tertiary catchments X12 and W55**

| Catchment Name | Catchment Size (Ha) | Gullies Count | Gullies Affected Area (Ha) | Percentage of Area Affected |
|---|---|---|---|---|
| X12 | 250820.7 | 5397 | 1535.8 | 0.6% |
| W55 | 166143.0 | 1654 | 276.6 | 0.2% |
| Total for all Catchments | 416963.7 | 7051 | 1812.4 | 0.4% |

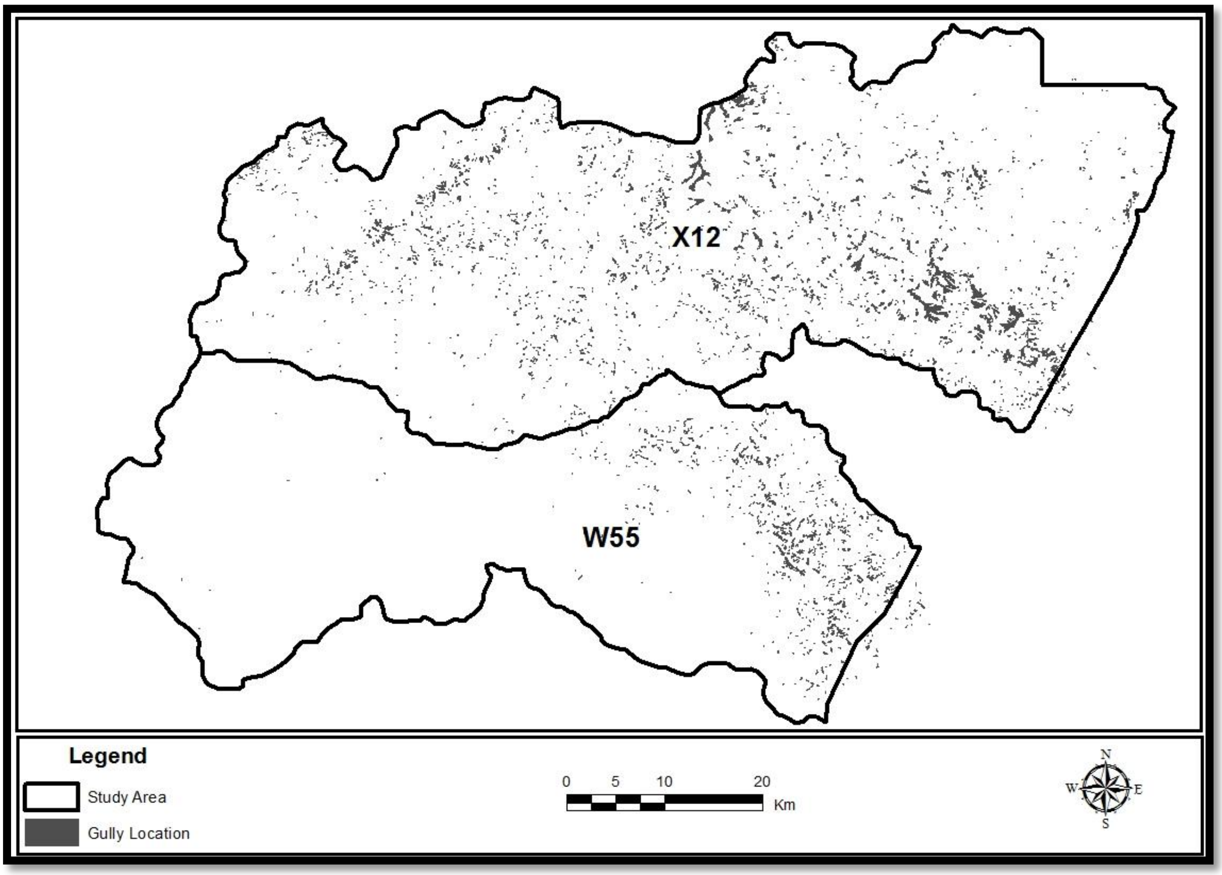

**Figure 5.6: Gully location map in tertiary catchments X12 and W55**

## 5.3. Gully system change and land use dynamics

Historical land use and gully dynamics were observed from two selected gully systems representing each tertiary catchment. For the purpose of this study, gullies are distinguished into continuous and discontinuous based on their connection or link to the main gully systems or streams. The correlation between gully systems change and historical land use dynamics is discussed in Chapter 6.

### 5.3.1. Gully system change in catchment X12

A total of 47 gullies within 1km radius of the main selected gully system in catchment X12 were observed, 29 did not have any connection to the main gully or river, thus were classified as discontinuous and eighteen were classified as continuous because they discharge into a river/stream. The trends for selected gully polygons were observed for the period 1936, 1962 and 1984. Results in Table 5.3 show that most of the 47 gully polygons postdate the earliest date aerial photograph. Specifically, the majority of discontinuous gullies were non-existent from the 1936 and 1962 aerial photographs as shown in Table 5.3. Most remarkably, an increase in the number of discontinuous gullies occurred in 1984 wherein 23 gullies were observed and six were non-existent. The land use activities prior and after the establishment of these discontinuous gullies are discussed in the next sections. In contrast, the majority of continuous gullies pre-date the earliest available aerial photograph i.e. 1936. Only five and three continuous gullies could not be observed from 1936 and 1962 aerial photographs respectively. Although continuous gullies are relatively smaller in size, they link up to the main gully system and can be regarded as an extension to the main gully.

**Table 5.3: Historical occurrence of gullies within 1km radius of the selected gully system in tertiary catchment X12**

| Gully Type | Number of gullies per year for each gully type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1936 | | 1962 | | 1984 | | 2010 | |
| | Exist | Non-existent | Exist | Non-existent | Exist | Non-existent | Exist | Non-existent |
| Continuous | 13 | 5 | 15 | 3 | 18 | 0 | 18 | 0 |
| Discontinuous | 9 | 20 | 12 | 17 | 23 | 6 | 29 | 0 |
| Total | 22 | 25 | 27 | 20 | 41 | 6 | 47 | 0 |

### 5.3.2. Gully system change in catchment W55

A total of 52 gully polygons (25 continuous and 27 discontinuous) within 1km buffered main gully system were observed. The continuous gullies include those discharging to the main selected gully system and to the adjacent streams and channels. Most of the discontinuous gullies observed postdate the historical aerial photographs (Table 5.4), implying that gullying in and around the selected gully system is relatively recent. The majority of discontinuous gullies never existed prior to 1979. However, continuous gullies formed rapidly during the years of investigation, increasing from seven in 1950 to eleven and thirteen in 1977 and 1979 respectively.

**Table 5.4: Historical occurrence of gullies within 1km radius of the selected gully system in tertiary catchment W55**

| Gully Type | Number of gullies observed per year for each gully type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1950 | | 1977 | | 1979 | | 2010 | |
| | Exist | Non-existent | Exist | Non-existent | Exist | Non-existent | Exist | Non-existent |
| Continuous | 7 | 18 | 11 | 14 | 13 | 12 | 25 | 0 |
| Discontinuous | 1 | 26 | 1 | 26 | 0 | 27 | 27 | 0 |
| Total | 8 | 44 | 12 | 40 | 13 | 39 | 52 | 0 |

### 5.3.3. Land use dynamics in catchment X12

The 1km buffer of the selected gully system in tertiary catchment X12 covers an area of 1 614ha. Table 5.5 shows two land use classes, namely cultivation and an aerodrome from the 1936, 1962, 1984 and 2010 aerial photographs. The rest of the area is classified as grazing land or land available for grazing. Estimated proportions of land use for the years 1936, 1962, 1984 and 2010 are illustrated in Table 5.5 and the spatial distribution is shown in Figures 5.7, 5.8, 5.9 and 5.10 respectively. Table 5.5 shows that the area has undergone considerable change during the years investigated mainly due to land abandonment. In 1936, cultivation was practised in 10% of the total area observed. Approximately 90% of of the area is grazing land. During the 1962 year, 6% of the cultivated fields were abandoned, resulting in only 4% cultivated land. Cultivation increased tremendously in 1984 with the introduction of irrigation easily discernible in Figure 5.9. The cultivation in 1984 occupied an area approximately 24%. Approximately 16% of the areas under cultivation were abandoned in 2010. The 2010 data also shows the presence of an aerodrome occupying 1% of the total area on a land that was previously cultivated. The main land use change observed here is the abandonment observed in the 1962 and 2010 aerial photographs. Land abandonment in 1962 and 2010 was preceded by the extensive cultivation observed in the 1936 and 1984 aerial photographs respectively.

**Table 5.5: Dynamics of land use activities within 1km radius of the selected gully system in tertiary catchment X12**

| **Land use category** | **Percentage (%) of the land use category per year** | | | |
|---|---|---|---|---|
| | **1936** | **1962** | **1984** | **2010** |
| Cultivation | 10% | 4% | 24% | 8% |
| Aerodrome | 0% | 0% | 0% | 1% |
| Not categorised | 90% | 96% | 76%% | 91% |

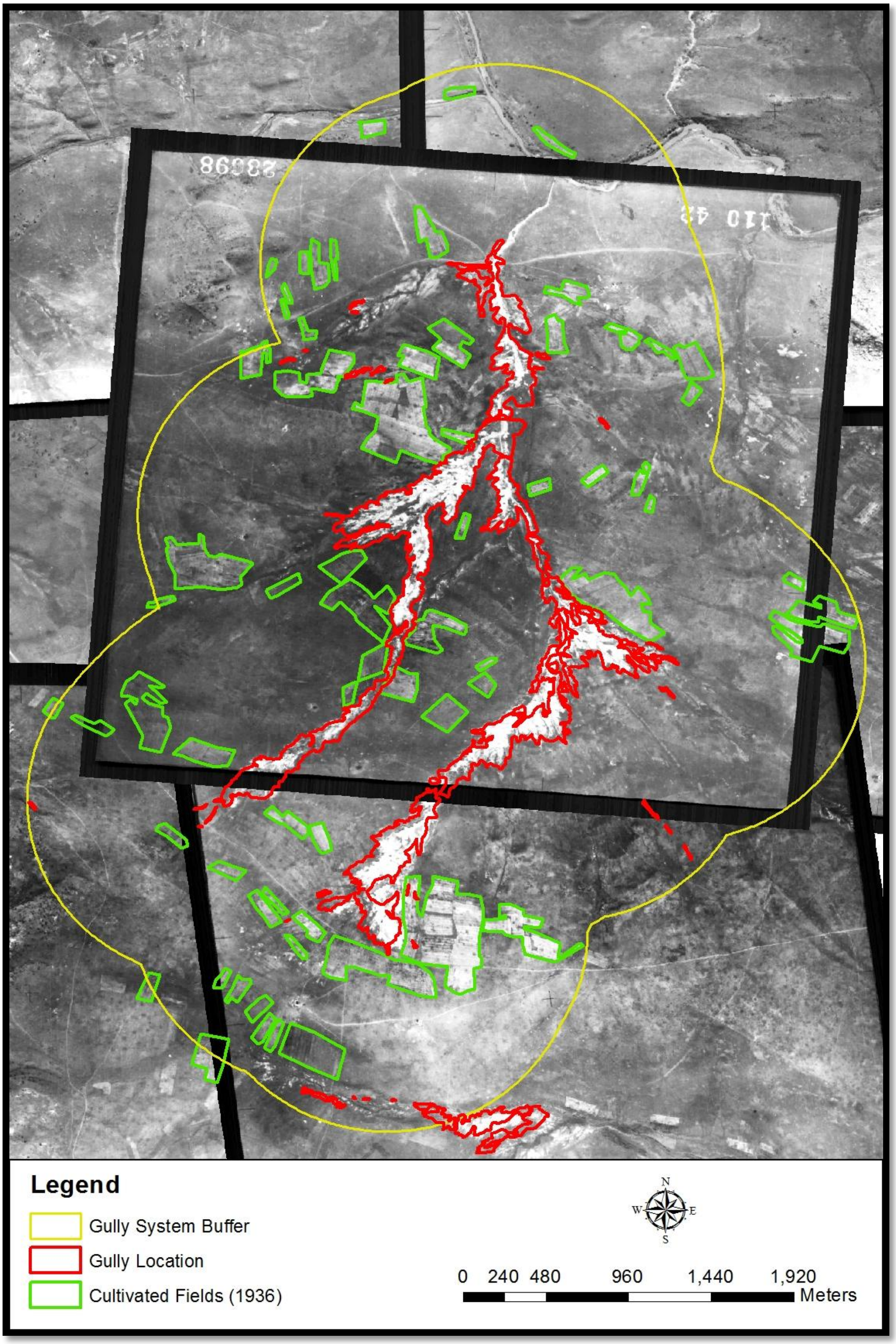

Figure 5.7: Distribution of land use around the selected gully system in tertiary catchment X12 (1936)

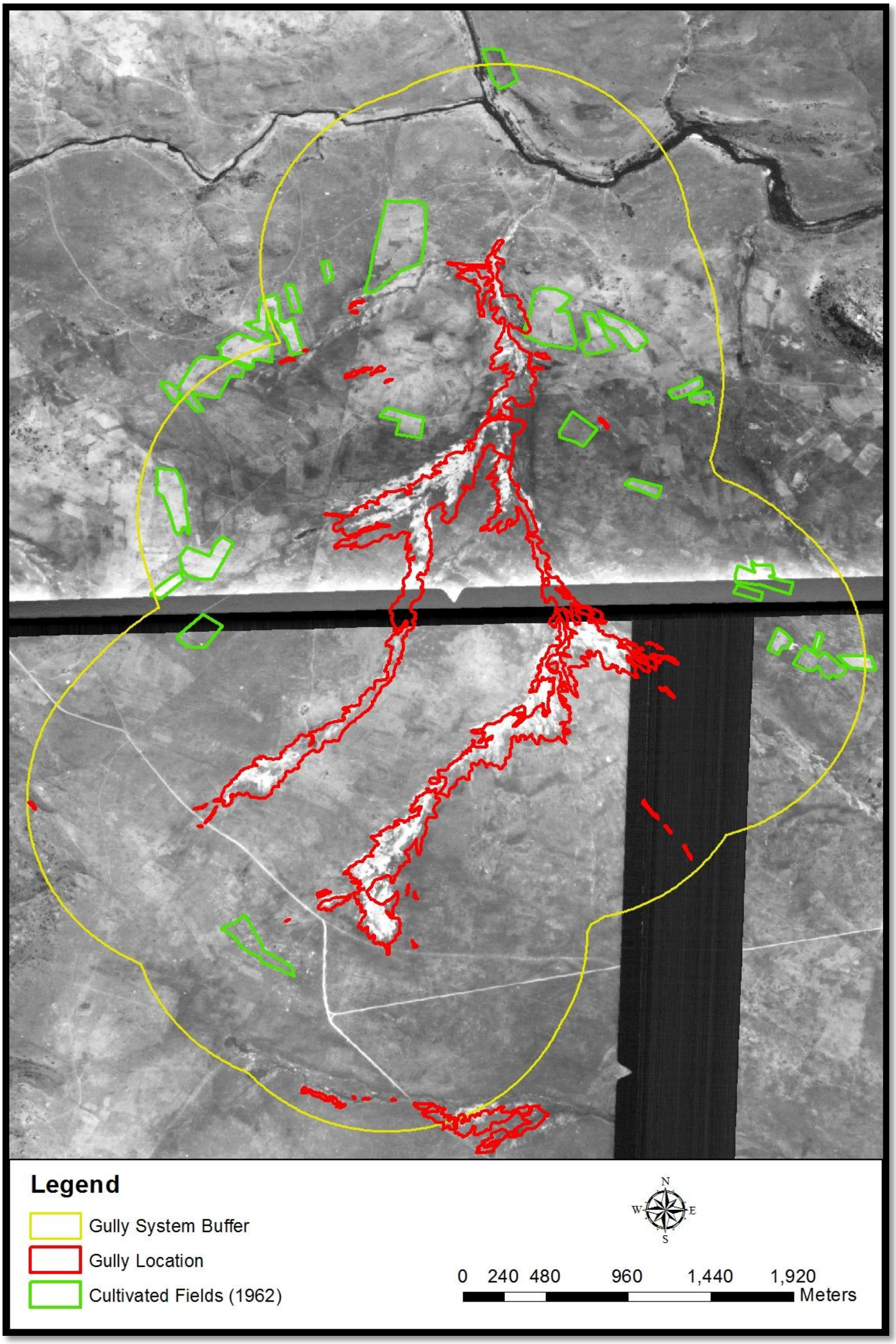

**Figure 5.8: Distribution of land use around the selected gully system in tertiary catchment X12 (1962)**

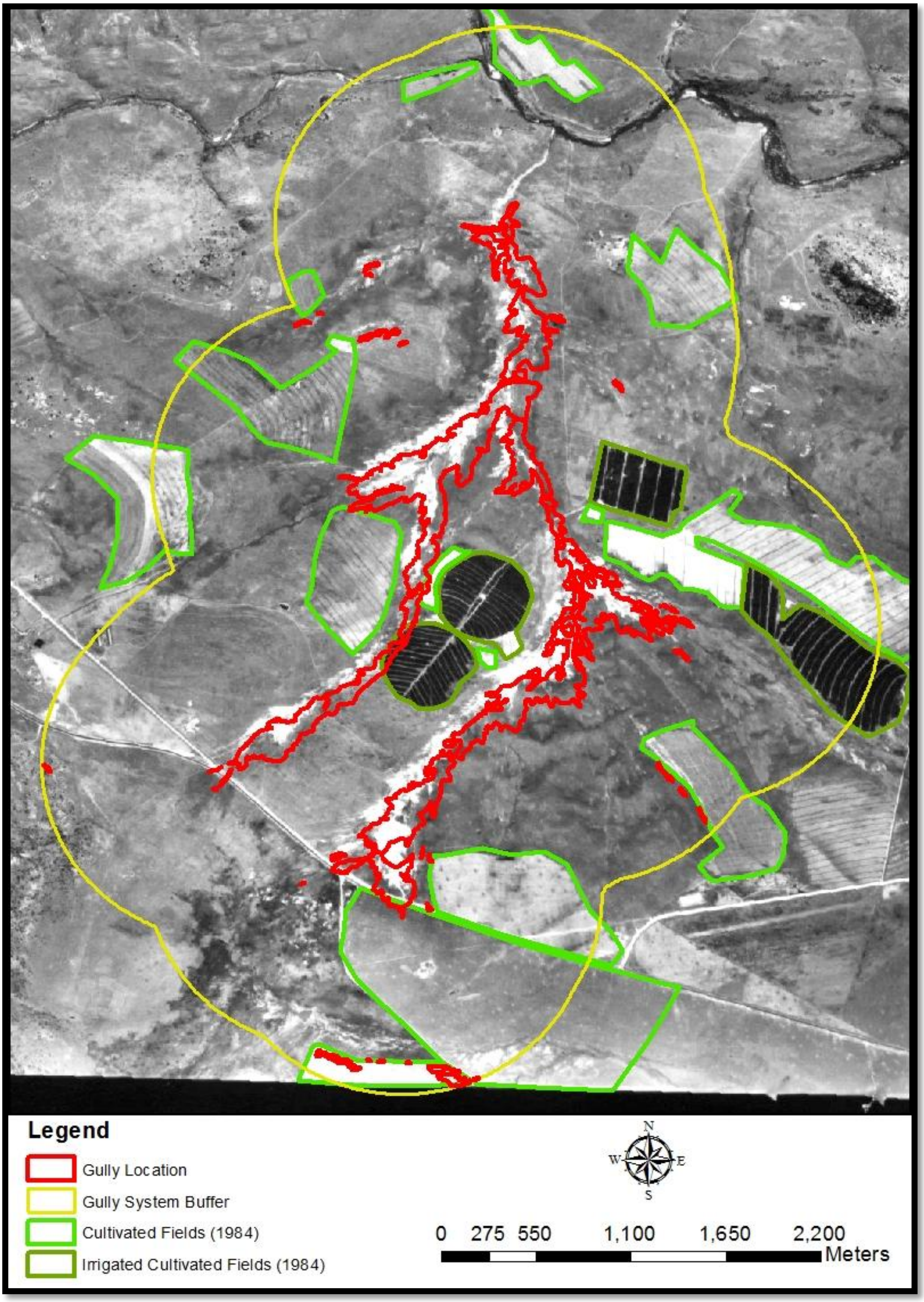

**Figure 5.9: Distribution of land use around the selected gully system in tertiary catchment X12 (1984)**

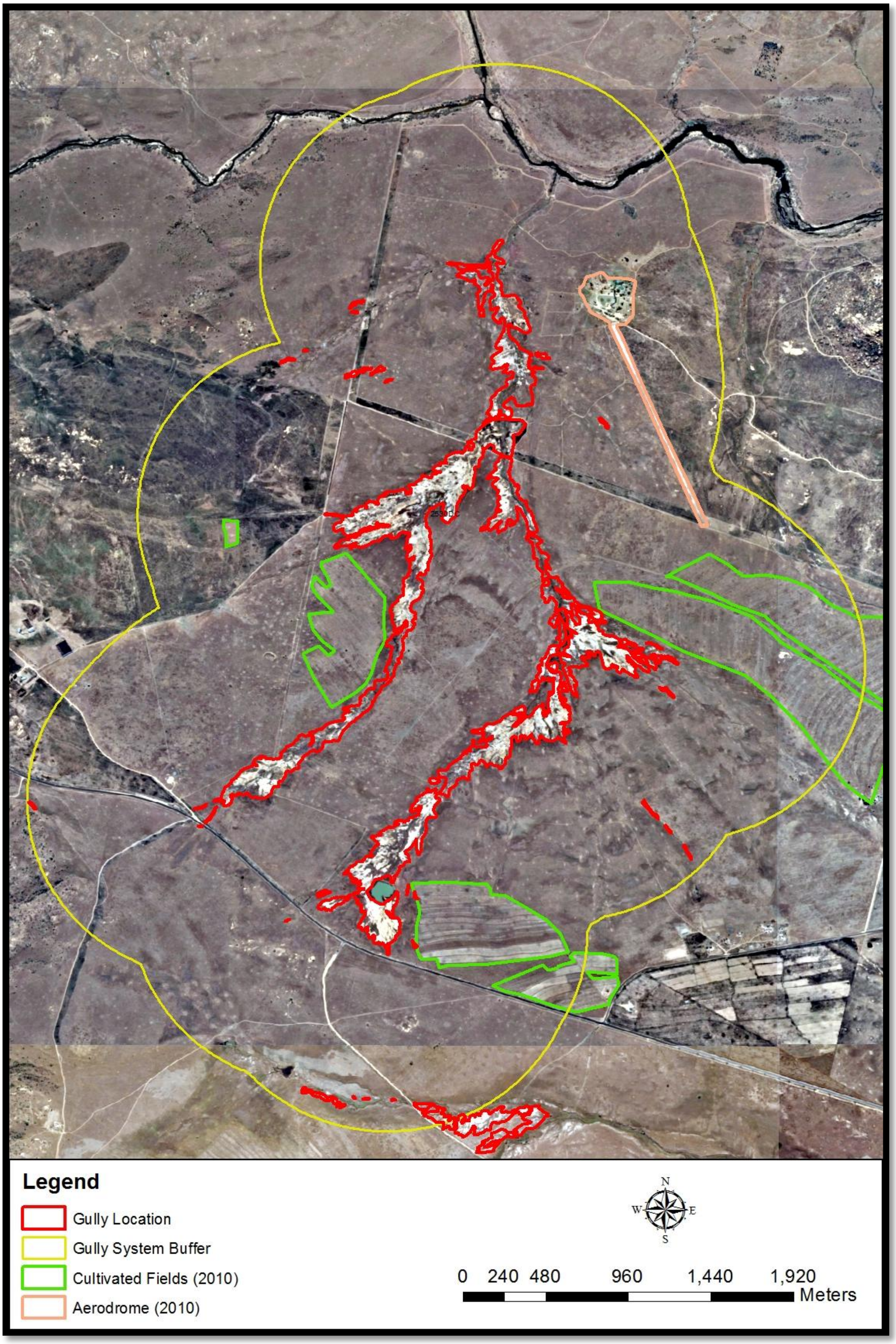

**Figure 5.10: Distribution of land use around the selected gully system in tertiary catchment X12 (2010)**

### 5.3.4. Land use dynamics in catchment W55

The total size of the buffered area around the selected gully system in tertiary catchment W55 is 624ha. A total of two land use classes were mapped and observed in the 1950, 1977, 1979 and 2010 aerial photographs, namely cultivation and residential development (Table 5.6). Land use distribution for the mentioned photographs is shown in Figures 5.11, 5.12, 5.13 and 5.14 respectively. The rest of the area is assumed to be grazing land. Cultivation was the only mapped land use activity within a 1km radius of the selected gully system in 1950 aerial photograph (Table 5.6). Majority of the cultivated fields were later abandoned as shown in the 1977 and 1979 aerial photographs, making way for the residential development appearing to be fast spreading predominantly north-west of the main gully system (Figure 5.12 and 5.13). The 1979 mapping results show that only a single field, equating to 1% of the total area, was cultivated (Figure 5.13 and Table 5.6). By 2010, residential development of the Empuluzi communal land had spread to approximately 24% of the total area (Figure 5.14). Cultivated fields were re-established and occupy 17% of the total area (Table 5.6). Empuluzi represents a typical communal land where residential development, cultivation and grazing are the main land use activities. The main change observed here is the shift from predominately cultivated land to a communal land use system consisting of a mixture of settlement, grazing and cultivation.

**Table 5.6: Dynamics of land use activities within 1km radius of the selected gully system in tertiary catchment W55**

| Land Use | Percentage (%) of the land use category per year | | | |
|---|---|---|---|---|
| | 1950 | 1977 | 1979 | 2010 |
| Cultivation | 11% | 6% | 1% | 17% |
| Residential or Settlement | 0% | 1% | 1% | 24% |
| Not categorised | 89% | 93% | 98% | 59% |

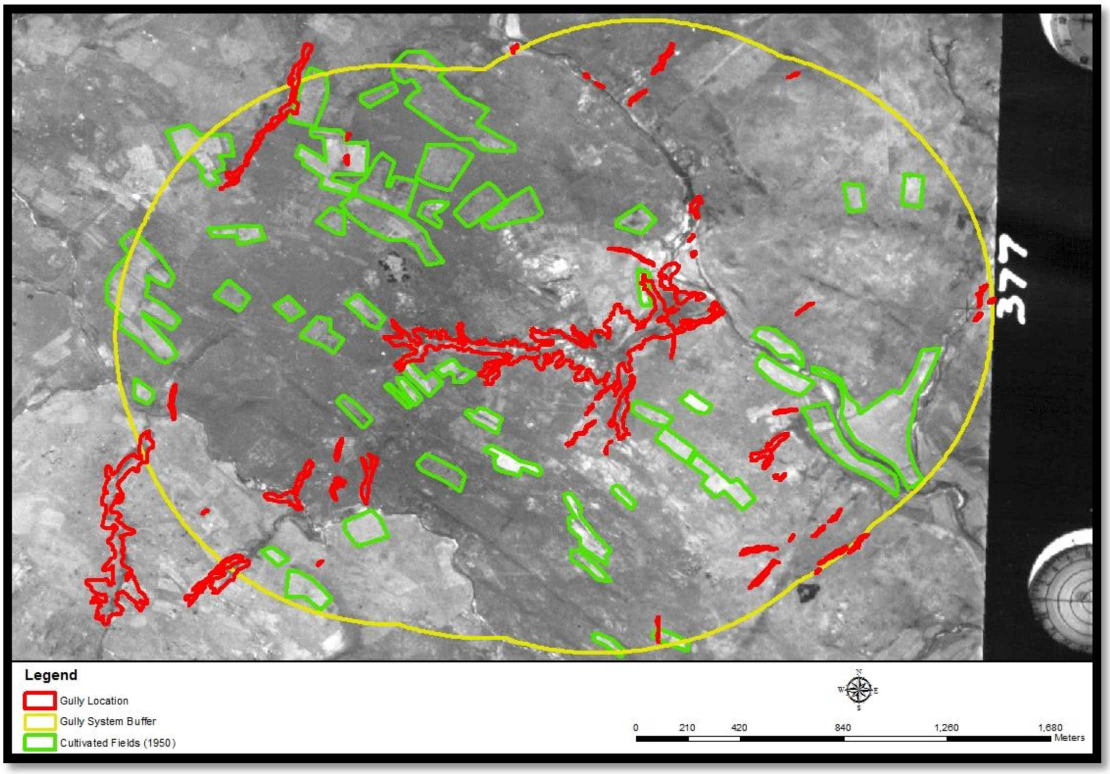

Figure 5.11: Distribution of land use around the selected gully system in tertiary catchment W55 (1950)

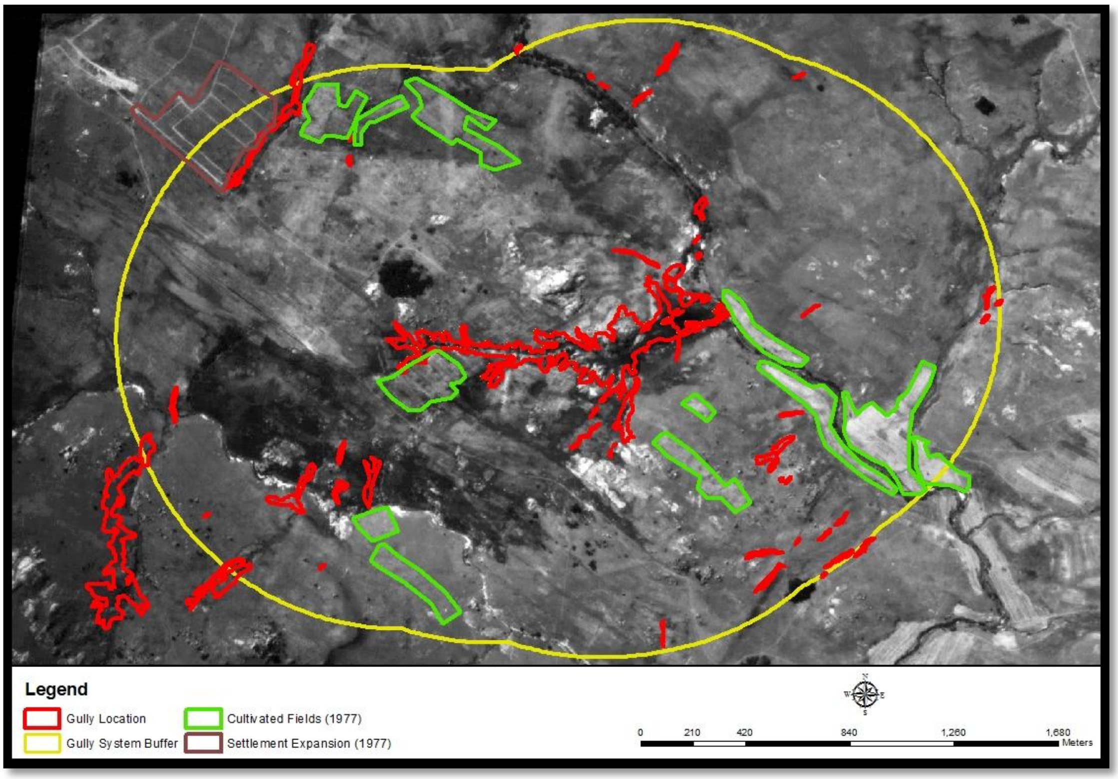

Figure 5.12: Distribution of land use around the selected gully system in tertiary catchment W55 (1977)

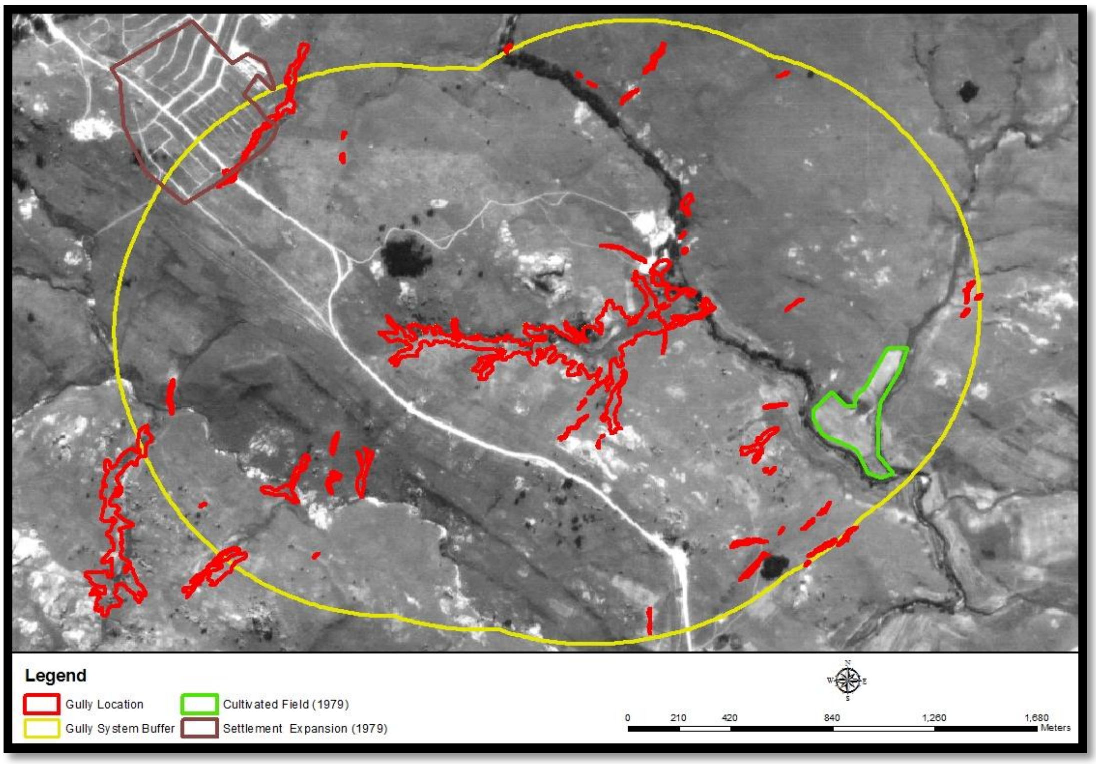

**Figure 5.13: Distribution of land use around the selected gully system in tertiary catchment W55 (1979)**

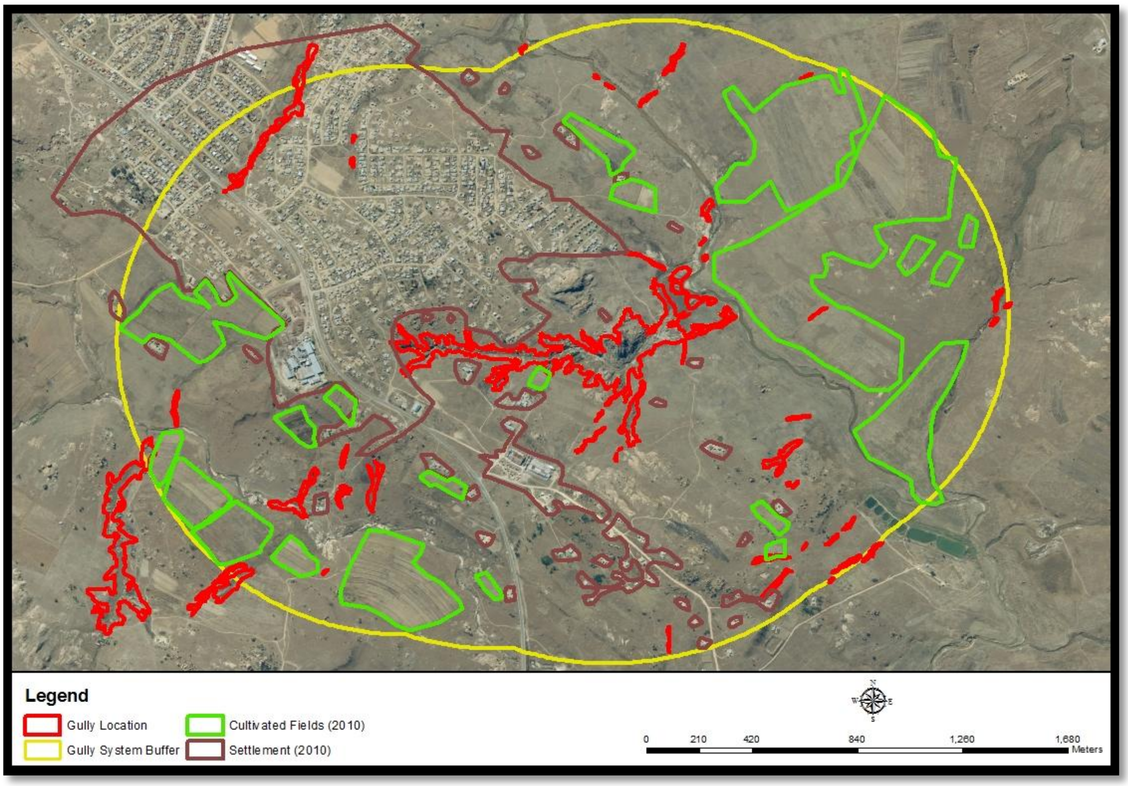

**Figure 5.14: Distribution of land use around the selected gully system in tertiary catchment W55 (2010)**

## 5.4. Results of the contributing factors assessment

### 5.4.1. The influence of soil on gully erosion

Table 5.7 compares the Information Value (InfVal) weight (Wi) of clay content classes between tertiary catchments W55 and X12. Classes such as very sandy (Wi = 1.7), loamy sand (Wi = 1.6) and sandy (Wi = 0.7) in tertiary catchment W55 are susceptible to gully erosion based on their significant InfVal weight. This is expected since the number of pixels affected by gullies in the mentioned classes is high. However, it was not anticipated of loam clay (Wi = -0.2) and loam (Wi = -1.2) soils to have insignificant influence on gully based on the large number of pixels affected (NpixSi = 4 682 and NpixSi = 2 236 respectively). In tertiary catchment X12, a strong influence on gully was observed on clay (Wi = 1.5) and loam (Wi = 0.3) soils classes. Previous studies have shown that soils with high clay content are generally not easily erodible because of the high cohesive forces between particles (Wischmeier and Mannering, 1969; Le Roux *et al.*, 2006) except for dispersive clays. Similar to tertiary catchment W55, loamy sand (NpixSi = 16 336) and sandy (NpixSi = 7 305), and in addition loam clay (NpixSi = 28 998), very sandy (NpixSi = 15 906), sandy loam (NpixSi = 3 991) and clayey (NpixSi = 1 966) soils have a greater number of gullied pixels but have low InfVal weight.

**Table 5.7: Comparison of the Information Value (InfVal) weight index (Wi) for each class of the soil clay content in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Clay Content Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Clay | 3012 | 0 | 0.00000 | - | 296471 | 8216 | 0.02771 | 1.5 |
| Loam | 4281642 | 2236 | 0.00052 | -1.2 | 8668761 | 70671 | 0.00815 | 0.3 |
| Loam Clay | 3540119 | 4682 | 0.00132 | -0.2 | 5103376 | 28998 | 0.00568 | -0.1 |
| Loamy Sand | 699992 | 5569 | 0.00796 | 1.6 | 3046407 | 16336 | 0.00536 | -0.1 |
| Clayey | 597559 | 67 | 0.00011 | -2.7 | 444430 | 1966 | 0.00442 | -0.3 |
| Sandy | 1226262 | 4163 | 0.00339 | 0.7 | 1658127 | 7305 | 0.00441 | -0.3 |
| Very Sandy | 1237492 | 10952 | 0.00885 | 1.7 | 4034080 | 15906 | 0.00394 | -0.5 |
| Sandy Loam | 4356482 | 10 | 0.00000 | -6.6 | 1471076 | 3991 | 0.00271 | -0.8 |
| Non-perennial Pans | 32167 | 0 | 0.00000 | - | 1232 | 0 | 0.00000 | - |
| Waterbodies | 630961 | 0 | 0.00000 | - | 0 | 0 | - | - |
| **Total** | **∑NpixNi W55 = 16605688** | **∑NpixSi W55 = 27679** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24723960** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

Table 5.8 shows a strong influence of steep slopes (Wi = 1.6) and very deep soils (Wi = 0.3) on gullies in tertiary catchment W55. Steep slope is not a soil depth class per se, it was included as a class by Van den Berg (2000) to indicate steep areas where there were insufficient representative soil sampling points. Le Roux *et al*. (2006) found that steep slopes are normally characterised by shallow soils with high erodibility compared to deep soils. The findings in Table 5.8 suggest that very shallow (Wi = 0.6), shallow (Wi = 0.5) and medium shallow (Wi = 0.4) soils have a strong influence on gullies in tertiary catchment X12. In tertiary catchment X12, all soil depth classes except medium deep have significant influence on gullies and in addition deep (Wi = 1.2) and very deep (Wi = 0.4) soils. Deep soils have potential for crop production, which may influence land use and erodibility.

**Table 5.8: Comparison of the Information Value (InfVal) weight index (Wi) for each class of the soil depth in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Soil Depth Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Very Deep | 8500391 | 18235 | 0.00215 | 0.3 | 4632121 | 42689 | 0.00922 | 0.4 |
| Deep | 1482963 | 15 | 0.00001 | -5.1 | 123543 | 2527 | 0.02045 | 1.2 |
| Medium Deep | 4157638 | 0 | 0.00000 | - | 1078290 | 2360 | 0.00219 | -1.0 |
| Medium Shallow | 1399 | 0 | 0.00000 | - | 4562384 | 41907 | 0.00919 | 0.4 |
| Shallow | 539 | 0 | 0.00000 | - | 896248 | 8839 | 0.00986 | 0.5 |
| Very Shallow | 674014 | 124 | 0.00018 | -2.2 | 2034467 | 22129 | 0.01088 | 0.6 |
| Very Steep Slopes | 0 | 0 | - | - | 400915 | 127 | 0.00032 | -3.0 |
| Steep Slopes | 1125616 | 9305 | 0.00827 | 1.6 | 10994760 | 32811 | 0.00298 | -0.7 |
| Non-perennial pans | 32167 | 0 | 0.00000 | - | 1232 | 0 | 0.00000 | - |
| Waterbodies | 630961 | 0 | 0.00000 | - | 0 | 0 | - | - |
| **Total** | **∑NpixNi W55 = 16605688** | **∑NpixSi W55 = 27679** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24723960** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

Generally, soil forms susceptible to gully development in tertiary catchment W55 belong to three soil groups, namely, oxidic (Hu, Cv), lithosols and plinthic (Glencoe [Gc]). The oxidic soils are characterised by red or yellow-brown apedal B horizon or red structured B horizons, while lithic have lithocutanic B or hard rock and plinthic soils have soft or hard plinthic B horizon (Fey, 2009). Lithosols, Hu, Cv, Gc class has Wi = 1.1 and Hu-dominant class has Wi

= 0.5 (Table 5.9). In tertiary catchment X12, soil forms with notable influence on gullies are from the oxidic (Hu, Cv, Shortlands [Sd]), vertic (Arcadia [Ar]), duplex (Estcourt [Es], Swartland [Sw], Valsrivier [Va]), lithic (Glenrosa [Gs], Cartref [Cf]) and Melanic (Bonheim [Bo], Mayo [My]) soil groups. Vertic soils are distinguished by vertic A horizon and have a tendency to swell and shrink with changes in water content, developing deep cracks. Duplex soils have pedo- or prismacutanic B horizon and a marked increase in clay compared to the overlying horizon. Melanic soils have melanic A horizon which overlies a variety of subsurface horizons (Fey, 2009). The soil form association classes with a strong influence on gullies are Es, Gs, Cf (Wi = 1.0), Sd, Bo, My, Ar, Hu (Wi = 0.8), Hu, Sd, Sw, Gs (Wi = 0.8), Lithosols, Cv, Va (Wi = 0.6), Gs, Cf, Es (Wi = 0.1) and Hu [30%], Sd [30%] (Wi = 0.03).

**Table 5.9: Comparison of the Information Value (InfVal) weight index (Wi) for each class of the soil form association in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | | | | **Tertiary Catchment X12** |
|---|---|---|---|---|---|---|---|---|
| **Soil Form Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Es, Gs, Cf | 945 | 0 | 0.00000 | - | 1618823 | 28625 | 0.01768 | 1.0 |
| Sd, Bo, My, Ar, Hu | 0 | 0 | - | - | 298630 | 4130 | 0.01383 | 0.8 |
| Hu, Sd, Sw, Gs | 0 | 0 | - | - | 738779 | 10063 | 0.01362 | 0.8 |
| Lithosols, Cv, Va | 0 | 0 | - | - | 67148 | 777 | 0.01157 | 0.6 |
| Gs, Cf, Es | 3013 | 0 | 0.00000 | - | 3941863 | 26149 | 0.00663 | 0.1 |
| Hu (30%), Sd (30%) | 11455 | 0 | 0.00000 | - | 6398157 | 38165 | 0.00596 | 0.0 |
| Hu-dominant | 9695951 | 26103 | 0.00269 | 0.5 | 7081150 | 41038 | 0.00580 | -0.1 |
| Lithosols, Hu, Cv, Gc | 286724 | 1509 | 0.00526 | 1.1 | 799185 | 2859 | 0.00358 | -0.6 |
| Lithosols, Cv, Gc, Hu | 394481 | 12 | 0.00003 | -4.0 | 76188 | 124 | 0.00163 | -1.3 |
| Lithosols, Hu, Cv, Sd, Sw | 914 | 0 | 0.00000 | - | 2767320 | 1334 | 0.00048 | -2.6 |
| Hu, Av, Cv, Gc | 3950777 | 5 | 0.00000 | -7.2 | 800665 | 90 | 0.00011 | -4.0 |
| Ar, My, Va | 48789 | 0 | 0.00000 | - | 19093 | 15 | 0.00079 | -2.1 |
| Rg, Ar | 1032396 | 50 | 0.00005 | -3.5 | 112308 | 20 | 0.00018 | -3.6 |
| Non-perennial pans | 32167 | 0 | 0.00000 | - | 1232 | 0 | 0.00000 | - |
| Waterbodies | 630961 | 0 | 0.00000 | - | 0 | 0 | - | - |
| Av, Gc, We, Cv | 517115 | 0 | 0.00000 | - | 3419 | 0 | 0.00000 | - |
| **Total** | **∑NpixNi W55 = 16605688** | **∑NpixSi W55 = 27679** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24723960** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

### 5.4.2. The influence of topography on gully erosion

Table 5.10 illustrates the influence of slope gradient on gullies in tertiary catchments W55 and X12. Significant influence on gully was observed on strongly sloping (4.5 – 6.75°) (Wi = 0.7), moderately steep (6.75 – 13.5°) (Wi = 1.3) and steep slopes (13.5 – 27°) (Wi = 0.6) classes in tertiary catchment W55. Although gently sloping (0.9 – 2.25°) and sloping (2.25 – 4.5°) classes have numerous gullied pixels (NpixSi = 3 622 and NpixSi = 6 162 respectively), their InfVal Wi is insignificant. Significant influence on gullies of strongly sloping (Wi = 0.3) and moderately steep (Wi = 0.1) slopes was also observed in tertiary catchment X12. The strongest influence was observed on nearly level or flat (0 - 0.23°) to moderately steep slopes. The level of influence observed seems to decrease with an increase in slope gradient. For example, the highest influence (Wi = 1.2) was observed on nearly level or flat slopes, followed by very gentle sloping class (0.23 - 0.9°) (Wi = 0.9), then gently sloping (Wi = 0.5), sloping (Wi = 0.2), increasing on strongly sloping (Wi = 0.3) and dipping on a moderately steep slope (Wi = 0.1). It is also worth mentioning that a significant number of gullied pixels (NpixSi = 4 518) was observed on steep slopes yet the InfVal weight is low (Wi = -1.5).

**Table 5.10: Comparison of the Information Value (InfVal) weight index (Wi) for each class of slope gradient in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Slope Gradient Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| 0 - 0.23° | 1738915 | 443 | 0.00025 | -1.9 | 179573 | 3653 | 0.02034 | 1.2 |
| 0.23 - 0.9° | 1823276 | 736 | 0.00040 | -1.4 | 338812 | 5305 | 0.01566 | 0.9 |
| 0.9 - 2.25° | 4918041 | 3622 | 0.00074 | -0.8 | 2481182 | 26670 | 0.01075 | 0.5 |
| 2.25 - 4.5° | 4311991 | 6162 | 0.00143 | -0.2 | 6028314 | 44275 | 0.00734 | 0.2 |
| 4.5 - 6.75° | 2089047 | 6762 | 0.00324 | 0.7 | 4045964 | 33098 | 0.00818 | 0.3 |
| 6.75 - 13.5° | 1446409 | 9152 | 0.00633 | 1.3 | 5101778 | 33824 | 0.00663 | 0.1 |
| 13.5 - 27° | 215992 | 657 | 0.00304 | 0.6 | 3280283 | 4518 | 0.00138 | -1.5 |
| 27 - 45° | 65704 | 68 | 0.00103 | -0.5 | 3266980 | 2046 | 0.00063 | -2.3 |
| **Total** | **∑NpixNi W55 = 16609375** | **∑NpixSi W55 = 27602** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24722886** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

Table 5.11 shows a good correlation between tertiary catchments W55 and X12 on the strength of influence of the upslope contributing area on gully. Logarithmic scale values of the upslope contributing area were used. Class greater than seven has a very strong influence

on gullies for both tertiary catchments. This insinuates that gully erosion favours areas with relatively higher upslope pixels that flow into them as observed elsewhere (e.g. Le Roux and Sumner, 2012). Tertiary catchment W55 has a Wi = 1.3 for class greater than seven, whilst a Wi = 1.5 was observed in catchment X12. The class range 6 – 7 also has a significant influence on gullies for both tertiary catchments W55 and X12 with the Wi = 0.1 and Wi = 0.5 respectively. Although many gullies were observed in the rest of classes as shown in Table 5.11, the negative values of InfVal weight observed suggests that they do not have an influence on gullies.

**Table 5.11: Comparison of the Information Value (InfVal) weight index (Wi) for each class of the upslope contributing area in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Upslope Contributing Area Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| 2 – 4 $m^2$ | 1951617 | 1790 | 0.00092 | -0.6 | 4203894 | 20569 | 0.00489 | -0.2 |
| 4 – 5 $m^2$ | 5215718 | 6268 | 0.00120 | -0.3 | 9351568 | 32642 | 0.00349 | -0.6 |
| 5 – 6 $m^2$ | 5680682 | 7389 | 0.00130 | -0.2 | 7329291 | 37494 | 0.00512 | -0.2 |
| 6 – 7 $m^2$ | 2491693 | 4485 | 0.00180 | 0.1 | 2422123 | 25119 | 0.01037 | 0.5 |
| > 7 $m^2$ | 1268323 | 7665 | 0.00604 | 1.3 | 1413411 | 37496 | 0.02653 | 1.5 |
| **Total** | **∑NpixNi W55 = 16608033** | **∑NpixSi W55 = 27597** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24720287** | **∑NpixSi X12 = 153320** | **DensMap X12 = 0.00620** | |

Table 5.12 shows the correlation of gullies and planform curvature classes in tertiary catchments W55 and X12. The results highlight the influence of concave surfaces on gully erosion. A very strong influence of concave surface was observed in tertiary catchment W55 where Wi = 1.9 whilst in tertiary catchment X12, a strong influence of Wi = 0.7 was observed. A slightly significant influence of convex surface (Wi = 0.04) on gullies was observed in tertiary catchment W55. Notwithstanding the significant influence of convex surfaces observed, the number of gullied cells or pixels (NpixSi = 3 054) is relatively insignificant compared to the rest of classes. The number of gullied cells on a flat surface (NpixSi = 6 981) in tertiary catchment W55 as well as flat (NpixSi = 64 495) and convex (NpixSi = 21 492) surfaces in tertiary catchment X12 are very high, yet insignificant in influencing gullies based on their InfVal weight.

**Table 5.12: Comparison of the Information Value (InfVal) weight index (Wi) for each class of curvature in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Curvature Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Concave | 1648226 | 17664 | 0.01072 | 1.9 | 5612750 | 67402 | 0.01201 | 0.7 |
| Flat | 13213273 | 6981 | 0.00053 | -1.1 | 12357986 | 64495 | 0.00522 | -0.2 |
| Convex | 1750026 | 3054 | 0.00175 | 0.0 | 6755408 | 21492 | 0.00318 | -0.7 |
| **Total** | **∑NpixNi W55 = 16611525** | **∑NpixSi W55 = 27699** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24726144** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

Table 5.13 shows the correlation between gullies and the Topographic Wetness Index (TWI) values for both tertiary catchments W55 and X12. For tertiary catchment W55, all but class 8 – 10 have significant influence on gullies. The strongest influence was observed in class 4 – 6 (Wi = 0.4), followed by class 2 – 4 (Wi = 0.3), class 10 – 26.8 (Wi – 0.2) and class 6 – 8 (Wi = 0.1). Although class 2 – 4 has a strong influence on gullies, it is important to note that it has the lowest number of pixels affected by gullies (NpixSi = 35) and thus the strength level of weight is influenced by the total pixel sizes of the class (NpixNi = 15 988). In tertiary catchment X12, the significant influence on gullies was observed on the two classes with highest TWI values. The highest Wi = 1.6 was observed in class 10 – 26.8 whilst class 8 – 10 has Wi = 0.4. The lowest influence on gullies Wi = -2.0 was observed in the lower most class 2 – 4.

**Table 5.13: Comparison of the Information Value (InfVal) weight index (Wi) for each class of Topographic Wetness Index (TWI) in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **TWI Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| 2 - 4 | 15988 | 35 | 0.00219 | 0.3 | 309631 | 269 | 0.00087 | -2.0 |
| 4 - 6 | 943432 | 2310 | 0.00245 | 0.4 | 7220615 | 18927 | 0.00262 | -0.9 |
| 6 - 8 | 6347943 | 11810 | 0.00186 | 0.1 | 11352447 | 57145 | 0.00503 | -0.2 |
| 8 - 10 | 6540225 | 7588 | 0.00116 | -0.4 | 4773785 | 45092 | 0.00945 | 0.4 |
| 10 - 26.8 | 2760075 | 5853 | 0.00212 | 0.2 | 1063126 | 31868 | 0.02998 | 1.6 |
| **Total** | **∑NpixNi W55 = 16607663** | **∑NpixSi W55 = 27596** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24719604** | **∑NpixSi X12 = 153301** | **DensMap X12 = 0.00620** | |

Table 5.14 emphasises a very strong influence of higher SPI values on gully erosion in tertiary catchments W55 and X12. The highest InfVal weight values were observed in class 6 – 8 in both tertiary catchments W55 (Wi = 2.6) and X12 (Wi = 1.4) followed by the upper most class (8 – 14) where a Wi = 2.1 and 1.0 were observed respectively for each tertiary catchment. Class 4 – 6 in tertiary catchment W55 also has a very strong influence on gullies where a Wi = 1.4 was observed. In tertiary catchment X12, class 4 – 6 has a Wi = 0.3. In tertiary catchment X12, a high strength was also observed in the two lowermost classes < 0 (Wi = 0.4) and 0 – 2 (Wi = 0.1). The only class with a low influence on gullies in tertiary catchment X12 is 2 – 4 (Wi = -0.3).

**Table 5.14: Comparison of the Information Value (InfVal) weight index (Wi) for each class of Stream Power Index (SPI) in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **SPI Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| < 0 | 1216262 | 241 | 0.00020 | -2.1 | 448158 | 4018 | 0.00897 | 0.4 |
| 0 to 2 | 5896768 | 2644 | 0.00045 | -1.3 | 4162947 | 27293 | 0.00656 | 0.1 |
| 2 to 4 | 8150519 | 12902 | 0.00158 | 0.0 | 14855935 | 67594 | 0.00455 | -0.3 |
| 4 to 6 | 1128594 | 7558 | 0.00670 | 1.4 | 4521757 | 36999 | 0.00818 | 0.3 |
| 6 to 8 | 170324 | 3665 | 0.02152 | 2.6 | 546340 | 14164 | 0.02593 | 1.4 |
| 8 to 14 | 45196 | 586 | 0.01297 | 2.1 | 184467 | 3233 | 0.01753 | 1.0 |
| **Total** | **∑NpixNi W55 = 16607663** | **∑NpixSi W55 = 27596** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24719604** | **∑NpixSi X12 = 153301** | **DensMap X12 = 0.00620** | |

### 5.4.3. The influence of geology on gully erosion

In tertiary catchment W55, the InfVal statistics show a significant relationship (Wi = 0.7) between gullies and the intrusive rocks of Randian age (Rb, Rpg & Rtg) (see Groenewald and Groenewald, 2014) wherein the majority of gullied pixels occur (NpixSi = 27 411). The mentioned intrusive rocks also have numerous pixels affected by gullies (NpixSi = 17 198) in tertiary catchment X12, but the InfVal weight of -0.9 suggests they do not have significant influence on gullies. Numerous geology classes in tertiary catchment X12 show a strong influence on gully erosion, such as the Komati formation (Zk) (Wi = 1.3), the Vaalian Diabase intrusive rock (Vdi) (Wi = 1.1), caenozoic superficial deposits comprising the alluvial and colluvial (Q) (Wi = 1.0), the Sandspruit formation (Zts) (Wi = 0.9), Swazian age intrusive rocks (Zmg, Zg, Zu, Zs & Zd) (Wi = 0.8), Theespruit formation (Zt) (Wi = 0.7), Hooggenoeg formation (Zh) (Wi = 0.3) and Ztk (Wi = 0.1).

**Table 5.15: Comparison of the Information Value (InfVal) weight index (Wi) for each class of geology in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Geology Class** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Jd | 1656226 | 129 | 0.00008 | -3.1 | 126266 | 5 | 0.00004 | -5.1 |
| Pv | 6080503 | 20 | 0.00000 | -6.2 | 1002780 | 116 | 0.00012 | -4.0 |
| Q | 332671 | 39 | 0.00012 | -2.7 | 280955 | 5056 | 0.01800 | 1.1 |
| Rb, Rpg & Rtg, | 8517967 | 27411 | 0.00322 | 0.7 | 6727588 | 17198 | 0.00256 | -0.9 |
| Vb | 0 | 0 | - | - | 21147 | 3 | 0.00014 | -3.8 |
| Vbr | 0 | 0 | - | - | 95858 | 144 | 0.00150 | -1.4 |
| Vdi | 0 | 0 | - | - | 100268 | 1962 | 0.01957 | 1.1 |
| Vdw | 0 | 0 | - | - | 19985 | 21 | 0.00105 | -1.8 |
| Vh | 0 | 0 | - | - | 12186 | 0 | 0.00000 | - |
| Vha | 0 | 0 | - | - | 328733 | 731 | 0.00222 | -1.0 |
| Vm | 0 | 0 | - | - | 335076 | 200 | 0.00060 | -2.3 |
| Vr | 0 | 0 | - | - | 67608 | 6 | 0.00009 | -4.2 |
| Vs | 0 | 0 | - | - | 12199 | 8 | 0.00066 | -2.2 |
| Vt | 0 | 0 | - | - | 1010525 | 366 | 0.00036 | -2.8 |
| Za | 13901 | 0 | 0.00000 | - | 179902 | 406 | 0.00226 | -1.0 |
| Zb | 0 | 0 | - | - | 24014 | 0 | 0.00000 | - |
| Zf | 0 | 0 | - | - | 896255 | 965 | 0.00108 | -1.8 |
| Zfh | 0 | 0 | - | - | 29469 | 0 | 0.00000 | - |
| Zfs | 0 | 0 | - | - | 24003 | 0 | 0.00000 | - |
| Zmg, Zg, Zu, Zs & Zd | 0 | 0 | - | - | 6366450 | 84131 | 0.01321 | 0.8 |
| Zgh | 0 | 0 | - | - | 1305612 | 1897 | 0.00145 | -1.5 |
| Zgk | 0 | 0 | - | - | 1546988 | 962 | 0.00062 | -2.3 |
| Zh | 0 | 0 | - | - | 1026175 | 8330 | 0.00812 | 0.3 |
| Zj | 0 | 0 | - | - | 293 | 0 | 0.00000 | - |
| Zk | 0 | 0 | - | - | 257563 | 5857 | 0.02274 | 1.3 |
| Zm | 0 | 0 | - | - | 219651 | 33 | 0.00015 | -3.7 |
| Zmb | 0 | 0 | - | - | 2062 | 0 | 0.00000 | - |
| Zmc | 0 | 0 | - | - | 298266 | 364 | 0.00122 | -1.6 |
| Zt | 0 | 0 | - | - | 1342528 | 17315 | 0.01290 | 0.7 |
| Ztk | 0 | 0 | - | - | 343010 | 2452 | 0.00715 | 0.1 |
| Zts | 0 | 0 | - | - | 286256 | 4435 | 0.01549 | 0.9 |
| Ztt | 0 | 0 | - | - | 278078 | 362 | 0.00130 | -1.6 |
| Zz | 0 | 0 | - | - | 161458 | 207 | 0.00128 | -1.6 |
| Pd | 12416 | 0 | 0.00000 | - | 0 | 0 | - | - |
| **Total** | **∑NpixNi W55 = 16613684** | **∑NpixSi W55 = 27599** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24729207** | **∑NpixSi X12 = 153532** | **DensMap X12 = 0.00621** | |

### 5.4.4. The influence of rainfall erosivity on gully erosion

Table 5.16 illustrates the correlation between gullies and rainfall erosivity (MJ.mm/ha.hr.yr) classes in tertiary catchments W55 and X12. In tertiary catchment W55, there are three class distributions ranging from 3 000 to 4 500. Significant influence on gully erosion was observed in class 4 000 – 4 500 (Wi = 0.8) and class 3 500 – 4 000 (Wi = 0.6). The lower most class 3 000 – 3 500 (Wi = -2.1) has a low influence on gullies. In contrast with tertiary catchment W55, erosivity values range from 2 922 to 6 000 in tertiary catchment X12. A strong influence was observed on classes with low rainfall erosivity values, in sharp contrast with the expectation since higher rainfall erosivity values in this region are associated with heavy rainfall and very high daily rainfall totals (see Le Roux *et al.*, 2006). The highest weight (0.6) was observed on the lower most class (2 922 – 3 000), followed by class 3 000 – 3 500 (Wi = 0.2), then class 3 500 – 4 000 (Wi = 0.11) and class 4 000 – 4 500 (Wi = 0.06). The two upper classes (5 000 – 5 500 and 5 500 – 6 000) have a significantly low influence on gully erosion where Wi = -1.9 and -1.6 were observed respectively.

**Table 5.16: Comparison of the Information Value (InfVal) weight index (Wi) for each rainfall erosivity (MJ.mm/ha.hr.yr) class in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Erosivity Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| 2922 - 3000 | 0 | 0 | - | - | 145370 | 1651 | 0.01136 | 0.6 |
| 3000 - 3500 | 8273432 | 1618 | 0.00020 | -2.1 | 4392025 | 34778 | 0.00792 | 0.2 |
| 3500 - 4000 | 5713565 | 16797 | 0.00294 | 0.6 | 10742083 | 74926 | 0.00697 | 0.1 |
| 4000 - 4500 | 2560079 | 9268 | 0.00362 | 0.8 | 4885857 | 32129 | 0.00658 | 0.1 |
| 4500 - 5000 | 0 | 0 | - | - | 2469132 | 7760 | 0.00314 | -0.7 |
| 5000 - 5500 | 0 | 0 | - | - | 1399639 | 1292 | 0.00092 | -1.9 |
| 5500 - 6000 | 0 | 0 | - | - | 624360 | 815 | 0.00131 | -1.6 |
| **Total** | **∑NpixNi W55 = 16547076** | **∑NpixSi W55 = 27683** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24658466** | **∑NpixSi X12 = 153351** | **DensMap X12 = 0.00622** | |

### 5.4.5. The influence of vegetation on gully erosion

Table 5.17 shows the correlation between gullies and vegetation types in tertiary catchment W55 and X12. In tertiary catchment W55, there is little variation in vegetation classes and only three classes occur. The majority of gullied pixels affect KaNgwane Montane grassland (NpixSi = 27 400), which is in accordance with the significant InfVal weight (Wi = 0.6). The rest of gullied pixels affect the Eastern Highveld grassland (NpixSi = 199) but the InfVal weight is very low (Wi = -4.1). In contrast, a wide variety of vegetation types were observed in tertiary catchment X12. Significant influence on gully erosion was observed in Barberton serpentine sourveld (Wi = 1.1) and Swaziland sour bushveld (Wi = 0.7) vegetation. Although numerous gullied pixels were observed in KaNgwane Montane grassland (NpixSi = 70 652) the weight of -0.2 shows a lack of influences on gully erosion.

**Table 5.17: Comparison of the Information Value (InfVal) weight index (Wi) for each vegetation type in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **Vegetation Types** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Eastern Highveld Grassland | 7511013 | 199 | 0.00003 | -4.1 | 421349 | 44 | 0.00010 | -4.1 |
| KaNgwane Montane Grassland | 8635511 | 27400 | 0.00317 | 0.6 | 14474252 | 70652 | 0.00488 | -0.2 |
| Swaziland Sour Bushveld | 0 | 0 | - | - | 6201798 | 76779 | 0.01238 | 0.7 |
| Barberton Serpentine Sourveld | 0 | 0 | - | - | 191358 | 3657 | 0.01911 | 1.1 |
| Barberton Montane Grassland | 0 | 0 | - | - | 3368839 | 2400 | 0.00071 | -2.2 |
| Eastern Temperate Freshwater Wetlands | 467777 | 0 | 0.00000 | - | 0 | 0 | - | - |
| Northern Mistbelt Forest | 0 | 0 | - | - | 73044 | 0 | 0.00000 | - |
| **Total** | **∑NpixNi W55 = 16614301** | **∑NpixSi W55 = 27599** | **DensMap W55 = 0.00166** | | **∑NpixNi X12 = 24730640** | **∑NpixSi X12 = 153532** | **DensMap X12 = 0.00622** | |

Table 5.18 shows the correlations between gullies and Normalised Difference Vegetation Index (NDVI) classes in tertiary catchments W55 and X12. Results show a good correlation between tertiary catchments W55 and X12 on the strength of influence of the NDVI on gullies. The highest weight of 0.7 and 0.6 values were observed in the moderate NDVI

classes for both tertiary catchments W55 and X12 respectively. Moderate to high NDVI class also shows a significant effect on gully erosion in both tertiary catchments W55 and X12, where a weight of 0.01 and 0.1 were observed respectively. High NDVI class in both tertiary catchments has a low influence on gully erosion.

**Table 5.18: Comparison of the Information Value (InfVal) weight index (Wi) for each Normalised Difference Vegetation Index (NDVI) class in tertiary catchments W55 and X12**

| | **Tertiary Catchment W55** | | | | **Tertiary Catchment X12** | | | |
|---|---|---|---|---|---|---|---|---|
| **NDVI Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Moderate | 2074261 | 6831 | 0.00329 | 0.7 | 4450398 | 48445 | 0.01089 | 0.6 |
| Moderate to High | 8329174 | 13524 | 0.00162 | 0.0 | 13648083 | 97015 | 0.00711 | 0.1 |
| High | 6057054 | 6070 | 0.00100 | -0.5 | 6488793 | 6423 | 0.00099 | -1.8 |
| Low to Moderate | 13680 | 0 | 0.00000 | - | 0 | 0 | - | - |
| **Total** | **∑NpixNi W55 = 16474169** | **∑NpixSi W55 = 26425** | **DensMap W55 = 0.00160** | | **∑NpixNi X12 = 24587274** | **∑NpixSi X12 = 151883** | **DensMap X12 = 0.00618** | |

### 5.4.6. The influence of land use or land cover on gully erosion

Table 5.19 shows the correlations between gullies and land cover/ land use classes in tertiary catchments W55 and X12. The high weight values of 5.6 and 3.8 on degraded – erosion class in tertiary catchments W55 and X12 respectively, indicates the strong correlation of the current gully location map with the Mararakanye and Le Roux (2012) map. The degraded – erosion class in the land cover map utilised here was compiled using Mararakanye and Le Roux (2012) dataset. Apart from degraded – erosion class, the influence of land cover and land use varies between tertiary catchments W55 and X12. A wide variety of classes in tertiary catchment W55 have a significant effect on gully erosion. A very strong influence was particularly observed in degraded grassland (Wi = 1.7) and Bare rock and soil (Wi = 1.1). Thicket and bushland (Wi = 0.5) as well as indigenous forests (Wi = 0.2) also have a significant effect on gullies. In tertiary catchment X12, a strong influence on gully erosion was observed on cultivated land (Wi = 0.2).

**Table 5.19: Comparison of the Information Value (InfVal) weight index (Wi) for each land cover class in tertiary catchments W55 and X12**

| | Tertiary Catchment W55 | | | | Tertiary Catchment X12 | | | |
|---|---|---|---|---|---|---|---|---|
| **Land Cover Classes** | **NpixNi W55** | **NpixSi W55** | **DensClass W55** | **Wi W55** | **NpixNi X12** | **NpixSi X12** | **DensClass X12** | **Wi X12** |
| Indigenous Forests | 3854 | 8 | 0.00208 | 0.2 | 99223 | 4 | 0.00004 | -5.0 |
| Thicket & Bushland | 119717 | 341 | 0.00285 | 0.5 | 2710957 | 3383 | 0.00125 | -1.6 |
| Grassland | 8977987 | 14694 | 0.00164 | -0.0 | 15058893 | 59187 | 0.00393 | -0.5 |
| Forest Plantations | 4289325 | 2602 | 0.00061 | -1.0 | 4167962 | 1659 | 0.00040 | -2.7 |
| Dams / Lakes | 605299 | 0 | 0.00000 | - | 14020 | 42 | 0.00300 | -0.7 |
| Bare Rock & Soil | 112571 | 564 | 0.00501 | 1.1 | 165206 | 268 | 0.00162 | -1.3 |
| Degraded: Grassland | 176795 | 1626 | 0.00920 | 1.7 | 644250 | 3766 | 0.00585 | -0.1 |
| Cultivated Land | 2094406 | 2871 | 0.00137 | -0.2 | 1252405 | 9865 | 0.00788 | 0.2 |
| Degraded: Erosion | 10562 | 4680 | 0.44310 | 5.6 | 264498 | 74752 | 0.28262 | 3.8 |
| Urban | 206166 | 313 | 0.00152 | -0.1 | 348730 | 463 | 0.00133 | -1.5 |
| Wetland | 14812 | 0 | 0.00000 | - | 0 | 0 | - | - |
| **Total** | **∑NpixNi W55 = 16611494** | **∑NpixSi W55 = 27699** | **DensMap W55 = 0.00167** | | **∑NpixNi X12 = 24726144** | **∑NpixSi X12 = 153389** | **DensMap X12 = 0.00620** | |

## 5.5. Summary

The key findings of this study are that gully densities vary with catchments due to the interaction of different factors. A consistency was observed on the influence of the upslope contributing area and NDVI for tertiary catchments X12 and W55. The main reasons for these variations and consistency observed are explained in the next Chapter. Historical land use activities that could be linked to gully erosion include cultivation, land abandonment and expansion of residential settlement. The role of historical land use on gully erosion is also discussed in the next Chapter.

# CHAPTER 6: DISCUSSION

From the findings presented in Chapter 5, several discussion points emerged. The attempt is made to draw a comparison of each major finding with previous observations as a point of departure. First, gully density appears to be high compared to previous study by Mararakanye and Le Roux (2012). Second, a change in historical land use was found to be correlated with gully expansion and initiation. Last, several contributing factors were dominant in influencing gully development in both tertiary catchments X12 and W55. In this discussion, reasons for the strong influence of certain variables on gully erosion are explained.

## 6.1. Gully location mapping

The potential for generating a high accuracy gully location map with the use of high resolution (0.5m) aerial photographs was demonstrated in this study. Although no quantitative comparison was made, visual observation shows that the density of gullies produced by Mararakanye and Le Roux (2012) in both tertiary catchments X12 and W55 is less than the current gully density map. The effect of spatial resolution between the aerial photographs and the SPOT 5 imageries utilised by Mararakanye and Le Roux (2012) is evident. The 0.5m spatial resolution of the aerial photographs potentially enables the detection of gully erosion features as small as 1m, compared to a minimum of 10m detectable using merged bands of SPOT 5 imageries at 5m spatial resolution (Tobler, 1988) previously utilised by Mararakanye and Le Roux (2012). Detection of smaller discontinuous gullies becomes a challenge when the feature is less than or equal to the spatial resolution of the imagery. In most cases, even a feature twice the spatial resolution of the imagery is difficult to discern or interpret as a gully. In this study, the smallest gully observed is 4m$^2$ with length and width of approximately 5m and 1m respectively. It is highly likely that in the study area there are gullies smaller than 4m$^2$ or 5m length, however, they could not be easily interpreted as gullies. For example, field observation described in Chapter 4 shows that three small gullies less than a metre width were not discernible from aerial photographs. The detectability of smaller gullies is not only an issue of visual interpretation. According to Taruvinga (2008) semi-automatic extraction of smaller gullies using the pixel based approach is made difficult when gullies are imbedded in a spectrally mixed pixel that has non gully areas.

The mapped gully erosion features included both the active and stabilised gully systems. It was observed during field surveys and from aerial photographs that some of the large gully systems (continuous gullies) in both catchments are overgrown with vegetation particularly on the gully floor. Field observation shows the occasional presence of Black Wattle invasive trees on gully floors. The observed gully systems are stabilising and may not necessarily contribute to large sediment yields in the Komati and Usutu River catchments, but they remain a cause of concerns to both land users and decision makers since they may be rejuvenated by poor land management (see Alt *et al*., 2009; Frankl, 2012). Continuous gully systems still cause impediment of access to land and remain the potential source of sediment due to their actively eroding sidewalls. Small discontinuous gullies that fade before reaching the main continuous gully systems (see Le Roux and Sumner, 2012) were also observed from the field and aerial photographs. Discontinuous gullies occur within the vicinity of large gully systems, are generally active and have a distinct head, as well as low vegetation cover, particularly of grass species.

Variation in the spatial distribution of gullies is most probably caused by the difference in the distributions of contributing biophysical and land use factors. The main factors contributing to the difference in gully density between tertiary catchments W55 and X12 are discussed in section 6.3. It was most notable that large areas of low or no gullies in tertiary catchment W55 are characterised by level to nearly level slopes, higher upslope contributing area values and high topographic wetness index values near wetlands and pans.

## 6.2. Historical land use and gully dynamics

Historical aerial photograph evidence shows that gully erosion is not a recent phenomenon. It can be proclaimed with confidence that the two main gully systems selected in this study for further observation and correlation with historical land use existed prior 1936 and 1955 in tertiary catchments X12 and W55 respectively, but the formation or initiation dates remain unresolved. Previous historical evidence analysis in SA associated gullies with overstocking and overgrazing by the European settlers during the 19th century (e.g. Boardman *et al*., 2003; Keay-Bright and Boardman, 2006; Foster *et al*., 2012) but these studies were concerned with degradation in the Karoo region. The European settlement in SA started gradually in the Western Cape province during the 15th century, spreading towards the north during the early 19th century and eventually reaching the former Transvaal region (currently Gauteng, Mpumalanga, North West and Limpopo provinces) during the middle 19th century (De

Villiers, 1896). Literature evidence of the late 19th centuries shows that the farming community in the former Transvaal region, which includes the study area was small and dominated by tobacco, vines, fruits, vegetables, coffee, sugarcane, cotton and livestock breeding in patches. According to De Villiers (1896) the area under cultivation in the whole Transvaal region was estimated at 202km$^2$ consisting of approximately 30 000 farms of which about 16 000 were privately owned. The population of Transvaal region in the mid 19th century was estimated at 489 276 with a black majority estimated to be 370 148 (De Villiers, 1896). Whether the European settlers or the original inhabitants were responsible for the initiation of gullies in and around the study area is not clear here. A previous study in the Eastern Transvaal region attributed soil erosion to the original inhabitants' improper cultivation methods (Walters, 1940). Walters (1940) regards grazing, old roads, footpaths and diversion of canals as the main contributor to gully incision in the Transvaal region.

While the above explanation is inconclusive in relating gully initiation to the activities of the European settlers or the original inhabitants, studying discontinuous gullies provides further insight. In tertiary catchment X12, the number of gullies in and around the selected gully system increased from 22, 27 to 41 in 1936, 1962 and 1984 aerial photographs respectively. During that time, 10% of the area was under cultivation (1936), 6% was abandoned in 1962 and cultivation significantly increased to 24% in 1984 and later abandoned by 2010. It was observed that cultivation accelerated and initiated gullies in and around the selected gully system in tertiary catchment X12. Figure 6.1 illustrates the initiation of gully associated with cultivation. It was observed that in 1936 (Figure 6.1: A) and 1962 (Figure 6.1: B) the land was not cultivated and there was no sign of gully erosion. In 1984 (Figure 6.1: C), a gully along the edge of cultivated field emerged and is also discernible in 2010 (Figure 6.1: D) after the field was abandoned. The majority of cultivated land in tertiary catchment X12 was abandoned significantly in 1962 and 2010, most probably due to the occurrence of high rates of soil erosion. The correlation between land abandonment and gullies was observed elsewhere in SA by Kakembo and Rowntree (2003), but the underlying reasons for land abandonment there could not be ascertained. In and around the selected gully system in tertiary catchment W55, a greater number of gullies were non-existent in 1950, occurring gradually in 1977 and 1979. A greater number of gullies occurred between the period 1979 and 2010. Once again, cultivation and land abandonment were the major activities during the study period. Remarkably, the majority of cultivation (17%) and residential settlement (24%) was observed in the 2010 aerial photographs, coinciding with the increase in the number of gullies. It is thus highly likely that cultivation played a telling role in the initiation and acceleration of gullies in the study area.

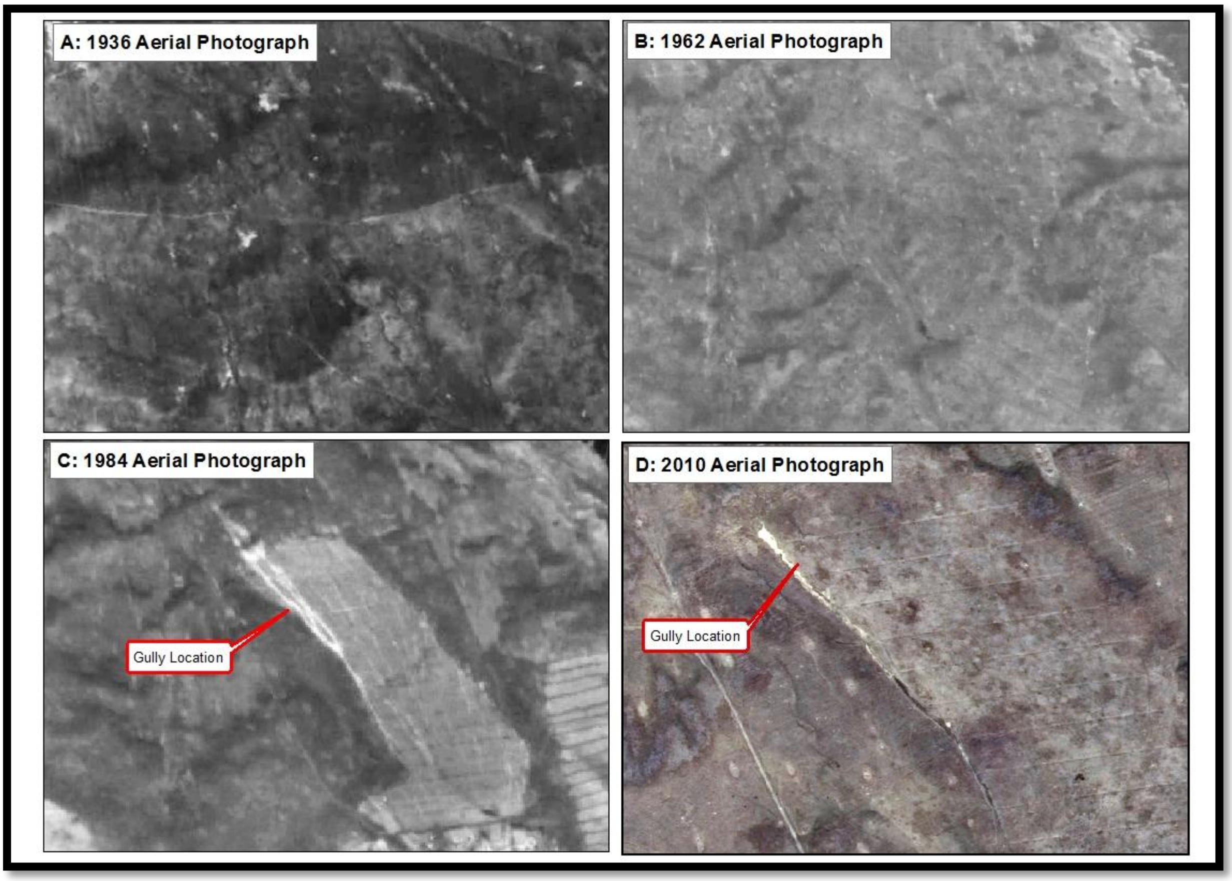

**Figure 6.1: An example of gully initiation associated with the cultivation of land around the selected gully system in tertiary catchment X12**

## 6.3. Dominant factors contributing to gully erosion

### 6.3.1. The contribution of geology and soil

Geology and soil are interrelated and their contributions to gully erosion are discussed simultaneously. First, the results in tertiary catchment W55 highlight the strong influence of the Randian age granitic intrusive igneous rock on gully erosion (Wi = 0.7). Gullied pixels (NpixSi = 17 198) on the mentioned rock in tertiary catchment X12 could also not be ignored though the weight of -0.9 suggests the low influence on gullies. To confirm that these findings are not coincidence, other granitic rocks of the Swazian age have a strong influence (Wi = 0.8) on gully erosion in tertiary catchment X12. Other studies consider all forms of igneous rocks such as the granite, dolerite, basalt and pyroclastic as resistant to erosion or less erodible (e.g. Huggett, 2007; Vetter, 2007) but the observation made here differs. The reason granitic rocks significantly influence gullies in this study is that, soils developed there are dispersive and easily lose aggregation (Elges, 1985). According to Elges (1985), soils developed from the granite rocks are prone to high sodium, especially in low lying areas and where rainfall is such that seepage water has high SAR. Sodium is the most dispersive cation in soils as proclaimed by Laker (2004).

Dispersive soils are highly favourable to the development of gullies particularly through tunnel erosion (Rienks *et al*., 2000). Dispersion normally occurs on any soil with high ESP including sand (Elges, 1985). In this study, the loam soils within the low lying Swazian age granite rocks in tertiary catchment X12 appear to be the preferred zone for gully development. Loam soils spatially correlate with the association of lithic and duplex soil forms (Gs, Cf, Es) also with significant influence (Wi = 0.1) on gully location and additionally the medium shallow soils that strongly influence gullies (Wi = 0.4). Although no soil chemical analysis was undertaken, it is postulated that these loam soils contain high exchangeable sodium content compared to similar soils observed in high lying areas in tertiary catchment X12. The Randian age igneous rocks within both tertiary catchments X12 and W55 have deep, sandy to very sandy Hu-dominant soil affected by gullies. Sandy soils are highly erodible due to collapsible grain structure (e.g. Hu and Cv soil forms), are characterised by red to yellow apedal pattern (includes the dystrophic and mesotrophic soils) and are usually deep to very deep (Turner, 2000; Paige-Green and Turner, 2008).

The preferential development of gullies on volcanic ultramafic igneous rocks in tertiary catchment X12 was observed as the most distinguishing factor explaining the variation of the gully distribution with tertiary catchment W55. Some of the examples of the ultramafic volcanic rocks include the komatiites, komatiitic basalts and basalts (see Hofmann and Harris, 2008). A significant influence on gullies in tertiary catchment X12 occurs in ultramafic rocks such as the Komatiite rock of the Komati formation (Wi = 1.3), mafic-ultramafic schists of the Sandspruit formation (Wi = 0.9), basalt rock of the Theespruit formation (Wi = 0.7), Hooggenoeg (Wi = 0.3) formations and the basalt equivalent Diabase rock (Wi = 1.15). An ultramafic igneous rock is the common parent material for vertic soils in SA (Bühmann and Schoeman, 1995) but is absent in tertiary catchment W55. McCallum (2006) observed dark coloured soils with greater proportions of silt and clay developed from the Swaziland ultramafic rocks, typical of vertisols. Vertic soils are identified by cracking and swelling associated with high smectite minerals (Bühmann and Schoeman, 1995; Igwe, 2012). As a result, vertic soils are expansive (Bühmann and Schoeman, 1995; Department of Public Works, 2007) and promote gully erosion when water passes through the cracks and saturates the subsoil horizon, moving soil particles laterally as seepage causing subsurface channels (Henkel *et al*., 1938; Beckedahl, 1977; Beckedahl, 1996) as discussed in Chapter 2. In the current study, the preferential development of gullies on clay soils (Wi = 1.5) with probably high smectite due to associated underlying geology reaffirms the erodibility of vertic soils.

Gullies in tertiary catchment X12 are influenced by the alluvial and colluvial caenozoic superficial deposits (Q) (Wi = 1.1), but these have low influence on gully erosion in tertiary catchment W55 (Wi = -2.7). The stability of the alluvial and colluvial deposits in tertiary catchment W55 could probably be influenced by the effect of other factors. For example, observation shows that these Quarternary sediments in tertiary catchment W55 are located in the privately owned land compared to their location in the communal land in tertiary catchment X12. Le Roux and Sumner (2012) found relatively low proportions of gullies in unconsolidated alluvium materials and attributed this to good vegetation cover. Therefore, poor vegetation cover due to communal land use system in tertiary catchment X12 could be the overriding factor. Elsewhere, gully erosion development is widely reported to favour the alluvial or colluvial deposits (e.g. Botha *et al*., 1994; Rienks *et al*., 2000). Rienks *et al*. (2000) found that the loose unconsolidated or slightly cemented colluvium materials in northern KwaZulu Natal are characterised by deep erodible duplex soils. In the current study, the duplex Swartland soil amongst other soil forms occurs within the alluvial or colluvial deposits in tertiary catchment X12 which additionally serves to illustrate the dominance of gullies in these deposits.

### 6.3.2. The contribution of topography

The preferential development of gullies on strongly sloping (4.5 – 6.75°), moderately steep (6.75 – 13.5°) and steep slopes (13.5 – 27°) in tertiary catchment W55 is highlighted. For tertiary catchment X12, significant influence on gullies was observed on slope gradient ranging from nearly level/flat (0 – 0.23°) to moderately steep slopes. Studies in SA mainly observed significant proportions of gullies on lower slope gradients (e.g. Kakembo *et al*., 2009; Le Roux and Sumner, 2012). Specifically, Kakembo *et al*. (2009) observed a greater proportion of gullies on slope gradients 5 – 9° followed by 10 – 14° and 0 – 4°. The dominance of gullies on slope gradients less than 10° was confirmed by Le Roux and Sumner (2012). The reason gentle slopes and lower slopes are vulnerable to gully erosion is that they experience greater runoff sufficient to cause the incision due to an increase in critical drainage area (Poesen *et al*., 2003). For upper or steep slopes, the opposite is true, however, tertiary catchment W55 shows significant influence of steep slopes (Wi = 0.6) on gully erosion. This observation is not surprising since several studies elsewhere in the world observed a strong influence of steep slopes on gully erosion (e.g. Valentin *et al*., 2005; Kheir *et al*., 2007; Conforti *et al*., 2011). According to Valentin *et al.* (2005), steep slopes can produce greater runoff than gentle slopes given climatic conditions and surface crusting rate. Furthermore, steep slopes are associated with the development of highly erodible shallow soils (Le Roux *et al*., 2006). However, slope gradient alone is not sufficient to explain the influence of topographic factor on gullies. Several studies used a combination of slope and critical drainage area/ upslope contributing area to determine the critical topographic threshold for the initiation of gullies (e.g. Morgan and Mngomezulu, 2003; Vanwalleghem *et al*., 2005) and found that steep slopes with shorter contributing area are largely affected by gullies.

Previous studies consider upslope contributing area as the major factor affecting the rate of surface runoff and thus gully erosion development (e.g. Mathis, 2007; Le Roux and Sumner, 2012). Similar to Le Roux and Sumner (2012), the preferential development of gullies on higher upslope contributing areas is confirmed here. The results for both tertiary catchments W55 and X12 show a similar trend where the highest class >7 possesses the strongest influence on gully erosion (Wi = 1.3 and 1.5 respectively). A significant influence of class 6 – 7 on gully erosion also highlights the favourability of gullies on areas where water flow concentrates such as linear landscape (Mathis, 2007). Areas of concentrated flow are highly affected since gullies are linear erosion features occurring mainly along drainage lines (e.g. Stocking and Murnaghan, 2000; Vanwalleghem *et al*., 2005; Hancock and Evans, 2006). A high upslope contributing area promotes gully erosion due to an increase in runoff generation as stated above.

Similar to findings by Kakembo *et al.* (2009), the preferential development of gullies on concave planform curvature is evident in this study. Findings elsewhere in the world also show that gullies commonly develop on concave surface than convex surface (Meyer and Martınez-Casasnovas, 1999; Conforti *et al*., 2011). The concave and convex planform curvatures are associated with flow convergence and divergence respectively, and thus erosion patterns. Preferential development of gullies on concave planform curvature is an indication that convergence flow promotes greater gully erosion than convex and flat areas since it is associated with linear landscape elements. Mathis (2007) showed that concave surfaces cause the upslope contributing area to increase downslope, and the opposite is true for convex surface. In this study, concave surfaces are correlated visually with the higher upslope contributing area, and *vice versa* with convex surface. The observation of a significant influence of convex planform curvature on gully erosion is coincidental and other factors may have played a significant role.

The relationship between gullies and the Topographic Wetness Index (TWI) could not be established in tertiary catchment W55 since all classes except for class 8 – 10 show a significant influence on gully erosion. Other factors could have played a bigger role in neutralising the effect of TWI. The TWI values represent zones of saturation that correlate with the distribution of surface soil water where high values correspond with high soil moisture content (Kheir *et al*., 2007). In contrast, a strong influence on gully erosion was observed on higher TWI classes, namely 8 – 10 (Wi = 0.4) and 10 – 26.8 (Wi = 1.6). The results in tertiary catchment X12 show a positive linear trend where an increase in TWI values was associated with an increase in the greater strength of influence. The influence of higher TWI values on gully erosion was observed elsewhere (e.g. Kheir *et al*., 2007; Conforti *et al*., 2011; Le Roux and Sumner, 2012). The higher TWI values are mostly observed in valley floors, terraced surfaces and gentle slopes (Conforti *et al*., 2011). The preferential development of gullies in the zones of saturation is influenced by the inability of the soil to hold together when wet. As the soils are detached by overland flow from the bed and walls of channels, gullies are widened and deepened (Kheir *et al*., 2007). In this study, observation of the high TWI values shows that they constitute an area where upslope contributing area is high and where the slope gradient is less than 8.5°.

Previous studies observed greater proportions of gullies on classes with high Stream Power Index (SPI) values (e.g. Kakembo *et al*., 2009; Conforti *et al*., 2011). High SPI values indicate potential energy available to entrain sediments and thus greater potential for erosion (Kakembo *et al*., 2009). Here, the influence of SPI on gully erosion is strongest on classes with high values in both tertiary catchments. This is despite the observation of strong influence on lower SPI values in tertiary catchment X12. Le Roux and Sumner (2012) claim that the slope limits the impact of upslope contributing area when calculating the sediment transport capacity index (equivalent to SPI), which is why lower SPI also have a strong influence on gullies.

### 6.3.3. The contribution of rainfall erosivity

The influence of rainfall erosivity on gully erosion in tertiary catchments W55 and X12 varies. For tertiary catchment W55, a strong influence is observed on classes with relatively higher erosivity values. The opposite is true in tertiary catchment X12 where lower erosivity values have a greater influence on gullies. One would normally expect a significant contribution of higher rainfall erosivity values to gully erosion since these values are associated with heavy rainfall and very high daily, monthly and annual rainfall totals (see Le Roux *et al*., 2006). Higher rainfall erosivity in tertiary catchment X12 occurs along the mountain ranges, east of the catchment where the slopes are steep to very steep. The mountainous areas receive higher mean annual rainfall (see Schulze, 2010) as is the case in the study area. As already stated in the earlier section, gully erosion development in SA conditions favour gentle sloping to flat slopes with very deep soils as opposed to mountainous steep slopes with shallow soils (Kakembo *et al*., 2009; Le Roux and Sumner, 2012). The highest density of gullies in regions with relatively lower mean annual rainfall was previously observed by Liggitt and Fincham (1989) in the KZN province and attributed this to poor vegetation cover. It is also worth mentioning that regions dominated by gullies in both tertiary catchments W55 and X12 have an annual rainfall greater than 800mm, which is relatively high considering that only approximately 9% of SA receives rainfall over this amount (see Schulze, 2010). The decrease in strength of influence associated with an increase in erosivity values observed in tertiary catchment X12 is explained here by the low favourability of steep slopes to gullies. Steep slopes often increase with increasing altitude and thus a high erosivity values.

### 6.3.4. The contribution of vegetation and land use

The influence of vegetation (cover and type) and land use or land cover on gully erosion is interrelated and interdependent. The high influence of degraded-erosion land cover class on gullies is recognised. It is important to note that degraded-erosion is a land cover class included to represent various forms of erosion, particularly gullies. Thus, a very strong influence of degraded-erosion class on gully erosion was expected. The overwhelmingly strong influence observed is an illustration of the correlation between gullies mapped in this study and the gully location map of Mararakanye and Le Roux (2012). The difference between the resolution of SPOT 5 imagery and the aerial photographs played a role in what would have been otherwise a good correlation. As already discussed in section 6.1, the 0.5m resolution of aerial photograph enabled the detection of smaller gullies compared to the SPOT 5 imagery resolution of 5m (merged panchromatic and multispectral bands). As a result, more discontinuous gullies were mapped in the current study, compared to the study by Mararakanye and Le Roux (2012).

A difference in the influence of vegetation on gully erosion between tertiary catchments W55 and X12 is recognised. Significant influence on gullies in tertiary catchment W55 was observed in KaNgwane Montane grassland (Wi = 0.6). The reason KaNgwane Montane grassland shows a significant influence on gully erosion is linked to the degradation status of this vegetation type particularly observed in communal areas. It was observed that the majority of gullied pixels occur within the proximity of degraded grassland. Degraded grassland shows the strongest influence on gully erosion (Wi = 1.7). According to Le Roux and Sumner (2012), degraded grassland represents areas where soils are frequently disturbed, probably due to overgrazing and trampling effects. This is particularly true considering that the study area is rural, consisting of the communal land use system. Vetter *et al*. (2006) regard the communal land as favourable to erosion due to higher stocking rates, higher population densities, lower basal cover and more bare ground than commercial farm land. In this study, moderate and moderate to high NDVI values as well as bare rock and soils were observed in the KaNgwane Montane grassland. These moderate and moderate to high NDVI classes have a significant influence on gullies as is shown by the weight of 0.7 and 0.01 respectively. The bare rock and soils class has an InfVal weight of 1.1 since they generate greater runoff as discussed in Chapter 2.

In tertiary catchment X12, significant effects on gully erosion were observed on Barberton serpentine sourveld (Wi = 1.1) and Swaziland sour bushveld (Wi = 0.7). The Barberton serpentine sourveld class comprises a small percentage of the total area and its smaller size contributed significantly in the determination of weight. Nevertheless, the high influence of serpentine vegetation on gully erosion is expected since its underlying Swazian age intrusive rock (Zu) favours the development of gullies as already discussed. However, what is unexpected is the spatial correlation between the two classes. One would normally expect serpentine vegetation to occur on ultramafic rocks (also known as serpentine rocks) since this vegetation type derives its name from these rocks (McCallum, 2006). This is particularly true considering that soils and geology have an influence on vegetation type and its distribution (Vetter *et al*., 2006). This anomaly of miscorrelation between ultramafic rocks and serpentine vegetation is however, outside the scope of the current study. Other Swazian age intrusive rocks (Zmg, Zg and Zs) including some Zu polygons are overlain by the Swaziland sour bushveld. The Swaziland sour bushveld itself significantly influences gullies probably due to its underlying ultramafic geology. Apart from the geological influence on the rate of erosion in Swaziland sour bushveld, cultivation appears to have played a role since many continuous large gully systems were observed adjacent to cultivated fields. Le Roux and Sumner (2012) consider the disturbance of soils as a result of cultivation as one of the main influences of soil erosion in the Eastern Cape province. In this study, the majority of cultivated areas are dominated by moderate to high NDVI values. Cultivation without implementing proper conservation measures has been blamed for severe forms of gullies in developing countries (Geyik, 1986). The analysis of historical data in section 6.2 serves to confirm the vulnerability of cultivated land to gully erosion initiation.

## 6.4. Summary

This Chapter discussed the major findings of the study. The mapped gully erosion features is an improvement to the previous map of Mararakanye and Le Roux (2012), attributed to the use of higher resolution aerial photographs compared to the relatively coarser resolution of SPOT 5 imagery used previously. Historical observation shows that gully erosion in the study area is not recent, thus could not be attributed to current land use alone. Cultivation in the mid 20th century played a major role in the extension and initiation of the main continuous and discontinuous gullies respectively. Various biophysical factors significantly influence gullies, but it was the upslope contributing area and NDVI where similar trends were observed for both tertiary catchments X12 and W55. The next Chapter presents the conclusions, limitations and recommendations for future research.

# CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

## 7.1. Conclusions

Gully erosion is a serious environmental problem conspicuous in both tertiary catchments X12 and W55, however, the former seems to be highly affected. A commonly held view is that several biophysical and land use factors contribute to gully erosion development. However, little effort has been made to quantify the contribution of a wide variety of factors to gullies often resulting in over or under emphasising the less or more important factors respectively. The importance of various forms of igneous rocks on gully erosion development is emphasised here, in contrast with previous findings that igneous rock is not erodible (e.g. Huggett, 2007; Veter, 2007). In tertiary catchment W55, the majority of gullied pixels occur in the Randian age igneous rock and the Information Value statistical weight observed shows its significant influence on gullies. Though the Randian age igneous rock has a large number of gullied pixels in tertiary catchment X12, the Information Value weight is insignificant, but, other igneous rock types such as the Vaalian Diabase intrusive, Swazian age intrusive, Theespruit, Hooggenoeg, Komati and Sandspruit significantly influence gullies. Literature shows that materials developed there are highly erodible (e.g. Elges, 1985), and thus should be emphasised in future.

The influence of upslope contributing area and Normalised Difference Vegetation Index (NDVI) is consistent within the two tertiary catchments, though not identical, but their respective classes' influence on gullies follow the same trends. The upslope contributing area classes above six have a significant influence on gullies for both tertiary catchments, whilst the opposite is true for classes lower than six. Moderate and moderate to high classes of NDVI also have a statistically strong influence on gullies whilst no significant influence was observed for the high and low to moderate classes in both tertiary catchments. It can therefore be concluded that upslope contributing area and NDVI are the most overriding gully erosion contributing factors in the study area. Previous studies also found the upslope contributing area amongst the most dominant factors contributing to gully erosion (e.g. Le Roux and Sumner, 2012) as discussed in Chapter 6.

The role of historical land use has often not been considered in gully erosion research in South Africa, except for studies in the Karoo region (e.g. Keay-Bright and Boardman, 2006;

Foster *et al*., 2012). It was important to correlate gully occurrence with land use at the time of initiation since the current land uses rarely suggest the cause. The importance of historical land use in gully erosion initiation and expansion was highlighted in this study. A good correlation between historical cultivated or abandoned fields with gully erosion was observed. The occurrence of gullies in cultivated fields is the result of improper cultivation methods implemented as described in the literature (e.g. Walters, 1940). Other historical land use activity often associated with gully erosion is overgrazing (e.g. Keay-Bright and Boardman, 2006). Kakembo and Rowntree (2003) observed gully erosion in abandoned cultivated fields, but could not ascertain whether cultivation caused gully initiation. They attributed severe forms of erosion to a complex interaction of social, economic and environmental factors which lead to land abandonment. Contrary to this, the influence of improper cultivation methods was observed in this study as a direct cause of land abandonment.

The difference in the density of gullies between tertiary catchments X12 and W55 was caused by the variation in controlling factors occurring in these two areas. First, the unique geology types observed in tertiary catchment X12 such as as the Vaalian Diabase intrusive, Swazian age intrusive, Theespruit, Hooggenoeg, Komati and Sandspruit contributed significantly in the variation of gullies with tertiary catchment W55. Similar observations were made for the associated vegetation, soils and rainfall erosivity. The Barberton serpentine sourveld and Swaziland sour bushveld vegetation types uniquely occur in tertiary catchment X12, so too the presence of vertic (Arcadia) and duplex (Estcourt, Swartland, Valsrivier) soils, as well as the lowest erosivity class 2922 – 3000. The unique occurrence of these factors explains the favourability of tertiary catchment X12 to gullies since a significant Information Value weight was observed in these classes.

Similar to previous studies, it was observed that contributing factors important in one area are not necessarily important in the other (e.g. Sonneveld *et al.*, 2005; Le Roux and Sumner, 2012) even in areas where the occurrence of controlling factors is more or less the same. For example, loamy sand, sandy and very sandy soils have a large pixel count in both tertiary catchments and are all affected by gully erosion, but a good statistical correlation with gullies was only observed in tertiary catchment W55. In contrast, clay and loam soils significantly influence gully erosion in tertiary catchment X12 but do not have a significant influence in tertiary catchment W55, same as a variety of soil depth and form association classes, geology, slope gradient, topographic wetness index, planform curvature, stream power index, rainfall erosivity, vegetation types and land cover.

## 7.2. Limitations and recommendations

While the current study successfully highlighted the important factors contributing to gully erosion between the two tertiary catchments, certain limitations call for further investigations as described below.

- The Information Value method allows for the study of the individual effect of each factor on gully erosion. In reality, the analysed factors may be interdependent and need not to be considered independently. This is considered one of the main drawbacks of the bivariate Information Value method (Van Westen *et al*., 1997). It is recommended to compare multiple statistical analysis approaches, including the multivariate statistics.

- The Information Value method, like other statistical analyses depends on the quality of data (Nandi and Shakoor, 2009). The contributing factors data utilised here come from different sources and disciplines. As a result, their quality is not consistent and they are not intended for use at similar scale. Thus, results between the two factors from different sources are incomparable as observed in the ultramafic/serpentine rocks and the Barberton serpentine sourveld vegetation. Since conservation measures are implemented at the field or hillslope scale (Le Roux, 2012), it is recommended to derive datasets for the purpose of the study, applicable at field scale.

- The impact of historical land use is only understood within a kilometre radius of the two selected gully systems. While this provides examples of the role of historical land use on gully erosion, there is a need for further detailed investigations in the study area and beyond. Although the current study was able to demonstrate the effect of historical land use on gully initiation with a high degree of confidence, it is recommended that further historical aerial photographs be georeferenced to enable the accurate measurements of gully erosion expansion as well as for proper alignment of maps with the digitised gullies in the whole study area.

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# APPENDIX A: FIELD DATA

**Table A1: Sample points for verification of gully mapping**

| Sample point number | Date of observation | North coordinates | South coordinates | Comments |
|---|---|---|---|---|
| 1 | 16 April 2014 | 30.17219 | -26.30587 | Gully - confirmed on the map |
| 2 | 16 April 2014 | 30.18110 | -26.29963 | Gully - confirmed on the map |
| 3 | 16 April 2014 | 30.18238 | -26.29870 | Gully - confirmed on the map |
| 4 | 16 April 2014 | 30.56944 | -26.21540 | Gully - confirmed on the map |
| 5 | 16 April 2014 | 30.81515 | -26.26083 | Gully - confirmed on the map |
| 6 | 16 April 2014 | 30.78940 | -26.27198 | Gully - confirmed on the map |
| 7 | 16 April 2014 | 30.75812 | -26.28845 | Gully - confirmed on the map |
| 8 | 16 April 2014 | 30.74531 | -26.28447 | Gully - confirmed on the map |
| 9 | 16 April 2014 | 30.73712 | -26.28255 | Gully - confirmed on the map |
| 10 | 16 April 2014 | 30.73401 | -26.28441 | Gully - confirmed on the map |
| 11 | 16 April 2014 | 30.77030 | -26.30180 | Gully - confirmed on the map |
| 12 | 16 April 2014 | 30.78245 | -26.31456 | Gully - confirmed on the map |
| 13 | 16 April 2014 | 30.79651 | -26.34186 | Gully - confirmed on the map |
| 14 | 16 April 2014 | 30.81415 | -26.36475 | Gully - confirmed on the map |
| 15 | 16 April 2014 | 30.81138 | -26.37574 | Small gully - not distinguishable from aerial photographs |
| 16 | 16 April 2014 | 30.79917 | -26.38432 | Small gully - not distinguishable from aerial photographs |
| 17 | 16 April 2014 | 30.78552 | -26.39531 | Small gully - not distinguishable from aerial photographs |
| 18 | 16 April 2014 | 30.78021 | -26.38779 | Gully - confirmed on the map |
| 19 | 16 April 2014 | 30.77828 | -26.38525 | Gully - confirmed on the map |
| 20 | 16 April 2014 | 30.78297 | -26.35903 | Gully - confirmed on the map |
| 21 | 16 April 2014 | 30.78468 | -26.34037 | Gully - confirmed on the map |
| 22 | 16 April 2014 | 30.78568 | -26.33414 | Gully - confirmed on the map |
| 23 | 16 April 2014 | 30.78654 | -26.32883 | Gully - confirmed on the map |
| 24 | 16 April 2014 | 30.78699 | -26.32567 | Gully - not initially mapped |
| 25 | 30 April 2014 | 30.32234 | -25.94858 | Gully - confirmed on the map |
| 26 | 30 April 2014 | 30.32724 | -25.95246 | Gully - confirmed on the map |
| 27 | 30 April 2014 | 30.32960 | -25.95329 | Gully - confirmed on the map |
| 28 | 30 April 2014 | 30.34290 | -25.95562 | Gully - confirmed on the map |
| 29 | 30 April 2014 | 30.59146 | -25.96340 | Gully - confirmed on the map |
| 30 | 30 April 2014 | 30.61956 | -25.97061 | Gully - confirmed on the map |
| 31 | 30 April 2014 | 30.67171 | -25.98979 | Gully - confirmed on the map |
| 32 | 30 April 2014 | 30.67709 | -25.99453 | Gully - confirmed on the map |
| 33 | 30 April 2014 | 30.68116 | -25.99667 | Gully - confirmed on the map |
| 34 | 30 April 2014 | 30.81234 | -26.00799 | Gully - confirmed on the map |
| 35 | 30 April 2014 | 30.83909 | -26.05571 | Gully - confirmed on the map |

| | | | | |
|---|---|---|---|---|
| 36 | 30 April 2014 | 30.84471 | -26.05700 | Gully - confirmed on the map |
| 37 | 30 April 2014 | 30.86371 | -26.06128 | Gully - confirmed on the map |
| 38 | 30 April 2014 | 30.90495 | -26.07015 | Gully - confirmed on the map |
| 39 | 30 April 2014 | 30.90874 | -26.07010 | Gully - confirmed on the map |
| 40 | 30 April 2014 | 30.93210 | -26.07381 | Gully - confirmed on the map |
| 41 | 30 April 2014 | 30.93498 | -26.08028 | Gully - confirmed on the map |
| 42 | 30 April 2014 | 30.93607 | -26.08514 | Gully - confirmed on the map |
| 43 | 30 April 2014 | 30.93636 | -26.08611 | Gully - confirmed on the map |
| 44 | 30 April 2014 | 30.93783 | -26.08942 | Gully - confirmed on the map |
| 45 | 30 April 2014 | 30.94147 | -26.09330 | Gully - confirmed on the map |
| 46 | 30 April 2014 | 31.00117 | -26.07047 | Gully - confirmed on the map |
| 47 | 30 April 2014 | 30.98466 | -26.14042 | Gully - confirmed on the map |
| 48 | 30 April 2014 | 30.99196 | -26.14294 | Gully - confirmed on the map |
| 49 | 30 April 2014 | 30.99764 | -26.15270 | Gully - not initially mapped |
| 50 | 30 April 2014 | 31.00346 | -26.16065 | Gully - confirmed on the map |
| 51 | 30 April 2014 | 31.00380 | -26.16371 | Gully - not initially mapped |
| 52 | 30 April 2014 | 30.99712 | -26.18208 | Gully - not initially mapped |
| 53 | 30 April 2014 | 30.99679 | -26.18437 | Gully - confirmed on the map |
| 54 | 30 April 2014 | 30.99471 | -26.18320 | Gully - confirmed on the map |
| 55 | 30 April 2014 | 30.99000 | -26.18317 | Gully - confirmed on the map |
| 56 | 30 April 2014 | 30.74922 | -26.11513 | Gully - confirmed on the map |
| 57 | 30 April 2014 | 30.74170 | -26.11259 | Gully - confirmed on the map |
| 58 | 30 April 2014 | 30.73670 | -26.10943 | Gully - confirmed on the map |
| 59 | 30 April 2014 | 30.73094 | -26.10477 | Gully - confirmed on the map |
| 60 | 30 April 2014 | 30.73009 | -26.10287 | Gully - confirmed on the map |
| 61 | 30 April 2014 | 30.73333 | -26.09278 | Gully - confirmed on the map |
| 62 | 30 April 2014 | 30.73527 | -26.08121 | Gully - confirmed on the map |
| 63 | 30 April 2014 | 30.73736 | -26.05908 | Gully - confirmed on the map |
| 64 | 30 April 2014 | 30.71976 | -26.00847 | Gully - confirmed on the map |
| 65 | 30 April 2014 | 30.71464 | -26.00690 | Gully - confirmed on the map |
| 66 | 30 April 2014 | 30.51907 | -26.03607 | Gully - confirmed on the map |
| 67 | 30 April 2014 | 30.51110 | -26.05477 | Gully - confirmed on the map |
| 68 | 30 April 2014 | 30.48062 | -26.06697 | Gully - confirmed on the map |
| 69 | 30 April 2014 | 30.47857 | -26.07008 | Gully - confirmed on the map |
| 70 | 30 April 2014 | 30.44260 | -26.08725 | Gully - confirmed on the map |
| 71 | 30 April 2014 | 30.46622 | -26.00409 | Gully - confirmed on the map |
| 72 | 30 April 2014 | 30.36764 | -26.05680 | Gully - confirmed on the map |
| 73 | 30 April 2014 | 30.75915 | -26.42047 | Gully - confirmed on the map |

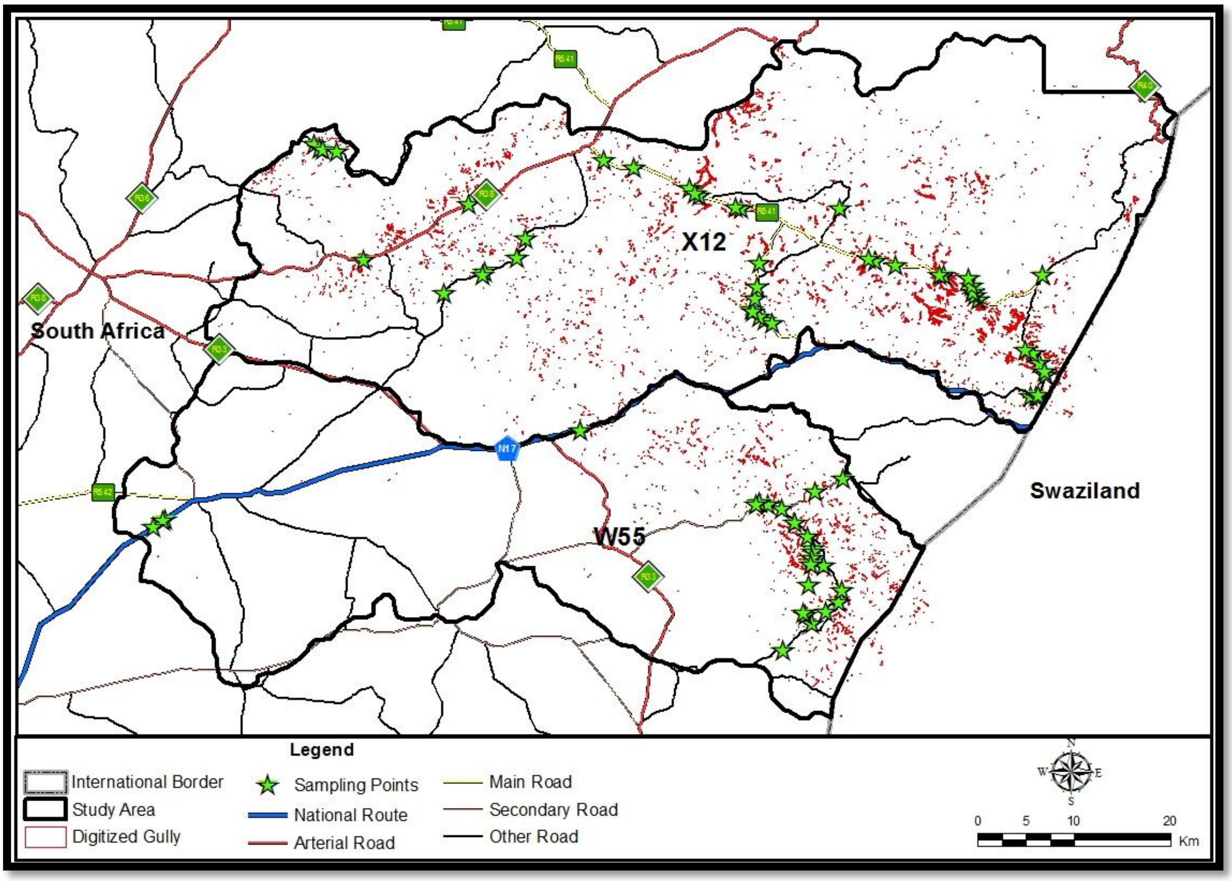

Figure A1: Location of sampling points for verification of gully map in tertiary catchments X12 and W55

# APPENDIX B: ARCGIS ANALYSIS MODEL

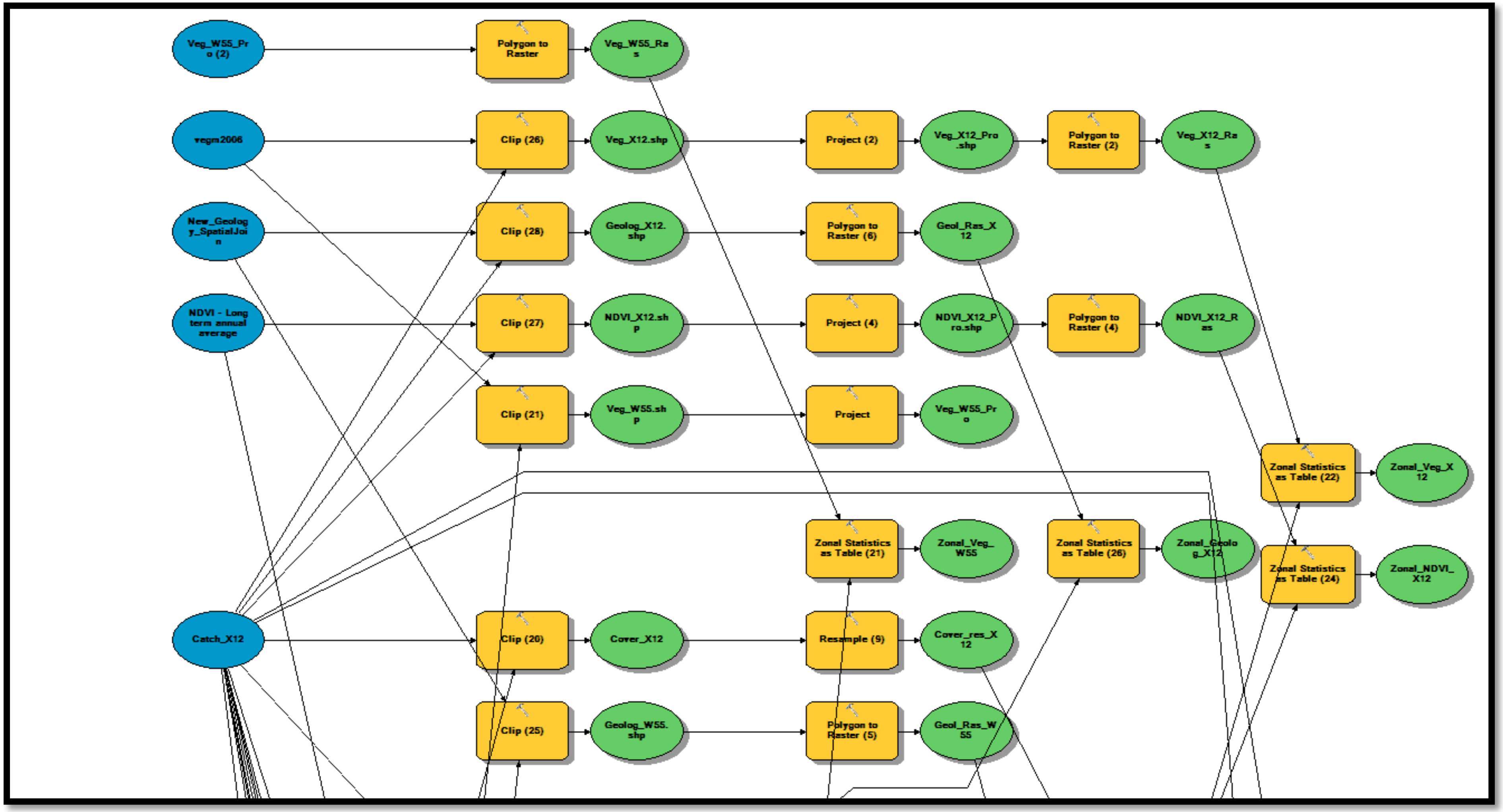

Figure B1: Model for analysis of contributing factors

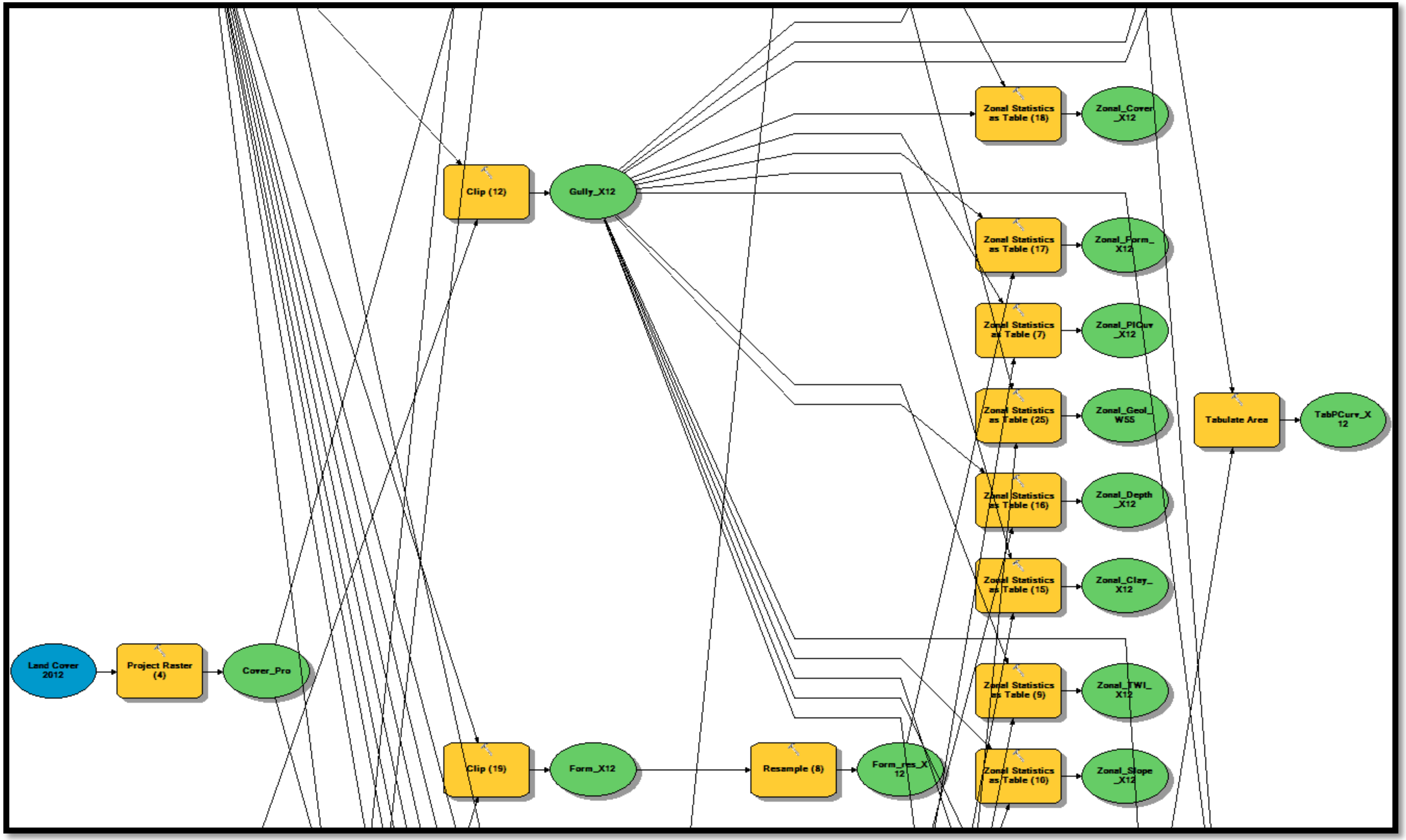

**Figure B1 (continued)**

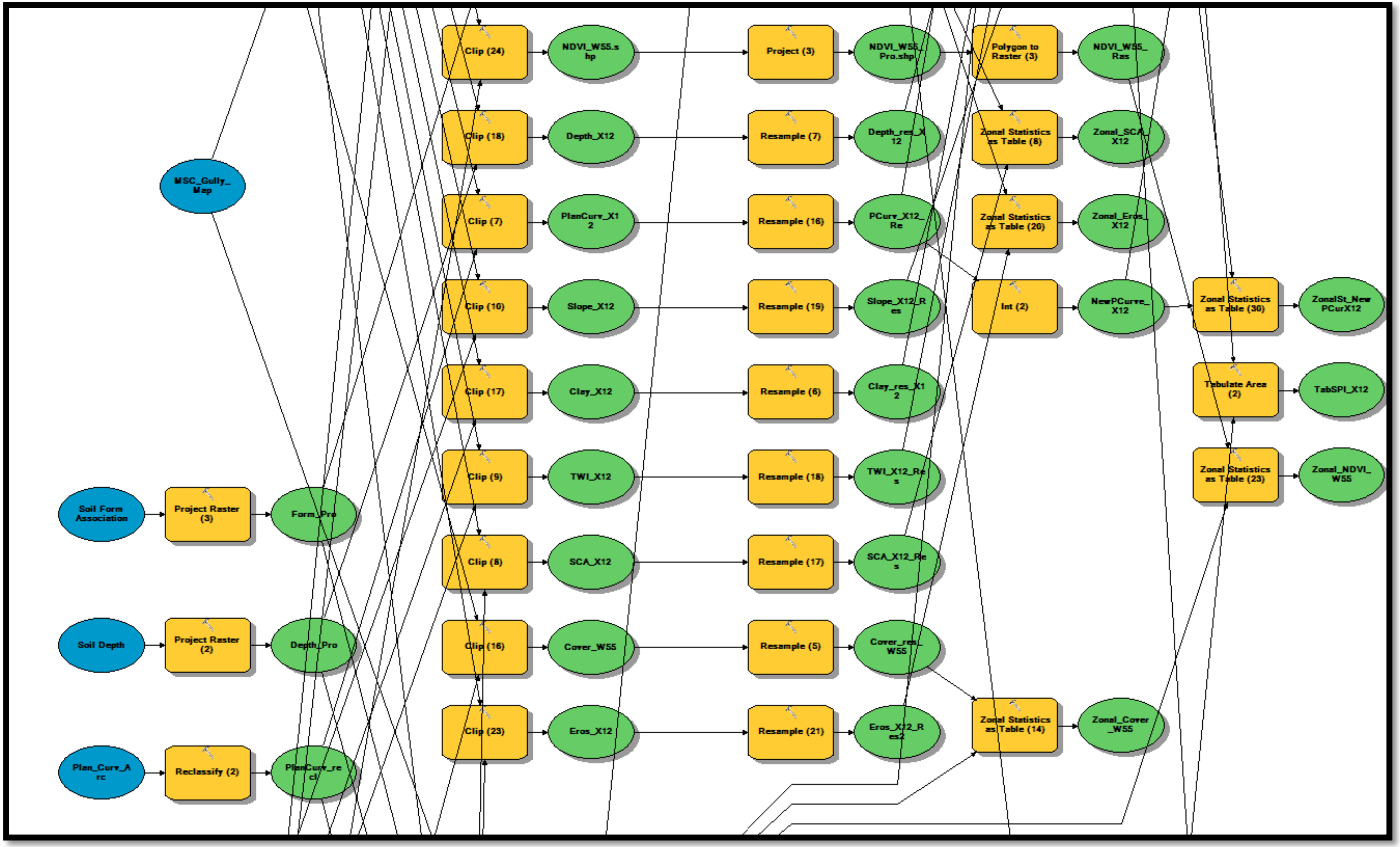

**Figure B1 (continued)**

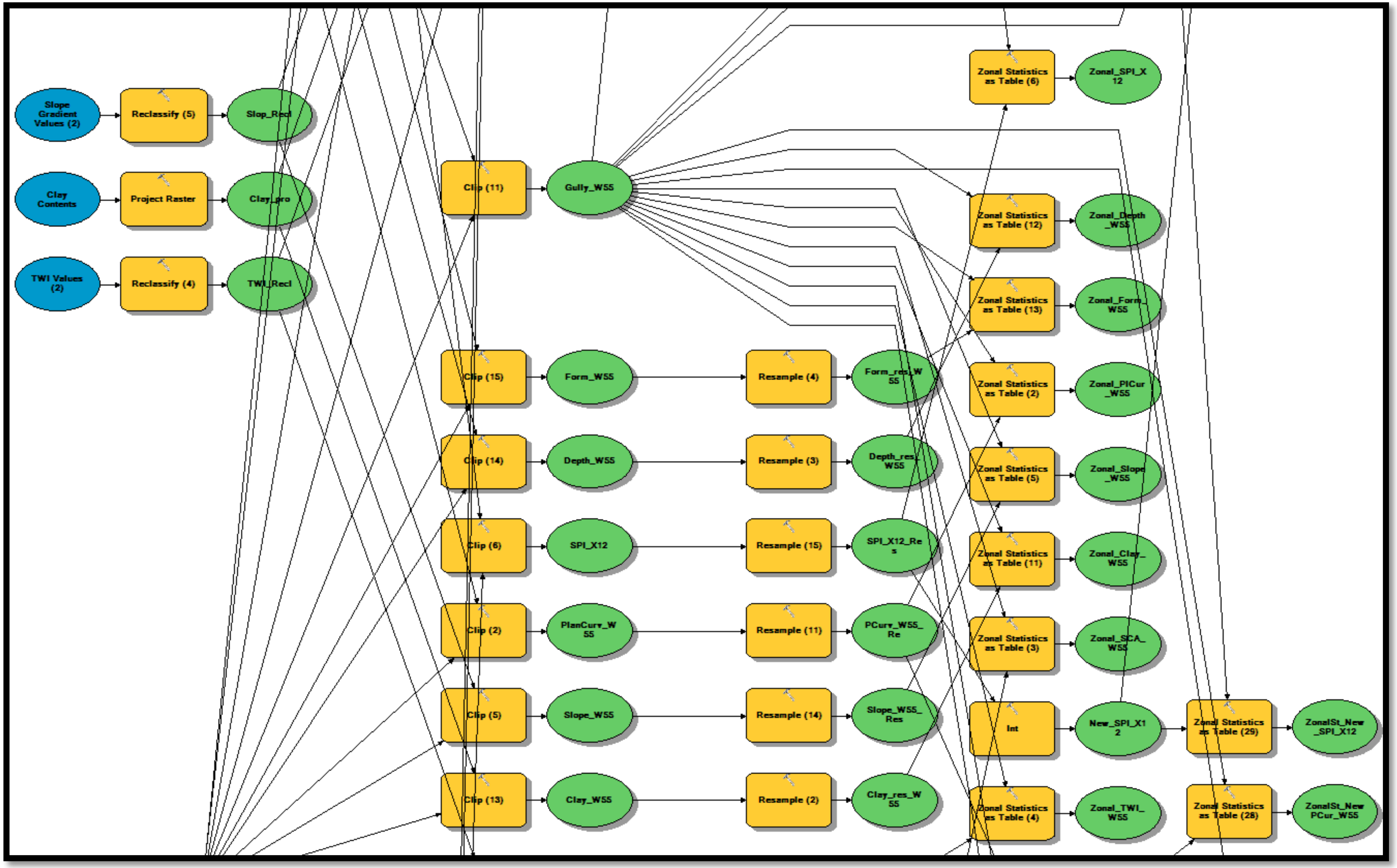

**Figure B1 (continued)**

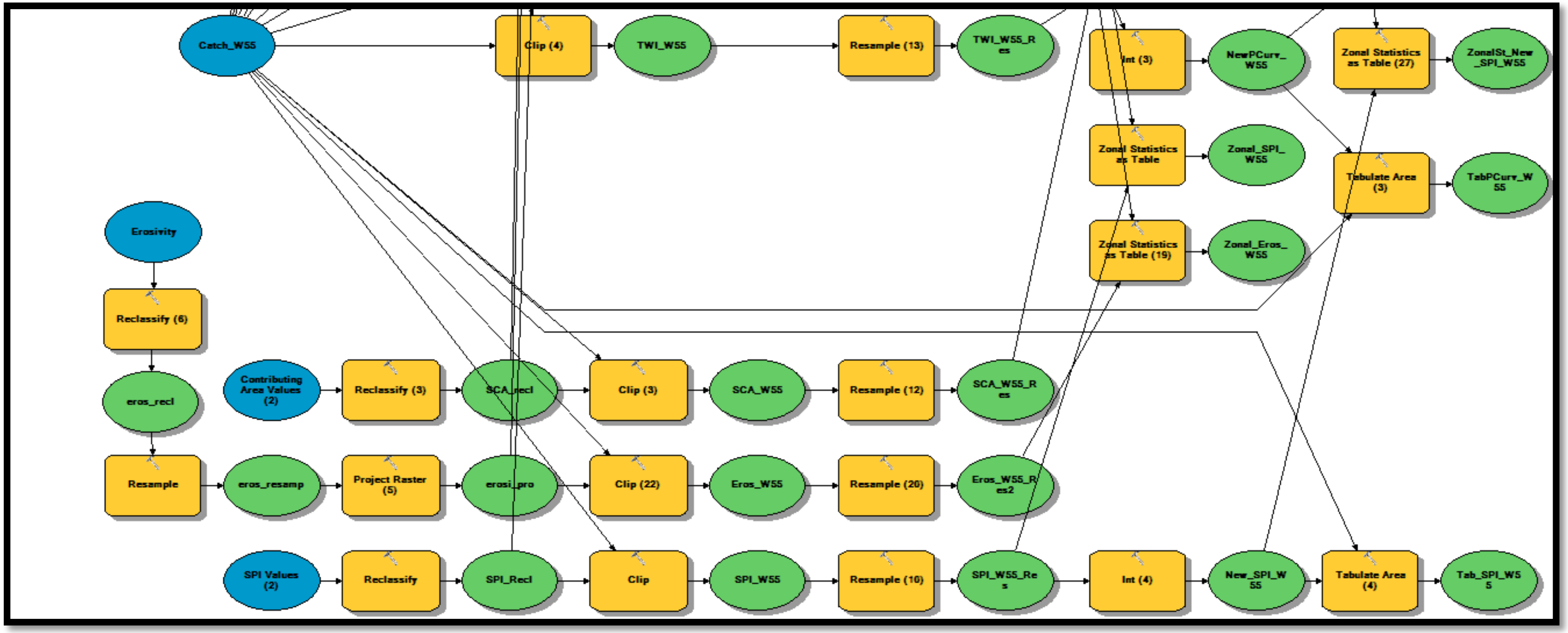

**Figure B1 (continued)**