Historical gully erosion growth in the Lower Thina Catchment, Eastern Cape

by

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DECLARATION

By submitting this thesis/dissertation, I, Lerato Mirriam Boihang declare that the thesis/dissertation, which I hereby submit for the degree Master of Science in Environmental Management 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 a complex phenomenon initiated by various erosion-related processes. Due to the complexity of drivers contributing to this degradation process, it has received, compared to sheet and rill erosion, less scientific attention on large spatial scales. In South Africa, erodible duplex soils coupled with inefficient land management result in gully erosion, with the Eastern Cape and KwaZulu-Natal the two provinces most prone to gullying. One of the greatest challenges in rural areas is the limited information regarding the actual location of gully systems. This study quantifies historical gully erosion for six time periods in the Lower Thina Catchment in the Eastern Cape of South Africa using parameters recognised as having the greatest impact on gully erosion (climate variability; land use change). A desktop-based research approach was followed to determine the effect of climate variability and land use on historical gully development and growth in the selected catchment.

Soils in this catchment are prone to extreme soil erosion and although several soil erosion studies have been conducted in the upper regions of the study area, no studies have been recorded in the lower parts of the catchment to date. The first part of this study made use of GIS and remote sensing techniques to identify, map and quantify the lateral growth rate of four selected gullies within the catchment using high-resolution aerial and satellite imagery. The second part involved determining the effects of various land use activities in the catchment, while the third part entailed using rainfall records from three weather stations (Umthatha, Cengcane and Papane) to calculate inter- and intra- annual rainfall variability (CV and PCI respectively), rainfall erosivity (MFI) and temperature patterns within the study area. Furthermore, regression analyses and ANOVA were conducted. Outcomes of the second and third parts were used to determine the drivers of gullying within the catchment.

Results show that all investigated gullies are permanent in nature, with lateral growth rates of gullies ranging between 0.07 and 0.1 ha.yr^{-1} across the 68-year time period. A clear increment in surface area is evident for all investigated gullies. Changing land use patterns and anthropogenic factors are associated with an increase in gully growth. A low inter-annual rainfall variation ($CV < \mu - \sigma$) and a moderate ($15 \geq PCI > 10$) to irregular ($20 \geq PCI > 16$) intra-annual distribution is evident across the years. Rainfall erosivity (MFI) values for Umthatha and Papane are moderate ($90 < MFI < 120$) and low ($60 < MFI < 90$) respectively, while that of Cengcane are high ($120 < MFI < 160$). Irregular and moderate intra-annual rainfall patterns (indicating seasonality of rainfall), coupled with heterogeneous temperature data suggest that investigated climate parameters can affect gully erosion with respect to altitude and the seasons. However, linear trends ($p > 0.05$) show little control of climate parameters on gully erosion at an inter-annual level. Furthermore, since risks of soil erosion parameters are directly proportional to erosivity potential within the catchment, based on PCI, CV, MFI, and temperature variability, the risk of gullying in the Lower Thina Catchment across the 68-year period is low to moderate. While factors such as underlying geology, unconsolidated and duplex soils, topography, as well as some climatic fluctuations contribute to gully erosion, agricultural practices, land use cover and proximity to roads and residential areas are identified as the main causes of gully erosion. Irrespective of this, no factor is solely responsible for gullying.

Keywords: *historical gully growth, Lower Thina Catchment, gully development drivers, land use/land cover, rainfall erosivity and variability*

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CHAPTER 1: INTRODUCTION

1.1. Overview

Soil is a fundamental resource that humans greatly depend on as it supports flora and allows for food, fuel and fibre (such as cotton) production (Kern, 2002; Schulte *et al.,* 2014; Ragnarsdottir & Banwart, 2015). It is also a non-renewable resource that varies in structure and is highly susceptible to degradation. Initially, it was thought that the main function of soil was to act as a medium for plant growth. However, it is now known that soil is not only a medium for growing various crops but is a multi-functional resource that underpins climate change and environmental quality (Blanco & Lal, 2010). Many economic, agronomic and environmental benefits result from the conservation of soil. It is thus, worthwhile to sustainably conserve and protect this resource since the rate of soil loss tends to exceed the rate of soil formation (Blanco & Lal, 2010).

Soil degradation occurs in several forms including soil erosion, fertility decline and soil compaction. Of the various forms of soil degradation, soil erosion is by far the most widespread and is caused by among others, the removal of vegetation cover, often due to overgrazing (Valentin *et al*., 2005; Jahantigh & Pessarakli, 2011). Oldeman *et al*. (2017) state that in the previous century, 22% of soil degradation was evident globally among four land use types namely, extensive cropland, woodland, pasture, and forest. Furthermore, it was noted that only a third of the world’s agricultural land consists of cropland area. In contrast, pastureland consists of two-thirds of the agricultural land and, as a result of overgrazing, experiences erosion at a rate greater than 100 tons.ha^{-1} yr^{-1}. Nevertheless, croplands exhibit the greatest erosion due to repeated tillage of soil and removal of vegetation (either anthropogenic and/or natural) as a result of various soil erosion agents (Pimental *et al*., 1995).

There are many known soil erosion agents, including glaciers, waves, wind and water (Igbokwe *et al*., 2008), with water and wind as two recurring agents in soil erosion related literature (Pimental *et al.*, 1995; Igbokwe *et al*., 2008; Blanco & Lal, 2010). The former is considered to affect 56% of the total degraded land while the latter only affects approximately 28% (Blanco & Lal, 2010). Of these two main agents, water erosion results in the most severe type of soil erosion and mostly affects humid, sub-humid, arid and semi-arid regions (Blanco & Lal, 2010). Globally erosion rates continue to intensify with South America, Asia and Africa the most susceptible to the high rates of soil erosion (Pimental *et al*., 1995). Eroded soil particles can potentially travel as sediments thousands of miles across countries, continents and oceans, affecting countries outside their area of origin. For example, Brazil and Florida have reported soil blown from eroded African land. Similarly, eroded soil from Hawaii is evident in China (Pimental *et al*., 1995).

Effects of soil erosion can be classed as either on- or off-site (Pimental *et al*., 1995). Both these classes impact the immediate agricultural land, as well as the surrounding environment. Depletion of soil biodiversity, loss of nutrients, ecological damage and loss of soil productivity, are some of the few common on-site effects associated with erosion (Pimental *et al*., 1995). Off-site effects on the other hand, include the transportation of soil away from the source, damage of public health and the modification of aquatic habitats (Pimental *et al*., 1995; le Roux *et al*., 2007, 2008). Additionally, hydrological functions of soil are also negatively affected. Soil erosion generally occurs in various forms, is a carrier of pollutants and is associated with negative side effects such as eutrophication, sedimentation and siltation (le Roux, 2012).

One common and severe type of soil erosion is gullying, which can occur as a result of surface runoff. Gullies are large and deep erosion channels, normally formed in drainage ways and can range from 30 cm to 30 m in depth (Mararakanye & Nethengwe, 2012). These landforms cause substantial soil loss during even a single rainfall event (Casali *et al*., 2000), resulting in increased sediment production (Poesen *et al*., 2003; Taruvinga, 2008; Blanco & Lal, 2010) and disrupted hydrological functions (Poesen, 2011). Furthermore, different intensities and durations of rainfall may also promote gullying (Casali *et al*., 1999).

Gully erosion is a complex phenomenon initiated by various erosion-related processes. Once gullies have formed, scouring may occur, actively enlarging the gully system in both size and depth. In some instances, gully walls may collapse; thus, resulting in the enlargement of these features (Bettis & Thompson, 1985; Stein & La Tray, 2002; Mararakanye, 2015). Gullying is a degradation process known to have received the least scientific attention on a large spatial scale compared to sheet and rill erosion, the reason being that gullies have a number of factors and processes affecting them, making them difficult to predict and study (Vandaele *et al*., 1997; Valentin *et al*., 2005; Mararakanye & le Roux 2012; le Roux *et al*., 2015). In South Africa, erodible duplex soils coupled with unsuitable land management practises result in gully erosion (Pretorius *et al*., 2015), with the Eastern Cape and KwaZulu-Natal provinces most prone to gullying (Mararakanye & le Roux, 2012). Nonetheless, gullies are also widespread in the Karoo region of the Northern Cape Province (le Roux *et al.,* 2008, Foster *et al*., 2012, Boardman, 2014). Irrespective of their location within South Africa, gully erosion research focuses mainly on the origin of gullies, soil loss rates and factors such as topography, geology, land use and rainfall, which contribute to the development and growth of gullies (Mararakanye, 2015).

Valentin *et al*. (2005) conducted a study in Europe that identified forested areas to exhibit the most gully erosion. High-intensity rainfall was related to the many gully erosion periods experienced in their study region. The study highlighted many factors that contribute towards gullying in the area but emphasized a combination of primarily land use and climatic factors to be the cause of accelerated erosional processes. These highlighted factors similarly affect soil erosion and sediment yield in many other studies (*e.g*. Kosmas *et al*., 1997; Vanwalleghem *et al*., 2005; Martínez–Casasnovas *et al*., 2009). In a separate study by Ward *et al.* (2009), Geographical Information Systems (GIS) were used to model suspended sediment yield present in the Meuse basin (France, Belgium, Netherlands) and it was evident that various land use practices under different climatic conditions exhibit varying extents of sediment yield. It is, therefore, clear that land use practises and climatic factors are linked to gullying. Such land use activities (*e.g.* abandoned fields, overgrazing and irrigation channels), within an area (Pimental *et al*., 1995; Poesen *et al*., 2003; Valentin *et al*., 2005; Taruvinga, 2008), may result in loss of top soil together with sedimentation as common gully-related challenges (*e.g.* Vandekerckhove *et al*., 2000; Sidorchuk, 2003; Desta & Adugna, 2012).

Gullied areas exhibit the highest magnitude of sediments compared to other forms of water erosion, such as sheet and rill erosion. Gullies further concentrate runoff into channels while enhancing drainage and accelerated aridification. Due to farming practices, gullies tend to form perpendicular to farm contours, constraining farmers' choices to parcel use patterns (Valentin *et al*., 2005). In addition to these, the greatest challenge associated with gully erosion is the limited information regarding the actual location of the gully systems in the landscape. This is partially related to the high costs associated with gully mapping, time and limited expert knowledge (Taruvinga, 2008).

Various soil erosion research has been conducted in South Africa and was considered baseline knowledge on South African erosion prior to this study. A few of these common studies with reference to the current study are summarised below. Works such as Poesen *et al*., (2003) and Mararakanye (2015) highlight the transportation of sediments into waterways by means of fast flowing Hortonian overland flow. Similarly, van der Waal & Rowntree (2017), acknowledge that sediment connectivity is a major problem in the Eastern Cape, enhanced by gullying within incised river channels. In the same light, le Roux *et al*. (2015) and Pretorius (2016) emphasise that gullies pose a challenge in the Eastern Cape as they contribute greatly towards sediment yield and sediment output. In addition to the gullying effects that result due to changing land use conditions, variability of climate in and around South Africa enables one to assess and relate the extent of gullying in an area. Increased atmospheric temperatures and rainfall events over past years may be related to such variabilities, resulting in changes in the rate of soil erosion. These differences are due to changes in the erosive power of rainfall, changes in plant residue and decomposition rates (Nearing, 2001). The three main reasons resulting in wavering extents of gullying are fluctuations in rainfall frequency, quantity and intensity (Kakembo, 2000; Vetter, 2007). These provide the complexity of the impact of climate on gully erosion not only in the Lower Thina Catchment, the chosen study area, but globally as well (Taruvinga, 2008).

The Lower Thina Catchment is in the Eastern Cape Province, formerly known as the Transkei homeland in South Africa. This river, together with four other tertiary rivers, feeds the main river system, the Mzimvubu River. The Lower Thina Catchment flows into the main river approximately 5 km downstream from the conflux formed with the Tsitsa River (le Roux *et al*., 2015). The catchment is a significant water resource for the Eastern Cape due to the high rainfall occurring within the area (van der Waal *et al*., 2015).

Research conducted in this study (Lower Thina Catchment) entails quantifying the historical changes of gully systems within the catchment through the application of the integrated use of GIS and remote sensing and the use of historical and available analogue and digital data. Furthermore, for the purpose of this study, land use and climate variability with respect to rainfall are the two factors of interest as these factors affect gullying on both global and local scales (*e.g.* Valentin *et al*., 2005; Seutloali *et al*., 2016). Moreover, the effects of both these chosen factors are expected to change over a period of time as a result of human activities (IPCC, 2007), making their investigation relevant and of interest.

The Lower Thina Catchment was firstly and primarily selected due to the absence of erosion-related studies in the area as opposed to the upper regions of the catchment where studies have been performed and significant erosion is evident (*e.g.* Rowntree *et al*., 2012; van der Waal, 2015; van der Waal *et al*., 2015). Second, Weepener *et al*., (2015) predicts some parts of the Eastern Cape to be suitable for sugarcane, avocado, maize and pasture cultivation under current climate conditions. This prediction together with land use maps, provides one with major land use activities and their effects on gully growth. Third, previous studies postulate that changes in livestock numbers and practices coincide with gully initiation. Van der Waal & Rowntree's (2017) study identified grazing and cropping as the main land uses within the upper Thina Catchment during apartheid (in the 1950s). After 1994, livestock grazing became the main land use within the catchment. This was associated with poor farming practices, land misuse, overgrazing and duplex soils, which are all major contributors to the accelerated erosion rates in the area (Beckedahl *et al*., 1988; van der Waal & Rowntree, 2017). Finally, substantial amount of data on the area in the form of aerial photographs and satellite images, are freely available for use and analysis, hence, allowing for the identification and mapping of gullies within the area.

1.2. Research problem

Recent studies performed in the Thina River Catchment indicate that there are communal households and ongoing subsistence farming in the region, which can negatively affect soil erosion in the area (van der Waal, 2015; van Dijk *et al*., 2017). Furthermore, the pedology within the catchment is sensitive and easily disturbed by intense land use pressure such as trampling, overgrazing and early winter burning (van der Waal, 2015). Reduction in vegetation coupled with a high volume of trampling results in the initiation of linear tracks, which serve as water drainage features concentrating flow of runoff water and later contributing towards the initiation of gullies. Another consequence of decreased vegetation is soil exposed to erosive rain, as well as the failed binding of sediment through roots (Rowntree *et al*., 2004).

Temme *et al*. (2008) show that some gullies in South Africa predate human occupancy while other authors (*e.g.* Huber, 2013; van der Waal & Rowntree, 2017), show gullies to rather be recent features, which formed post human settlement. Most South African research considers only a limited number of biophysical factors, which contribute to gully erosion, while few studies (*e.g.* Kakembo & Rowntree, 2003; Vetter, 2007) include historical land use. Le Roux & Sumner (2012), as well as Mararakanye (2015), in contrast, assessed the influence of various factors that contribute to the extent of gullying, while Pretorius' (2016) study determined the impacts of projected climate change on sediment yield.

The upper part of the Thina River Catchment has previously been studied with reference to erosion (*e.g.* Rowntree *et al*., 2012; van der Waal *et al*., 2015). Factors such as steep topography, increased cattle density and increased drainage efficiency were common contributing factors to gully initiation within the catchment. The lower part of the Thina Catchment, however, has not yet been explored for such water-related erosion. Furthermore, Mararakanye (2015) emphasises that no two areas have the same contributing factors to gullying due to spatial and temporal variations.

For the purpose of this study, two factors (land use and climate variability) were utilised in order to aid in the quantification of historical changes of gully erosion as the aim entails determining the dominant land use activities and relating climate variability to the extent of gullying in the Lower Thina Catchment. Furthermore, this study quantifies gully erosion and assesses the impact historical climate variability has on the extent of gullying in the Lower Thina Catchment.

1.3. Aim and objectives of the study

The aim of this study is to quantify the historical changes of gully erosion, determine dominant land use activities and relate climate variability on the extent of gullying in the Lower Thina Catchment in the Eastern Cape, South Africa. This aim is achieved through three key objectives given below.

1. Map a selection of gullies found within the Lower Thina Catchment and determine their growth rate using seven discrete years (1948, 1957, 1966, 1975, 1995, 2004, and 2016).
2. Establish whether there is any relationship between land use and gully growth.
3. Investigate historical climate variability and compare this to gully growth occurring over the various time periods.

1.4. Rationale

Progress in our understanding of gully erosion over the past decades is evident in literature. However, many gully erosion questions remain unanswered, and thus pose a challenge to the scientific community. Environmental scientists and geomorphologists are some of the few specialisations that address the interaction between environmental change (*e.g.* land use and climate) and land degradation. This is done in order to reconstruct and learn from the past to prevent or lessen the extent of current and future erosion (Poesen, 2011). According to Poesen (2011), no validated models for predicting the effects of environmental change on gully erosion exist. More studies should thus, be conducted in this regard.

Literature identifies rainfall variation, vegetation cover/land use and geology as the prominent factors influencing gully erosion (*e.g.* Vandaele *et al*., 1997; Watson & Ramokgopa, 1997; Poesen *et al*., 2003; Valentin *et al*., 2005). These factors vary per study site and it is, therefore, relevant to investigate the effect that these have on gullying within the Lower Thina Catchment. Climate variability is seldom studied compared to climate change. As a result, an opportunity to investigate the extent of gullying at different time scales in the Lower Thina Catchment exists. Determining this and comparing the different time scales to each other results in a better understanding of gully dynamics (Poesen, 2011). Vegetation cover is one of the factors of concern and is known to reduce the erosive action of surface runoff. The work of Dondofema *et al*. (2008) reveals, however, that a high tree density of plants per hectare and vegetation cover in an area is not always enough to hold the soil from experiencing further erosion. Investigating the relationship between vegetation cover and the extent of gullying in the Lower Thina Catchment is, therefore, worthwhile.

Regarding prevention and control measures of gullying, classical techniques are applied globally in many gully erosion studies. Commonly applied techniques are reforesting an area and building check dams (Danladi & Ray, 2014; Addis *et al*., 2015). These techniques are effective, however, there are some reported case studies that illustrate a rather low degree of effectiveness (*e.g.* check dams built in gullies occurring in Spain) (Conesa-García & García-Lorenzo, 2009). Le Roux & Sumner (2012) mention that many prevention and control techniques exist, however, finding the technique most suitable for an area would depend on the erosional process and the biophysical and land use factors driving the process.

From all the aforementioned aspects, it is clear that not all gullying components are critically studied and room for further investigation exists. As a result, this project focussed on quantifying historical changes of gully erosion in the Lower Thina Catchment in order to contribute towards the already existing knowledge of gully erosion and the spatial understanding on the extent of gullying. This was done using a desktop study that comprised of GIS and remote sensing techniques, as well as historical land cover and climate data analyses for the selected study sites. Furthermore, this is not a geomorphological investigation of gullies but rather, a desktop approach using GIS tools to determine if one can obtain the same/similar conclusions as other authors, who performed fieldwork and geomorphological studies.

1.5. Report outline

The dissertation is divided into seven chapters. This section provides an introduction where a brief overview of the study is provided together with the research problem, aim and objectives as well as the rationale. CHAPTER 2: LITERATURE REVIEW (on page 17) provides a comprehensive overview of the soil erosion in the context of gully erosion. Erosion on a national context and mapping and modelling approaches of gullying, as well as the control and prevention measures of gullying are also included. CHAPTER 3: STUDY AREA DESCRIPTION (pg.41) describes the chosen study site in greater detail in terms of location, geology, topography, climate, land use, and pedology. CHAPTER 4: METHODOLOGY (pg.48) describes all the materials and methodologies used in conducting the study, whereas CHAPTER 5: RESULTS (pg.57) presents results achieved in the form of tables and figures. CHAPTER 6: DISCUSSION (pg.87) in turn provides a detailed interpretation and evaluation of the results. The thesis concludes with CHAPTER 7: CONCLUSION AND RECOMMENDATIONS (pg.98), which also includes recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1. Soil erosion

Erosion is a common surface process known to sculpt the earth's landscape (Abdulfatai *et al*., 2014). Soil erosion, defined as the accelerated process where soil becomes displaced and transported onto a new location, occurs due to the actions of water, glaciers, waves and/or wind (Igbokwe *et al*., 2008). It is one of the most important and challenging land-degradation processes globally. Of the many soil erosion forming agents, water contributes to the most environmental problems world-wide, leading to the loss of fertile topsoil, which in turn is associated with lowered water holding capacity and reduction of soil productivity (Tebebu *et al*., 2010; Jahantigh & Pessarakli, 2011). Water is, therefore, the chosen agent of erosion for this study as it is the dominant erosion-causing agent in South Africa (Laker, 2004).

Water erosion occurs when the combined power of rainfall energy together with overland flow, exceeds the resistance of soil to detachment (Hadley *et al*., 1985). Erosion processes associated with runoff begin during a rainfall event when droplets dislodge soil particles. The soil particles are then transported and deposited at a new, different location. Soil erosion may occur either as sheet erosion or rills and/or gullies respectively resulting from unconcentrated or concentrated flow. The outcome is highly dependent on the interactive and combined effects of erosion factors such as rainfall erosivity, slope steepness and slope length (le Roux *et al*., 2007). This is because erosion processes differ from one place to another depending on the geology, geomorphology, land use practices, climate, nature and biodiversity, soil texture, land conservation practices and environmental management of the land (Igbokwe *et al*., 2008).

Sheet erosion as defined by Taruvinga (2008) and Wei *et al*. (2009), is the detachment and transportation of thin layers of soil by means of raindrop splash or overland flow. The topsoil layer containing finest soil particles, nutrients and organic matter, is thus, the shallow layer removed during sheet erosion. Sheet erosion usually occurs on soil with sparse vegetation cover or cultivated soils (Nearing *et al*., 1994). **Rill erosion** in turn is the removal of soil in small channels (Taruvinga, 2008) and is commonly found on overgrazed land and may be viewed as the intermediate stage between sheet and gully erosion. Rills are small intermittent water courses a few centimetres in depth characterised by steep sides (Soil Science Society of America, 2004). They are impermanent channels usually occurring in shallow depths of less than 30 cm (NSW Government, 2017) and may be recovered through normal tillage. In contrast to rill erosion, gully erosion is the removal of soil in large channels to great depths over a short time period (Poesen *et al*., 2003; Taruvinga, 2008). Gullies may be described as the advanced stage of rill erosion (Abdulfatai *et al*., 2014), which cannot be recovered through normal tillage operations (Bocco, 1991; le Roux & Sumner, 2012).

Most of the previously performed studies addressing soil erosion by water focus on sheet and rill erosion processes. On the other hand, gully erosion receives less attention (Poesen *et al*., 1996; Souchere *et al*., 2003; Kakembo *et al*., 2009). This can be attributed to the wide array of factors and processes affecting erosion, making gully processes difficult to study (Valentin *et al*., 2005).

2.2. Gully erosion

Bull & Kirkby (1997) define a gully as a V- or U-shaped incision characterised by side slopes close to the angle of rest of unconsolidated debris. Similar to this, are first order streams possessing V-shaped steep-sided incised channels adjoined by belts of no erosion. The stream channels may extend in size through the action of headward erosion, however, the stream channels do not extend until the watershed line is reached (Horton, 1945). An obvious transition from a gully to a first-order stream channel is hardly evident in the field (Hooke, 2000). Mararakanye & Nethengwe (2012) further describe gullies as large and deep erosion depressions/channels that usually occur in drainage ways and are deeper than 30 cm but do not exceed 30 m. Gully erosion is a process which results from the concentration of both subsurface and surface water in narrow paths (le Roux & Sumner, 2012). Gullies in turn form as a result of erosion due to intermittent flow of water (Poesen *et al*., 1996) and produce the largest volume of sediment in comparison to sheet and rill erosion (Valentin *et al*., 2005). Once formed, gullies may enlarge in size and depth as a result of scouring and/or the collapse of walls (Bettis & Thompson, 1985; Stein & LaTray, 2002; Mararakanye, 2015).

2.2.1. Mechanisms involved in gully erosion

Gully erosion is complex and involves various processes for its initiation. These include 1) overland flow (comprising of Hortonian and saturated overland flow), 2) rill expansion, 3) gully head retreat and deepening; and 4) subsurface erosion or piping (Mararakanye, 2015). Mechanisms involved in the formation of gullies may be linked to either Hortonian overland flow or saturation overland flow/subsurface flow (Souchere *et al*., 2003).

Hortonian overland flow occurs when the rainfall intensity exceeds infiltration capacity; the water in excess of that capacity may be stored in depressions, later becoming surface runoff. This type of overland flow occurs predominantly on hillslopes (Sami & Hughes, 1996) and also in arid and semi-arid regions, where rainfall intensities are high, and the soil infiltration capacity is reduced because of surface sealing. According to Ireland *et al*. (1939) and Addis *et al.* (2015) accelerated runoff of surface water increases the rate of cutting in excess and in return, deep, steep-sided gullies form by incision in the bottoms of old and well-adjusted normal valleys. In comparison, **saturation overland flow** occurs when the soil becomes saturated and any additional precipitation or irrigation causes runoff. Saturation overland flow may also occur when the water table reaches the ground surface and groundwater seeps out from the ground surface, generating overland flow, known as return flow (RF) (Mararakanye, 2015). This form of overland flow contributes dominantly to the process initiating ephemeral gully erosion (Desta & Adugna, 2012; Mararakanye, 2015).

In **rill expansion** a rill may erode at a faster rate than other neighbouring rills as a result of localised variations in soil erodibility. During the development of the rill, the flow of water is diverted into the rill, resulting in the destruction of neighbouring rills (Mararakanye, 2015). Further incision of the rill associated with continuous poor farming practices can further expand the rill beyond its 929 cm^2 critical cross-sectional value, thus forming a (ephemeral) gully (De Baets & Poesen, 2005; Desta & Adugna, 2012). The transition from rills to gullies is a continuum and the distinction between the two is vague. Nevertheless, the hypothesis that rill extension results in gullies was rejected by Oostwoud Wijdenes & Gerits (1994). Together with Billi & Dramis (2003), these authors state that the existence of rills does not automatically result in the formation of gullies because the former is not always the dimensional equivalent of gullies.

In comparison, **gully head retreat and deepening** occur when a knick point develops due to the absence of the resistant upper layer of soil or due to rapid erosion of the less resistant underlying layer within a channel (Mararakanye, 2015). Plunging of runoff occurring as a waterfall may also result in gully head retreat and deepening, due to undercutting and wall collapse or slumping, which then covers the gully head. This process also involves the throughflow of water from the scarp to the toe slope, where water scours the toe slope removing the soil until the bedrock is reached. Gullies form at this stage due to the scouring and collapse of walls (Mararakanye, 2015). Furthermore, Archibod *et al*. (2003) found scouring of channel beds and sides to be a triggering factor of gully development. This is attributed to headwall erosion resulting from either surface or subsurface water flow. Stein & LaTray (2002) elaborate further on scouring using two distinct layers, namely the erosive unbounded base layer and the thinner, cohesive, non-erosive surface layer. These authors further state that the flow geometry starts off steady on a constant slope and then approaches a pre-existing overfall, later forming a free-falling nappe. Flow then accelerates through the distance equal to the overfall height and impinges on the downstream erosive soil. A scour hole is rapidly generated as a result of impingement of flow water that is characterised by excess shear stress of the critical shear stress required to remove a particle from a downstream surface. The non-erosive layer is progressively undercut, leading to the eventual failure under its own weight and external forces. At this stage headward erosion takes place until the top of the slope or the bedrock is reached. The depth of the gully will proceed simultaneously with the advancement of the upstream waterfall erosion. The gully sides are also affected by erosion, because these tend to be bare, unstable and are normally slanted. Furthermore, secondary gullies may form on the sides of a gully due to concentrated runoff flows. As the secondary gullies advance, the gully bed/floor may experience further down-cutting resulting in a more stable gully (Carey, 2006).

Due to the newly deepened nature of the gully, the gully is now viewed in a more U-shaped cross section. The gully cross-section changes from a V-shaped manner to a more U-shaped one due to the slowed down rate of runoff flow or when the gully bottom reaches an impermeable layer (*e.g*. bedrock), becoming inactive (Kropáček *et al*., 2016). As such, a gully that takes up a U-shape is generally considered more stable and mature with reference to its development. During the drop in runoff flow, the gully bed/floor is susceptible to deposition resulting in a wider floor with sediment accumulation (Pathak *et al*., 2005). Gullies continue to deepen and widen until a new state of equilibrium is established. During runoff, water cascades over the headwalls, resulting in further plunge-pool erosion. The headwall later fails when an advanced stage of undercutting is reached, thus, lengthening the gully. Coupled with gully lengthening, is gully widening that occurs when the upper portions of the gully walls collapse into the gully (Bettis & Thompsom, 1985). As rainfall occurs and overland flow takes place, gullies may be faced with permanent concentration of these bodies of water (Pathak *et al*., 2005).

The last contributor to gully development, **subsurface erosion and piping**, leads to gully formation when water super-saturates the slowly permeable subsoil, moving soil particles in a lateral manner, resulting in subsurface channels. Water moves vertically into the soil and after reaching an impermeable layer moves laterally as subsurface erosion. The ground surface subsequently collapses, resulting in exposed pipes in the form of gullies (Desta & Adugna, 2012).

2.2.2. Gully classification

Gullies have various characteristics; classifying gullies, therefore, makes it easier for one to understand the processes involved in gullying. Gullies may be classified based on size/depth, drainage, discharge, shape (Desta & Adugna, 2012), continuation (le Roux & Sumner, 2012; Mararakanye, 2015) and gully head (Ireland *et al*., 1939). For the purpose of this study the only form of classification that is addressed, is the classification of gullies by type (Poesen *et al*., 2003; Capra, 2013; Mararakanye, 2015). Three types of gullies exist under this classification, namely 1) ephemeral, 2) permanent, and 3) bank gullies.

Ephemeral gullies are small incised channels that are larger than rills and may be recovered through normal tillage. These types of gullies may re-appear on the same location even after a single rainfall event (Poesen *et al*., 2003; Mararakanye, 2015). Ephemeral gullies can occur on two opposite slopes, along landscape linear elements and in natural drainage lines. They are common in cultivated fields as a result of the connection between a runoff contributing area and a runoff collecting network (Souchere *et al*., 2003; Capra, 2013). These gullies result essentially from hydraulic erosion by concentrated overland flow (Poesen *et al*., 1996). According to Capra (2013), ephemeral gullies may further be categorised into three types, classical ephemeral gullies (form as a result of concentrated runoff flowing in the same field where the runoff started), drainage ephemeral gullies (form due to concentrated flow draining upstream areas) and discontinuity ephemeral gullies (form in areas that have undergone a change in management practices). **Permanent gullies**, in contrast are channels that result due to concentrated but intermittent flow of water. Unlike ephemeral gullies, permanent gullies cannot be rehabilitated through normal tillage because they are usually deeper than 0.5 m (Poesen *et al*., 2003; Capra, 2013). Lastly, **bank gullies** form as a result of banks on outer curves of streams/rivers wearing out by means of undercutting and slumping (Mararakanye, 2015). Poesen *et al*. (1996) define a bank gully as one that forms where a wash-line, dead furrow, rill or an ephemeral gully crosses an earth bank. Once bank gullies form, they retreat by headcut migration into a moderate sloping soil surface and further into a river or agricultural terraces (Capra, 2013).

As previously discussed, gully erosion has received less attention compared to sheet and rill erosion. Nonetheless, there is progress evident in gully erosion research at both a national and global scale. Once gullies develop, they continue to grow in size until interventions by people or natural encroachment by vegetation occurs within the gully system. Knowing the rate at which gullies grow is thus of importance because the information may be used during the planning of gully erosion measures (Martinez-Casasnovas, 2003). Various gully erosion case studies have been done globally with many studies evident in Spain (*e.g*. Poesen *et al*., 1996; Casali *et al*., 1999; Oostwoud Wijdened *et al*., 2000; Nachtergaele *et al*., 2001a; Valcárcel *et al*., 2003) and Ethiopia (*e.g*. Nyssen *et al*., 2002; Billi & Dramis, 2003; Daba *et al*., 2003; Nyssen *et al*., 2006; Tebebu *et al*., 2010). A few of these case studies are described below, illustrating the factors contributing towards increased gully retreat rates.

A study by Martínez-Casasnovas (2003) in Alt Penedes Anoia (Catalonia), northeastern Spain, investigated the retreat rate of gullies and the associated rate of sediment production. The area is underlain by marls with occasional sandstones and conglomerates. The climate is classed as Mediterranean and associated with temperate to maritime conditions. Mean annual rainfall experienced in the region ranges from 471 to 670 mm. The dominant land use practice in the area relates to vineyards, with natural vegetation and forests dominating mountainous regions. Gully walls retreat rate was calculated at 0.2 m.yr^{-1} and the maximum channel incision rate ranged between 0.7 - 0.8 m.yr^{-1}. The maximum channel incision was dominant at the gully head and meandering zones with the rate of sediment produced 1322 ± 142 tons ha^{-1} yr^{-1}.

Another study performed in Catalonia, northeastern Spain, was one by Martínez-Casasnovas *et al*. (2009). As with the aforementioned study, the area is composed mainly of marls, sandstones and conglomerates; and the dominating land use is dedicated to vineyards. The area's climate is Mediterranean, with a mean annual rainfall of 550 mm and a mean annual temperature of 15 ºC. Martínez-Casasnovas *et al*. (2009) investigated the effect of land use change and vegetation cover on the rate of gully erosion. Infilling gullies reduced the total surface affected by erosion, occurring at a rate of 0.054 $ha.yr^{-1}$. Regardless of the filling action of gullies, gully erosion was still seen as an active process evident through sidewall retreat. High vegetation cover improved the control of gully retreat rates. On the other hand, changes in land use resulted in an increase in the moisture content within the gullies, thus favouring water recharge and consequent failure of gully walls by means of gravity.

Vandekerckhove *et al*. (2003) undertook a study in southeastern Spain within the Guadalentin basin. Like the aforementioned studies, the underlying lithology in this area consists of marls, sandstones and conglomerates. The annual average precipitation is 276 mm with a mean daily temperature of 16.4 ºC. Cultivated land and matorral (bushes) are the dominating land use activity and land cover respectively. The study aimed to determine both linear and volumetric gully retreat rates at different time scales within the basin. While no correlation was found between the linear retreat rate and the drainage basin area, a positive correlation was evident between the volumetric retreat rate and the drainage basin area. Headcut retreat rates under short term time scales were smaller than those of the medium-term time scale. Furthermore, in contrast to other studies, the clay content correlated positively to the volumetric retreat rate of gullies. Unfortunately, no direct explanation was provided for this correlation. Similar to the effect of rainfall, irrigation contributed towards the increment of gully headcut retreat seen through the 0.009 $ha.yr^{-1}$ rate.

Ethiopia is another country of interest due to the ubiquitous nature of gullies found irrespective of the climate, topsoil characteristics and the lithology of the substratum (Billi & Gramis, 2003). Kropáček *et al*. (2016) assessed gully erosion in the Upper Awash River basin within the central pan of the Ethiopian Highlands. Extensive mafic flows and ignimbrites are evident in the basin and the area is semi-arid with a mean annual precipitation of 982 mm. Arable land dominates the basin with trees scattered throughout the landscape. An expansion of settlements is also evident. Over the 49-year period investigated there was a three-fold increase evident for gully size together with an increase in the length of gullies. The gullies presented an increased rate of gully expansion in the initial stages and the expansion rate decreased with time due to gully filling. Changes in land use also promoted gully retreat rates. In comparison, rainfall variability in the region had minimal effect on the rate of gully expansion.

This was evident through the active gullies present in both wet and dry seasons throughout the entire study period.

Nyssen *et al*. (2006) also conducted a study in the Uplands of the Geba catchment, Ethiopia. Gully erosion rates were assessed over the previous decade and long and short-term rates of gully development were investigated within the region. Limestone, sandstone, basalt and Quaternary formations dominate the catchment and the mean annual rainfall in the area is 750 mm, concentrated in three months (mid-June to mid-September). The catchment's dominant land use, like the abovementioned study, is that of an arable one. Changes in land use from arable land to rangeland resulted in an increase in the extent of gullying. Gullying was correlated to vegetation cover in the region and it was evident that vegetation reduces the extent of gullying. Furthermore, droughts were prone to greater gully erosion in this study. The dry periods were related to death of vegetation, which then resulted in soil being susceptible to gully erosion. Long term gully erosion rates were 6.2 tons.ha^{-1} yr^{-1} with the short-term rate being 1.1 tons.ha^{-1} yr^{-1} (Nyssen *et al*., 2006).

The last study to be evaluated here in order to contextualise which factors contribute towards increased gully retreat rates is one by Frankl *et al*. (2012). This study was completed in northern Ethiopia with the aim of determining gully retreat rates at both short and medium to long term time scales. Similar to the study by Nyssen *et al.* (2006), the lithology in the area consists of limestone, sandstone and basalt. The climate is semi-arid with an annual precipitation of approximately 700 mm. Rain erosivity in this area, compared to other regions, occurs due to large raindrop sizes rather than the high rainfall intensity. Present in the area is low vegetation cover with patches of forests occurring only around churches. Under short term conditions, gullies indicated a daily retreat rate of 0 - 0.55 m.day^{-1} and 16 rain events. The number of active gullies revealed a positive correlation with the area's daily precipitation. An average linear retreat rate of 0.3 ± 0.49 m.yr^{-1} is evident, with an average areal retreat rate of 0.001 ha.yr^{-1} and an average volumetric retreat rate of 0.0005 ha.yr^{-1}. More gullies were evident in vegetated regions for a short-term time scale while few gullies were present in highly vegetated regions under medium to long term time scale conditions. No significant effect on the land use type was apparent for the medium to long term time scale on gully headcut retreat rates, lithology or headcut type. The short-term time scale had significantly smaller headcut retreat rates compared to the medium to long term time scale. This finding supports that of Vandekerckhove *et al*. (2003) and is explained by extreme rainfall events together with the soil and water conservation initiatives.

From the six examined case studies above, gully retreat rates are affected by lithology, changes in land use and vegetation cover. Moisture and precipitation are the two variables that may either stimulate or decrease gully retreat rates. The stimulation of gullying may be linked to the big raindrop sizes and not necessarily on the intensity of the rainfall. Reduction in the retreat rate may be associated with large inter-annual variability in rainfall, which is not evident for specific time scales.

2.2.3. Effects of climate variability and land use on gully erosion

Mararakanye's (2015) work highlights that gully erosion forms as a result of a combination of variables rather than individual factors. From the various definitions of gully erosion, it is clear that gully erosion occurs when a threshold has been exceeded (Poesen *et al*., 2003). Gullies are controlled by many factors (*i.e*. topography, geology, land use, soil properties, land cover/vegetation, climate change, and climate variability), which are explained in detail by *e.g.* Poesen *et al*. (2003), Valentin *et al*. (2005), Nel (2009) and Mararakanye (2015). This study is limited to thresholds recognised as having the greatest recognised impact on gully erosion, namely, 1) climate variability and, 2) land use.

Climate variability is the variation in the mean state together with other statistics of climate on a temporal and spatial scale beyond an individual weather event (WMO, 2017). It occurs in both global air temperature and precipitation. Increments in atmospheric temperatures and rainfall events are evident over the past years; these may result in the changes to soil erosion rates. Variations in the rate of soil erosion are due to changes in the erosive power of rainfall, changes in plant residue and decomposition rates, alterations in land use and modifications in biomass (Nearing, 2001). An example of changes in biomass is the anthropogenic increase in atmospheric CO_2 concentration. This results in an increase in the rate of plant production together with changes in plant transpiration rates, later leading to an increase in biological ground cover (Nearing *et al*., 2004). Warmer atmospheric temperatures are predicted to lead to vigorous hydrological cycles and extreme rainfall events (IPCC, 1995). This results in the predicted increase of more intense rainfall events in the coming decades (Mondal *et al*., 2015).

Many physical and chemical properties of soil (*e.g*. soil moisture, infiltration rates and organic carbon content) are affected by climate variability and climate change. The growing season for many crops is affected by changes in rainfall, temperature and CO_2 levels in the atmosphere (Pretorius, 2016). This generally leads to a shift in management practices, yielding a potential increase in soil erosion and concomitant land degradation. Previous studies (*e.g*. Nearing *et al*., 2005; Zhang, 2007) highlight a direct correlation between changing precipitation and soil erosion. Rain erosivity in other regions occurs as a result of large raindrop sizes as compared to other regions where the intensity of the rainfall is the one factor responsible for stimulating erosion (Frankl *et al*., 2012). Hortonian overland flow may then occur as a result of great rainfall intensities in the region and large volumes of fast flowing runoff carrying large amounts of sediments into waterways (Poesen *et al*., 2003; Valentin *et* *al*., 2005 and Mararakanye, 2015). At times, intense seepage of rainfall into the soil occurs and results in saturation of the soil (saturated overland flow).

The influence of climatic conditions on soil erosion has commonly been explained in terms of rainfall and not global air temperature. In regions where low rainfall or drought is evident, vegetation cover is reduced, leaving areas of land unprotected from rain-splash. Semi-arid regions are often characterised by rapid gully erosion rates due to the alternating climatic characteristics that promote the development of cracks in soils and the slowdown of vegetation growth. Due to land being free from vegetation, increased levels of runoff are evident, promoting gully erosion. Intense rainfall may further lead to soils depleted in organic matter and subsequent crusting that increases the volume of runoff and gully erosion (Mararakanye, 2015).

Variability in rainfall events was used in this study in order to assess and relate the extent of gullying within the Lower Thina Catchment. This was because most studies focusing on soil-loss modelling predominantly include rainfall events data (Nel *et al*., 2010). Studies based on historical trends in precipitation over southern Africa are reported by Kruger (2006) to have significant decrease in annual precipitation in northern Limpopo, western KwaZulu-Natal, southern Eastern Cape and the northeastern Free State. Recently, however, a difference is noticeable as increased inter-annual rainfall variability such as droughts and high rainfall anomalies, are evident in southern Africa. In South Africa, few studies on climate variability have been performed along the coastal provinces, the subtropical KwaZulu-Natal Province and the Limpopo Province. The Eastern Cape exhibits a bi-modal type of rainfall, which means the province experiences both summer and winter rainfall (DEA, 2010). Climate within the province is that of a sub-humid one (le Roux *et al*., 2015) that has temperatures ranging between -10.5 ºC and 31.4 ºC (Mucina *et al*., 2006) and mean annual rainfall of 707 mm – 928 mm (Mucina *et al*., 2006; Pulley *et al*., 2017). According to Zengeni *et al*., (2016), the province has a low annual rainfall variability with some weather stations indicating a decreasing trend in annual rainfall. It is noted that changing climate variability has a greater impact on environmental vulnerability compared to annual changing mean rainfall (Zengeni *et al*., 2016). To illustrate the inter- and intra-annual climate variability evident within the country, some examples from the Drakensberg and Limpopo province are provided here.

Rainfall trends in KwaZulu-Natal were investigated by Nel (2009), where 11 weather stations across the Drakensberg region were used to collect daily rainfall data. The collected rainfall data indicate no significant trend in inter-annual variability during the last half of the 20th century. The Precipitation Concentration Index (PCI) was used to determine the intra-annual variability and its temporal trends (Nel & Sumner, 2006; Nel, 2009). An increase in PCI was evident, indicating an increase in seasonality of monthly rainfall. Nel *et al*. (2010) further tested the hypothesis that rainfall erosivity decreases with an increase in altitude within the northern

KwaZulu-Natal Drakensberg. Findings indicate that there are prolonged rainfall events along the escarpment, however, the amount and intensity of the rainfall is lower on the escarpment than in the foothills. Furthermore, Nel & Sumner (2007) studied rainfall erosivity along the Drakensberg, KwaZulu-Natal. This study revealed varying storm events in both duration and depth. The erosive rainfall was associated with thunderstorms and was highly seasonal. Individual storm events had a great potential to detach soil, however, at higher altitude, a lower percentage of rainfall, erosive storms and cumulative kinetic energy produced was less. Lack of erosive rainstorms may, therefore, be used to explain altitudinal differences during early and late summers.

A study conducted in the Luvuvhu River Catchment by Odiyo *et al*. (2015), investigated the long-term changes and variability in daily rainfall and streamflow within the catchment, indictating that fluctuations in rainfall exist. Four of the six weather stations indicated increasing trends with only two of the six weather stations showing a decreasing trend. An overall increase in rainfall and streamflow was evident for the 86-year study period within the Luvuvhu River Catchment.

Rainfall is also a commonly known driving force for erosion processes associated with water (Mararakanye, 2015). Following a dry period, a single intense rainstorm is seen to initiate gully erosion particularly on bare ground (Vetter, 2007). Rainfall erosivity is the erosive force of rainfall and runoff (Vreiling *et al*., 2010) and is the interaction between kinetic energy of raindrops and the soil surface, resulting in greater or lower degree of detachment (da Silva, 2004). It is usually referred to as the R-factor, which is based on one of the factors forming part of the Universal Soil Loss Equation (USLE) model. Although Valentin *et al.* (2005) state that the R-factor assesses sheet and rill erosion and not gully erosion, high-intensity rain is seen to trigger the formation of gullies (Vreiling *et al*., 2010).

Rainfall erosivity of a storm event is equal to the product of the total storm energy and the maximum 30-minute rainfall intensity. This method is still in use in the Revised Universal Soil Loss Equation (RUSLE) model where total storm kinetic energy and maximum rainfall intensity in 30 minutes are considered. Nevertheless, not all rainfall erosivity is calculated at a 30-minute rainfall intensity. Predicted R-factor changes cannot be calculated because Global Circulation Models (GCMs) do not provide detailed storm information. According to Nearing (2001), statistical relationships between monthly and annual precipitation and the R-factor should, therefore, be used to analyse the GCM output relative to erosivity changes. Le Roux *et al*. (2006) created a rainfall erosivity map. Daily rainfall data of South Africa made it possible for le Roux *et al*. (2006) to derive a map for the whole country. The derived map together with other erosivity maps, are useful for soil conservationists, agronomists and engineers as they provide knowledge about the rainfall erosivity potential of various locations. Necessary precautions may thus, be implemented in order to minimise soil erosion in these areas.

It is noted by Kakembo (2000) and Vetter (2007), that the ability of a rainfall event to cause gully erosion is dependent on the quantity, frequency and intensity of the rainfall. Gully erosion rates differ depending on the amount of rainfall received annually (in mm). Erosive rainfall may be less than 900 mm (Ligget & Fincham, 1989), between 600 mm and 800 mm (Botha *et al*., 1994) or even between 550 mm and 560 mm (Watson & Ramokgopa, 1997) and still contribute towards gully erosion. This demonstrates the complex interactions of climate on gully erosion (Taruvinga, 2008).

To further illustrate the effect that climate variability has on various catchments, a few case studies are presented here. Long term rainfall records were assessed by Nel (2009) in the Drakensberg region, east of the escarpment. Eleven weather stations provided long-term rainfall data for the study area. Large-scale line thunderstorms together with orographically induced storms are the major sources of precipitation along the Drakensberg. Rainfall in the area is seasonal, furthermore, approximately 43 cold fronts result in occasional snow and widespread rainfall across the area. Mean annual rainfall in the study was related to altitude, where altitudes below 2,100 m a.s.l. reflected annual rainfall exceeding 1,500 mm. From the analysis of the collected data, no significant trend in inter-annual variability was evident. The Precipitation Concentration Index (PCI) was used to determine the intra-annual variability and high PCI values were evident along the Drakensberg, suggesting an increase in summer rainfall and a decrease in winter rainfall.

Odiyo *et al*. (2015) investigated long-term changes and variability in daily rainfall and streamflow within the Luvuvhu River Catchment, South Africa. The mean annual rainfall of the area is 608 mm and much of the rainfall falls in the upper reaches, with little rainfall present in the lower reaches. The dominating land use in the catchment is rangeland, with forestry, agriculture and settlement common land use activities. Most rainfall stations in the Luvuvhu catchment displayed a decreasing trend for 5- and 10-year mean rainfall. Increased variability of rainfall and streamflow was evident, increasing the variability of available water resources. Both rainfall and streamflow are, thus, highly variable in this catchment with global climate models used in the study indicating variation in rainfall over the entire study area. More rainfall was predicted for the east region while less rainfall was predicted for the west coast. A minor inter-annual variability was also projected within the catchment.

Decadal and long-term rainfall patterns were determined by Marengo (2004) for the entire Brazil Amazon basin. Almost 300 weather stations were used for the period 1929 – 1999. Sea Surface Temperatures (SST) data together with the circulation anomaly fields were used to investigate the surface conditions and near surface circulation over the tropical oceans. The basin indicated an average rainfall of 8.1 mm.day^{-1} with a negative trend in rainfall evident for Northern Amazonia. Rainfall data obtained from gauges displayed a positive trend for the Southern Amazonia. Both the Northern and Southern Amazonia reflect alternating wet and dry periods while showing opposite normalised rainfall departure series. Deficient rainy seasons in Northern Amazonia are related to the anomalously warm surface waters in the tropical, central and eastern Pacific Ocean. Rainy seasons in Southern Amazonia are consistent with anomalously warm surface waters in the tropical south Pacific, east Atlantic and the Indian Ocean. This reflects a contradiction in SST correlation for the rainfall anomalies occurring in the Northern Amazonia. Inter-annual variations are associated with both El Niño and La Niña events that occurred in Brazil.

Nicholls *et al*. (1997) performed a study in Australia in order to calculate the ratio of observed relative variability, to the relative variability predicted from the global relationship. A total of 341 rainfall stations were used; all stations had data from as early as 1910. Australia has a dry geographic centre with a mean annual rainfall of less than 100 mm. The spatial and temporal variability of rainfall is, therefore, large. Both El Niño and La Niña events were evident for the area with the Southern Oscillation Index (SOI) strongly negative and positive respectively. Rainfall has a negative strong correlation (r = - 0.52) with maximum temperatures while having a positive correlation (r = 0.13) with minimum temperatures. These relationships may be masked by the correlation (r = 0.62) between the maximum and minimum temperatures.

It is evident that different regions have varying inter- and intra- annual rainfall patterns as a result of the alternating wet and dry events. Variation in climate together with other factors such as land use, affect the type and extent of erosion occurring in an area. Pretorius' (2016) study is one of the few studies revealing the impact climate variability has on soil erosion. An increase in rainfall increased the rate and extent of soil erosion within the catchment investigated. Mullan *et al*. (2012) support this by stating that climate change has an impact on the erosive power of rainfall, the amount of erosion, and temporal rainfall patterns. Prediction of future climate conditions is, thus worthwhile because this aids in the long-term plans and management strategies of an area. The effect of rainfall variability within the Lower Thina Catchment is thus, investigated and a link made to the extent of gullying.

Land use change is another factor contributing to gully erosion, resulting in the reduction of vegetation cover and subsequent development of channels where water flows and concentrates (Mararakanye, 2015). While the influence of land use changes in gully erosion has received less attention, Valentin *et al*. (2005) and Kavian *et al*. (2017) argue that land use has a greater impact on soil erosion than climate change. Furthermore, the land use factor is considered more important in explaining differences in topographical thresholds for gully initiation (Martínez–Casasnovas *et al*., 2009), with land use effects estimated through RUSLE and GIS models (Kavian *et al*., 2017).

Vegetation change is also integral in assessing land degradation and erosion. It has a double-edged effect on erosion as it not only aids in reducing the rate and extent of surface erosion but may also increase the rate of subsurface erosion. Soils with little vegetation, or no vegetation cover at all, are prone to greater overland flow velocity as a result of the soil's inability to resist its erosive action (Igbokwe *et al*., 2008). Laker (2004) states that vegetation cover reduces the kinetic energy of raindrops, which then act as a soil surface barrier, holding soil particles together and preventing soil from being washed away (Jahantigh & Pessarakli, 2011). Parallel to this, vegetation absorbs the shear boundary stress caused by rainfall (Molina *et al*., 2009). With respect to subsurface erosion, stemflow from vegetation promotes infiltration of rainwater into the soil; much of the rainwater then reaches greater depths by following tree roots. This increased seepage of water into the soil may further stimulate subsurface erosion. Swelling and shrinking cycles of soil occurring as a result of the alternating wet and dry seasons, could possibly fuel gully retreat rates (Grellier *et al*., 2012). Soils poor in organic matter are also more susceptible to erosion, which may later result in the expansion and/or further growth of gullies. A study by Tamene *et al*. (2006) supports this by identifying poor vegetation cover as one of the main factors contributing to gully erosion. Moreover, le Roux & Sumner's (2012) study revealed a high number of gullies present in poorly vegetated areas. Vegetation is, therefore, required as a control and prevention measure for gully erosion, hence reducing the rate at which gullies grow. Both rill and gully erosion rates decrease exponentially with root length densities; this means that effective roots (roots with a diameter less than 1 mm) increase the resistance of soil to concentrated flow erosion (Gyssels *et al*., 2005).

A variety of catchemnets affected by gully erosion in the Eastern Cape uncover a robust link between land abandonment and gullying (Kakembo & Rowntree, 2003). Similar trends have also been identified in Kwazulu-Natal, South Africa (Sonneveld *et al*., 2005); in the Ecuadorian Andes (Harden, 1996), Taita, Kenya (Sirviö *et al*. 2004), and in Southeast Spain (Lesschen *et al*. 2007; Gutiérrez *et al*., 2009a). Construction of roads also results in the deviation and concentration of surface runoff to other catchments. If the road design is done poorly, the level of deviation and concentration of runoff will not be minimal, thus the development of gully erosion is more probable (*e.g.* Ethiopian Highlands). Rural areas without paved roads, i.e. non-tarred roads, may experience gully erosion due to the lack of measures that promote healthy vegetation cover. Gullies may also form when a change in urban drainage patterns occurs as a result of urbanisation (Poesen *et al*., 2003; Valentin *et al*., 2005). Finally, irrigation channels, overgrazing and abandoned fields are seen to promote and trigger gully erosion (Peosen *et al*., 2003; Taruvinga, 2008; Mararakanye, 2015). Valentin *et al*. (2005) highlighted three main periods in Europe when gully erosion was evident. Gully erosion occurred extensively during the 14th century when extensive forest clearance and expansion of farmlands took place in Europe. This period was followed by the period between the 16th century and the 1730s together with the Little Ice Age period (18th and 19th centuries), where gully erosion showed extensive and detrimental effects on the soil. In terms of the Southern African context, historical land use changes such as switching from cereals to maize, may also have dramatic erosional impacts, as is the case in Lesotho. The Basotho people fled to the mountains in the 1830s due to the infiltration of the Boer Trekkers that originated from the Cape. This led to an increase in soil erosion as the already vulnerable mountainous land experienced overgrazing and increase in footpaths in the areas where the Basotho people settled (Sibanda, 2003).

To further illustrate the effect of land use on the promotion of gully erosion, a few case studies are discussed below. Cropping (Weepener *et al.,* 2015), forestation, grasslands, irrigation channels, overgrazing, abandoned land (Peosen *et al*., 2003; Taruvinga, 2008; Mararakanye, 2015) and road construction or paved areas (Jungerius *et al*., 2002), are some of the few common land uses known to promote gully erosion. Gutiérrez *et al*. (2009b) conducted a study in the Parapunos experimental catchment located in southwest Spain. The purpose of the study was to analyse the evolution of gullies and relate it to land use and vegetation cover. Mean annual rainfall in the area is 525 mm with low rainfall intensities. The catchment is dominated by savannah-like wooded rangelands and has silt, sand and minor clays making up the underlying lithology. Initially (1945), the area had much livestock grazing and forest use. Crop production dominated most parts of the catchment in 1956, leading to a reduction in vegetation cover. During this period, valley bottoms/floors experienced a great change, although not completely colonised by grasslands, more grassland were now evident. Furthermore, the grassland was interspersed by sparse woody vegetation. During the study period, gullies increased in size, reaching a maximum in 1956. Natural vegetation recolonised post 1956; with this came a reduction in the area affected by gullying. Most agricultural activities were abandoned during this time. Between 1998 and 2006, the area experienced reactivation of gullies due to an increase in cultivated areas. This was related to increased livestock density, resulting in overgrazing.

Galang *et al*. (2007) completed a study in South Carolina that dealt with the effect of land use on gully erosion. The soil present in the study is that of sandy loam and the average annual total of rainfall energy-intensity approximately 250. Two land uses were identified in the area, being cultivated-to-forested and continually forested. Land use in the area was initially forested, changing to cultivated land and then back to forest. This was due to alternating deforestation, farming and abandonment of land, and reforestation. An increase in gullies occurred with an increase in forestation. This was related to slopes exceeding the 12% threshold and poor famring practices on the previously cultivated land. This, together with high rainfall intensity and highly erodible soils, was needed to stimulate gullying in the region.

A study by van Zijl *et al*. (2013) was conducted in the Maphutseng valley of the Mohale's Hoek region of Lesotho. Questions regarding why gullying was occurring and what could be done, were addressed. The underlying lithology consists of basalt, sandstones, red shale beds, and quartzite conglomerate. The rainfall occurring in the region is of an intense thunderstorm type, while the measured mean annual precipitation is 740 mm. The areas with lower gradients are used mainly for maize and sorghum production; dominating land uses are cultivation and vegetation grazing. The area was severely degraded and had a gully density of 6.4 km.km^{-2} in 2006. The nature of soil was a greater determinant of gullying than the land use, geology and gradient of the area. Areas with duplex soils had an extension rate greater than those which were not duplex in nature. Abandoned areas also showed a great deal of gully extension. Main gullies grew at a greater rate with new gullies forming from the already existing ones, indicating that formation of peripheral or new gullies is influenced by the presence of main gullies (van Zijl *et al*., 2013).

Kakembo & Rowntree (2003) conducted a study in the Eastern Cape, South Africa where one of the objectives was to examine land use changes and their relation to the distribution of erosion. The study area is located in the part of the dividing ridge between the Great Fish and Keiskamma rivers near Peddie. The underlying lithology consists of sandstones, shales and red mudstones and the mean annual rainfall is 488 mm. Dominant land use classes identified were cultivated land, grazing land, and abandoned land. Results show that a great shift from slight sheet erosion to gully erosion was evident with observable erosion confined to communal lands. This was seen through the 278% rise as a result of an increase in erosion class 4 (severe rill and gully) and 5 (intricate gully patterns and degraded gully remnants). Terrain factors and drainage density could be the two reasons why erosion is concentrated on communal lands. Abandoned cultivated fields were also characterised by severe gullies. This was mostly attributed to unvegetated fields that occurred due to abandonment (Kakembo & Rowntree, 2003).

It is noted from the land use case studies, that various land uses result in different extents of gullying. Land use on its own is not, however, the sole cause of extensive gullying. Other factors such as slope gradient, soil type and underlying geology, contribute to the effect land use has on gully erosion. Above all, overgrazing and abandoned fields result in the greatest and most severe gully systems. Furthermore, vegetation cover may reduce the size of gullies, as evident through stabilised gully systems due to vegetation encroachment.

2.3. Erosion on a national context

South Africa's latest State of Environment Report indicates that erosion is a serious matter in South Africa as it affects over 70% of the country and is costly (estimated at R2 billion annually) (le Roux *et al*., 2008). In the Eastern Cape Province, soil erosion occurs from both unconcentrated and concentrated flow with most of the sediment derived from gully erosion. Le Roux *et al*. (2007) highlight that the Department of Agriculture (DoA) together with the Water Research Commission (WRC) have funded many South African regional-based research projects. Global Assessment of Soil Degradation (GLASOD) was one of the first major regional-scale degradation studies performed worldwide. This study was conducted by the International Soil Reference and Information Centre (ISRIC) and the United Nations Environmental Programme (UNEP) beginning in 1988 and ending in 1991 (ISRIC, 2017). The study entailed dividing soil erosion areas into uniform units based on the most important erosional processes. Two achievements were evident from the study, namely the production of a soil erosion map together with the relative ranking of human-induced soil erosion analysed per area (le Roux *et al*., 2007; Pretorius, 2016).

In 1993, remote sensing together with GIS applications in soil degradation management was investigated by the Agricultural Research Council-Institute for Soil, Climate and Water (ARC-ISCW). The Erosion Susceptibility Map (ESM) later became the first attempt to incorporate soil erosion risk factors at a national scale using GIS. Later in 1998, the Predicted Water Erosion Map (PWEM) was produced and it applied the Universal Soil Loss Equation (USLE) (le Roux *et al*., 2008). ESM and PWEM were based on oversimplification of the common USLE model as they combined soil and slope factors with sediment yield data. The South African National Biodiversity Institute later compiled a national soil degradation review with information used from 34 workshops held across South Africa in 1997 and 1998 (le Roux *et al,* 2007).

Pretorius *et al*. (2015) conducted a study in the Eastern Cape (Mzimvubu Catchment) and revealed that insufficient land management and poor soils, resulted in extreme soil erosion, particularly gully erosion. More recently, Seutloali *et al*. (2016) produced soil erosion severity index maps of the former homelands of Transkei. Currently, the Institution for Soil, Climate and Water (ISCW) is working on several region-based studies which are all funded by the (now) Department of Environment, Forestry and Fisheries (DEFF) and WRC.

2.4. Mapping and modelling approaches

Mapping of gullies is done through orthorectified aerial photographs. Orthorectified images are required in order to minimise distortions caused by earth curvature, displacements of terrain variations and varying scale from the centre of the image to the outer edge. Gullies may also be mapped using satellite imagery. Gully characteristics should be large enough to be visually detectable in a computer of high spatial resolution (*e.g.* 0.5 m) (Mararakanye, 2015). **Geographic Information Systems (GIS),** which is the manual or computer based storage and manipulation of geographically referenced data (Aronoff, 1989), together with **remote**

sensing (the study of the surface of the earth derived from scanners mounted on satellite platforms; Maguire, 1991) have proven to be important information system applications in creating soil erosion models (*e.g*. Conforti *et al*., 2011; Mhangara & Kakembo, 2012).

The majority of the recent soil erosion studies are conducted using GIS where catchment processes are simulated and modelled. Historical aerial photographs are widely used in the integrated GIS approach (*e.g*. Vandekerckhove *et al*., 2003; Pretorius, 2015; Kropáček *et al*., 2016), aiding in investigating various forms of erosion including the development and growth of gullies (Kropáček *et al*., 2016). Most GIS models are known to successfully simulate both complexity and heterogeneity found within the environment. Unlike many traditional field-based methods, GIS techniques are not susceptible to either animal or human disturbances. This, therefore, makes GIS a more preferred practice of determining soil erosion over the traditional field-based methods (Pretorius, 2016).

Nonetheless, both techniques include bias (Bocco, 1991); traditional methods (fieldwork) of mapping and analysing soil erosion are time consuming and less accurate without the coupled use of GIS and remote sensing techniques. In turn, manual interpretation is associated with human errors while GIS software (*e.g*. eCognition) are associated with erroneous identification (Pretorius, 2016). The software techniques are also expensive and are not always readily and freely available for use (Seutloali *et al*., 2016). Even with the shortfalls such techniques have, they are still widely used at a global scale (*e.g*. Vandaele *et al*., 1997; Poesen *et al*., 2003; Mullan *et al*., 2012; le Roux *et al*., 2015) with fieldwork serving as validation (Kropáček *et al*., 2016).

A variety of erosion models exist and are executed using GIS, from simple, empirical ones (*e.g*. USLE) to more complex, physically-based models such as Water Erosion Prediction Project (WEPP). Two of these models, USLE and RUSLE, are most widely used for the purpose of modelling soil erosion at a regional scale (le Roux *et al*., 2007; Capra, 2013; Vanwalleghem *et al*., 2017). These models together with the Soil Loss Estimation Model for South Africa (SLEMSA) model, are the most frequently used models in South Africa (Laker, 2004; le Roux *et al*., 2007). There are three common reasons which exist for the popularity of these three models, namely, 1) the relative simplicity of the model, 2) the possibility of introducing the effect of land use, management or climate on the key drivers of soil erosion to the model, and 3) because the models' average error and efficiency is similar in predicting soil loss (Vanwalleghem *et al*., 2017). These models are designed to predict long-term average soil loss from runoff plots, they, however, cannot predict soil loss from gully erosion as a result of the complexities associated with gullying (Vandaele *et al*., 1997; Valentin *et al*., 2005; Mararakanye, 2015).

Poesen *et al*., (2003) further state that gully erosion rates may be determined through flow models such as Chemical, Runoff and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects of Agricultural Loading Systems (GLEAMS), Ephemeral Gully Erosion Model (EGEM) and WEPP watershed model. The authors acknowledge that at the time of publication these models have not thoroughly been tested for gully erosional processes.

EGEM is one of the models which was developed and tested for gully width and soil loss by ephemeral gully erosion. In the early 21st century, Nachtergaele *et al*. (2001a) tested the EGEM model in the Mediterranean environment, however, the model did not successfully determine gully width and soil loss. Nachtergaele *et al*. (2001a, b) further tested the model in Spain, Portugal and Belgium where they concluded that the EGEM model is not capable of predicting ephemeral gully erosion in such environments. Capra *et al*. (2005) later adjusted the hydrology components of the model and applied the model in Italy. The study revealed that gully cross-section and width cannot be adequately predicted. REGEM was the next model developed by Gordon *et al*. (2006). This model was developed in order to address the challenges associated with EGEM. The model is not yet widely tested for ephemeral gullies and it requires a large amount of input data (Mararakanye, 2015). In comparison, the STREAM Ephemeral Gully Model was developed by Souchere *et al*. (2003) and was used to estimate the rate of erosion by the main runoff collector network. The model was deemed fit to predict gully erosion from simple information such as land use, soil surface crusting stage, plant cover and tillage direction. The model was, however, found to overestimate the erosion rate. Casali *et al*. (2003) in turn adapted an event-oriented process-based model in order to estimate ephemeral gully erosion. This model was tested in a small watershed and allowed for the proper estimation of soil loss and gully cross section shapes along a channel.

The 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*” (Mararakanye, 2015:24). ERU has successfully been applied in the Mkomazi River catchment in KwaZulu-Natal (South Africa) and in the Mbuluzi River catchment of Swaziland. ERU identifies areas affected by different forms of water erosion and is able to determine the susceptibility of a landscape to erosion. Different models can incorporate ERU and estimate the loss of soil from different types of soil erosion (Mararakanye, 2015). In order to successfully use ERUs, they need to be delineated and used for spatial scale transfer in regional modelling. ERUs can be applied as a modelling entity and may characterise the distribution of gully erosion features (Sidorchuk *et al.*, 2003).

The topographical threshold is a concept used to predict gully heads in a landscape. The threshold is widely understood in terms of the combination of upslope contributing area index and slope gradient (Mararakanye, 2015). Poesen *et al*. (2003) explained the index in a form of an equation ($S=aA^b$) and state that the slope gradient of the soil surface (S) and critical drainage area (A) are necessary to produce sufficient runoff, which then triggers gully incision. An inversely proportional relationship between the slope of a landscape and the critical drainage area was determined with the “*a*” and “*b*” coefficients highly dependent on environmental characteristics.

Other thresholds such as the rainfall erosivity, soil erodibility and vegetation cover are useful for modelling gullies (le Roux *et al*., 2008). Rainfall erosivity is the erosive force of rainfall and runoff (Vreiling *et al*., 2010) usually referred to as the R-factor and is based on the USLE model. Soil erodibility is the ability of the inherent properties of soil to influence erosion. There are primary soil properties that need to be considered when estimating the erodibility values, these being particle distribution, organic matter content, surface structure and profile permeability. Vegetation indices are other commonly used thresholds that are good indicators of land management practices. Gully mapping in South Africa has been done through vegetation indices such as Normalized Difference Vegetation Indices (NDVI), Soil Adjusted Vegetation Indices (SAVI) and Transformed Soil Adjusted Vegetation Indices (TSAVI). Taruvinga (2008) applied all three indices to Kwazulu-Natal with le Roux & Sumner (2012) only applying the TSAVI index in the Eastern Cape (Mararakanye, 2015). Finally, The Stable Gully Model is a model used to calculate gully flowline network at a gully’s final development stage (*e.g*. Marker & Sidorchuk, 2003; Sidorchuk *et al*., 2003). The model is based on the assumption that both gully bottom and gully walls reach a final morphological equilibrium. Once equilibrium is met, the gully bottom and width do not change any further. In order to successfully run the Stable Gully model, geomorphologic and geological data are required as input data. The data are obtainable from measurements and calculations accessible from hydrological stations and meteorological data respectively (Sidorchuk *et al*., 2003).

Gully erosion research in South Africa focuses on three key aspects being 1) the origin of gullies, 2) soil loss rates and 3) contributing factors (Mararakanye, 2015). In his paper, Mararakanye (2015) focuses on the last aspect but only addresses two of the factors (land use and climate variability in the form of rainfall) as they contribute greatly to gully erosion both at a global and local scale (*e.g*. Fernandez *et al*., 2003; Valentin *et al*., 2005; Seutloali *et al*., 2016). Previous South African literature (*e.g*. Vetter, 2007; le Roux & Sumner, 2012; Kakembo *et al*., 2009) suggests land use to be a factor extensively covered in gully erosion studies as compared to the briefly covered rainfall factor (*e.g*. Liggett & Fincham, 1989; Kakembo & Rowntree, 2003). It is important to examine the effects of these factors because according to the IPCC (2007), climate change and land use are expected to change as a result of human activities. This study, therefore, attempts to quantify the historical changes of gully erosion using GIS and remote sensing techniques and correlates these to land cover change and climate variability.

South Africa is affected by varying intensities of soil erosion with soil erosion rates poorly constrained throughout the country (le Roux *et al*., 2007). Despite this, most erosion occurs in the KwaZulu-Natal and Eastern Cape provinces (Mararakanye, 2015). Although other provinces also exhibit gully erosion, Mararakanye (2015) states that the severity of gully erosion in these provinces should not be underestimated especially in relation to soil conservation. Le Roux *et al*. (2007) performed a study using GIS techniques on the rates of soil erosion occurring in South Africa and found that spatial pattern predictions of soil erosion are not very accurate as a result of spatial and temporal variations (Jetten *et al*., 2003). As such, studies in other provinces should not be ignored.

Le Roux & Sumner (2012) also used GIS and remote sensing to digitise continuous and discontinuous gullies at a catchment scale using SPOT 5 imagery. Continuous gullies covered a greater area (2,905 ha) compared to the discontinuous gullies with an area of only 2,368 ha. Land use, soil properties and topographical factors were highlighted as factors having the greatest impact on gullying. Due to cultivated and degraded areas frequently disturbed, gully development was favoured in these areas.

The spatial distribution of gully erosion in Limpopo was mapped by Mararakanye & Nethengwe (2012) using remote sensing together with traditional techniques. Both traditional and software techniques were used in the study by van Zijl (2013), which aimed at investigating factors responsible for gully erosion. The study identified various factors, including land use as a contributing factor towards gulling. Mararakanye & le Roux (2012), used SPOT 5 satellite imagery at a 1:10 000 scale in order to highlight severe gullies found throughout South Africa. The authors further investigated and tested a Geographic Object Based Image Analysis (GEOBIA) technique called Imagine Object (IO) for the extraction of gully features in the Capricorn District Municipality, Limpopo Province. In contrast, le Roux & Sumner (2013) performed a study that looked at describing a multi-process and multi-scale approach for soil erosion risk assessment under South African conditions. Sheet-rill and gully erosion were assessed using GIS together with field observations for validation. Land use, together with rainfall parameters, were again identified as factors controlling gully development. A limitation was identified with reference to rainfall intensity data by le Roux *et al*. (2008), who stated that the data are usually incomplete and/or have short recorded periods (at a regional scale). Unlike the study by Poesen *et al.* (2003), abandoned croplands in Laker's (2004) study reflected less severe gullies. This could be as a result of the contouring present in the area.

Pretorius (2016) also conducted a study in South Africa and highlighted the effect of land use and climate change on sediment yield production in the Upper Tsitsa River Catchment, Eastern Cape. eCognition was used to identify gully location, whereas SWAT was used to determine sediment production from both sheet and rill erosion. Modelling of sediment generated in the catchment was further performed using projected climate change data.

Projected climate change scenarios together with changes in land use, showed an increase in soil erosion thus, an increase in sediment yield within the catchment.

While various erosion models exist and their use is acknowledged, this study does not make use of any of these. Rather, GIS are used to identify and map gullies over specific time spans using aerial photography and satellite imagery. GIS are then further utilised to overlay secondary historical data with identified gullies in order to identify forcings and impacts of gully extension.

2.5. Control and prevention measures

Poesen *et al*. (2003) and Poesen (2011) note that gully erosion control and prevention measures in South Africa have not adequately been addressed. By quantifying the historical changes of gullies in the Lower Thina Catchment, determining the influence of various land use activities, and relating historical climate variability to the extent of gully erosion, the processes of gullying are better understood. Through this, control and prevention measures may be applied as these are based on the understanding of erosional processes together with the biophysical and land use factors driving such processes (Boardman, 2014). Environmental management is vital for policy implementation countrywide for the reduction in degradation of land.

Gullies are known to negatively affect societies globally; it is thus important to understand the triggering factors of gully erosion to try and eliminate or lessen hazards associated with such erosion. In addition to the mechanisms involved in gullying, a few other trigging factors exist, namely, 1) poor drainage control, 2) land clearing on unstable land, 3) deep pads caused by stock, and 4) badly constructed roads. In order to implement control and prevention measures for gully erosion, a range of factors (*i.e.* the size of the gully, the geology of the land, the frequency of water flowing within the gully, the topography of the area, whether erosion is still actively in place or not, and what the land will be used for after rehabilitation) should be well understood as these have an influence on the outcome of the measures (Abegunde *et al*., 2006).

Although natural erosion results in gully formation, accelerated erosion (manmade) plays a bigger role in the formation of gullies (Pimental *et al*., 1995; Abdulfatai *et al*., 2014). Due to human influences contributing to accelerated gully erosion rates, humans should act accordingly to ameliorate gully growth. Many of the control measures taken for areas affected by gullies are those by communities residing near such landforms. These methods are usually cost effective and work for a certain period of time and include the use of vegetation, rotation of cattle, check dams, diversion banks, gully formalisation and usage of sandbags.

Vegetation is a common gully control measure proven effective not only in Africa (*e.g*. Ethiopia, Lesotho and Nigeria) but on other continents such as Asia (Pimental *et al*., 1995), Europe (Valentin *et al*., 2005) and Australia (Nicholls *et al*., 1997). As discussed previously, vegetation is useful in that it promotes water infiltration and protects the soil from intense erosion. The absence of ground cover results in the direct impact of soil through the breakdown of soil aggregates, dislodging of soil particles, sheet erosion and soil surface seals and crusts from dislodged clay particles (Shellberg & Brooks, 2013). Vegetation also plays a mediating role in the hydrological cycle. It intercepts precipitation, increases evaporation and infiltration, decreases water runoff and increases storage of water in small depressions due to surface roughness.

In New Zealand, gully erosion increased as a result of the conversion of land use to pasture. Reforestation of the area later resulted in the decline in sediment yield within the area (Gomez *et al*., 2003). In the semi-arid Mediterranean landscape of Spain, De Baets *et al*. (2009) determined the suitability of 25 plant species to control concentrated flow erosion. Plants having 1) the potential to improve slope stability, 2) the potential to prevent incision by concentrated flow erosion, 3) the potential to resist bending by water flow, and 4) the ability to trap sediments and organic debris were deemed effective for controlling both rill and gully erosion. Plants species such as *Stipa tenacissima* were preferred for the re-vegetation of abandoned terraces as compared to reeds *(Juncus acutus*), grasses (*Stipa tenacissima* and *Lygeum spartum*) and shrubs (*Salsola genistoides*), which were highly suitable for the control of gully erosion in the Mediterranean region. This illustrates that not all types of ground cover are equally effective in the reduction of soil erosion (Shellberg & Brooks, 2013). Danladi and Ray (2014) performed a study in Gombe, Nigeria with the aim of assessing socio-economic effects of gullying. The study indicated that accelerated erosion leads to both functional and structural damage to infrastructure. Although control measures such as tree planting and stone embankments were implemented, the measures were not entirely effective due to the lack of adequate information on the morphological parameters of the gullies.

Overgrazing may result in gully initiation; cattle rotation is therefore another technique that can be used to control gullying. This technique entails fencing the area, creating medium and large paddocks and installation of artificial water points and supplemental feed points. This decentralises the intensity of grazers on an area as it involves the proactive movement of cattle between paddocks over different time scales, allowing for the resting of other paddocks and recovery of plant species before being grazed again. Cattle rotation requires greater labour inputs in order to actively manage cattle, and greater infrastructure in order to improve the paddocks. However, long-term benefits associated with this technique are evident, such as that animals gain weight and grazing land may become more profitable and healthier (Shellberg & Brooks, 2013).

Check dams are small and temporary structure constructed across gully lines. This is done in order to counteract the loss of soil through the reduction of the runoff's energy. Check dams minimise runoff velocity, which favours infiltration rather than eroding channels. Similar to the vegetation technique, check dams are cost effective. They have a faster implementation timeline and will not result in the displacement of communities. Check dams are simple to construct and do not affect natural resources. The construction of check dams usually occurs along gully courses in order to decrease the original bed gradient, therefore reducing the erosive power of the runoff (Glenn, 2005; Desta & Adugna, 2012; Addis *et al*., 2015).

Controlling water flow by converting it to slower and less erosive flow reduces the extent of erosion. Diversion banks constructed along the length of a filled gully may help disperse runoff thus, lowering the effect of runoff. Some gullies are generally small and are not subjected to large water flow. In cases like these, gully formalization should occur. The gully head should be graded back in order to reduce the sharp drop to a gentler slope. The sides of the gully should then be smoothed off and the gully head stabilised using rock, concrete or rock mattresses. A layer of topsoil may then be used for the purpose of grass establishment later on (DLRM, 2016).

A variety of drop structures may also be applied towards the control of gullies. Logs may be used but this requires a trench to be dug into the sides and across the floor of the gully. Geotextile is then laid into the trench together with the logs, which need to be placed horizontally across the gully floor. The logs need to be securely keyed into each side of the gully. Pickets and droppers are then used to hold these stacked logs together. It is important for the logs to be high enough as this will prevent water flowing around the edges, therefore not resulting in the widening of gullies (DLRM, 2016). Stones built across smaller gullies may trap silt and rebuild gully floors (Glenn, 2005). Stone bund terraces may too, reduce erosion and recharge groundwater (Addis *et al*., 2015). In order to ensure rocks do not break free, rocks should be contained in wire baskets. Both these drop structures are of low cost and in addition to the drop structures, sandbags filled with soil may be used for the treatment of rills and small gullies (DLRM, 2016). Although placing stones and using sandbags is a useful form of initial gully control, these methods do not stop erosion. Pathak *et al*. (2005) further supports this statement by stating that even the refilling action of gullies does not prevent erosion because the refill soil is not as well compacted as the natural soil layers.

No tillage in turn is one of the most effective alternative methods. When tillage practices are put into place, soil becomes loose and less cohesive, thus becoming more prone to erosion. Topsoil compaction is the other alternative technique that works well because during compaction, the soil becomes more cohesive and resists incision due to concentrated flow (Poesen *et al*., 2003).

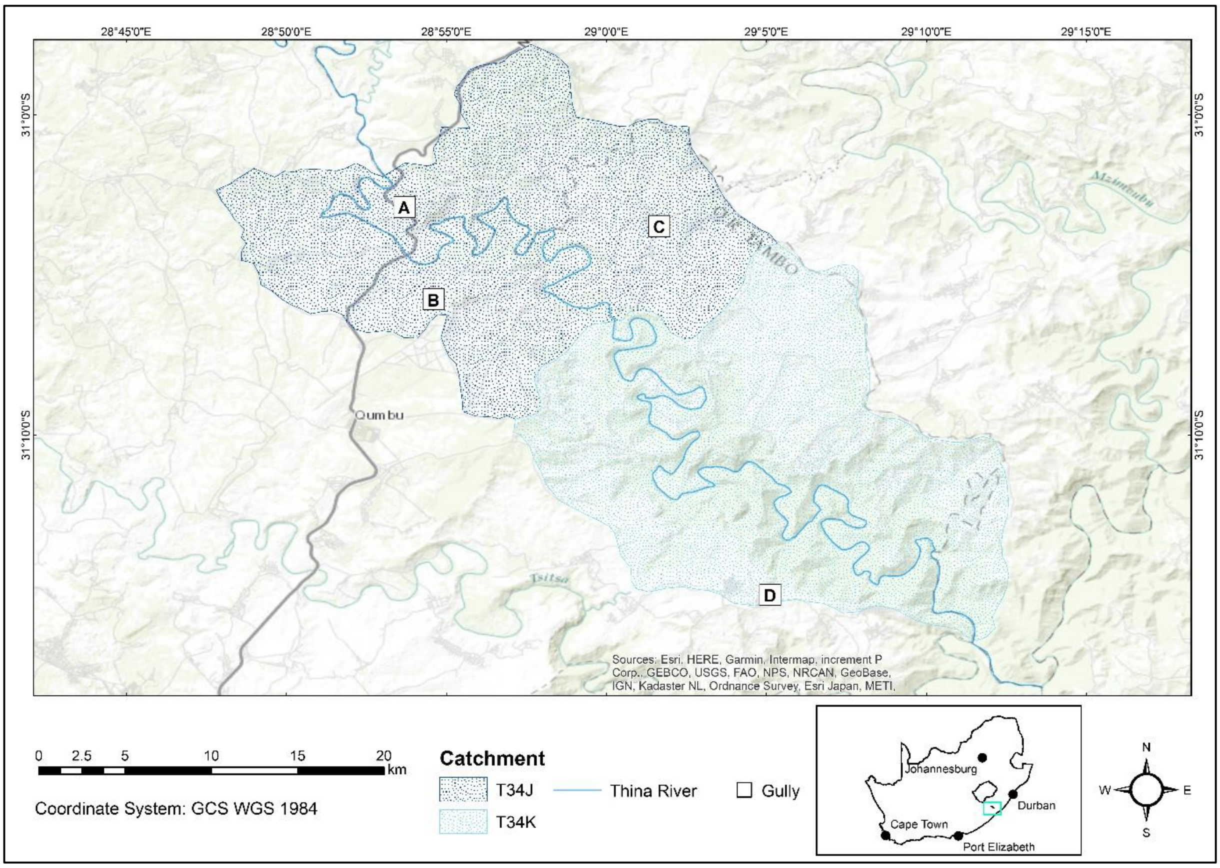
The construction of costly measures such as reshaping of gullies by reducing the slope angle and construction of gabion check dams, major drop structures, trenches and microbasins also have an equal chance of reducing gully erosion (Addis *et al*., 2015). Grouting when applied at early stages hinders the progress of gully formation. Dewatering methods such as the installation of wells, is effective because the groundwater level is controlled, and the water may be used for either industrial or domestic purposes. As possible as it is to control groundwater levels, moisture content should also be controlled and in doing so, the formation of tension cracks is avoided and erosion not as easily triggered (Obiadi *et al*., 2011).

Irrespective of the erosion control measure to be employed, assessment and experience are vital when addressing and or dealing with gully control measures because one gully is never the same as another one even when the gullies occur in the same area. Furthermore, a better understanding of gully formation provides insight into which erosion control measures or gully rehabilitation methods should be employed.

CHAPTER 3: STUDY AREA DESCRIPTION

3.1. Location

The Lower Thina Catchment forms part of the greater Mzimvubu River that has four tributaries flowing into it. It discharges into the Indian Ocean at Port St. John after flowing through deep gorges across the coastal plain. The study area is in the Eastern Cape Province (Figure 3. 1), which covers an approximate area of 169,000 m^2, 13.9% of South Africa's surface area (Hamann & Tuinder, 2012). The catchment is found at approximately 31.19° S and 29.00° E and is situated near Mount Frere and a small village (Qumbu). One metropolitan municipality exist in the province with six district municipalities. The catchment lies within the upper Amathole district situated near the O.R Tambo district (Hamann & Tuinder, 2012). Within this catchment four gullies were identified. These gullies are indicated as A (31.04° S, 28.90° E), B (31.10° S, 28.91° E), C (31.06° S, 29.03° E) and D (31.25° S, 29.08° E) on Figure 3. 1 below.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI,

Coordinate System: GCS WGS 1984

Figure 3. 1: Study area relative to South Africa. Gullies identified by labels A-D.

3.2. Geology and soils

The geology present within the overal Thina Catchment is mostly that of the Drakensberg, Clarens and Elliot Formation (WRC, 1994). A chronological view of these formations can be seen in Figure 3. 2.

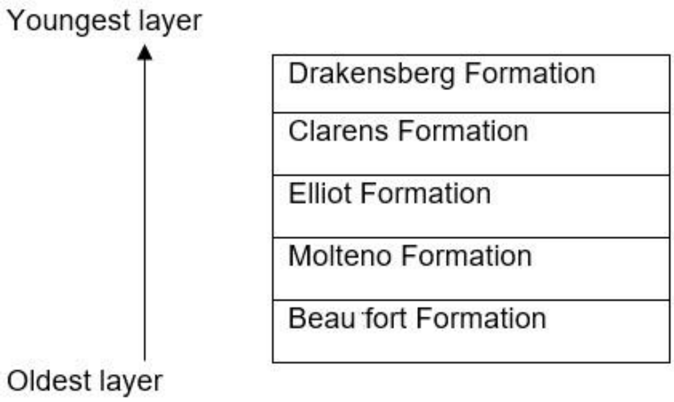


Figure 3. 2: Stratigraphy showing the order in which the Formations were laid.

The upper reaches of the catchment, composed of an extrusive igneous rock layer from the Drakensberg Formation (the youngest layer), formed during the breakup of Gondwanaland, in the early Jurassic age. This layer comprises sub-alkaline mafic lava flows and sub-volcanic plexus of dolerite dykes and sills (Botha & Singh, 2012). The various dolerite dykes and sills exploited pre-existing weaknesses and acted as magma conduits during their intrusion through the Drakensberg Formation (Pretorius, 2016).

The Clarens, Elliot, Molteno, and Beaufort Formations are overlain by the Drakensberg Formation. The uppermost layer of these sedimentary rocks is composed of quartz-rich sandstone of fine to medium grain sizes that were deposited during the Late Jurassic age as aeolian sediments (Bordy *et al*., 2005). Below the Drakensberg Formation lies the Clarens Formation, formerly known as the Cave Sandstone. This layer varies in thickness as a result of local palaeotopography and other erosional features. Sandstones of this layer are yellowish-brown, fine- to medium- grained and quartz-rich. These sandstones are associated with the emplacement of Aeolian sediments into the Karoo Basin (Botha & Singh, 2012). Between these are minor mudstone layers (le Roux, 2012).

The Elliot Formation, formerly known as the Red Beds due to the red colour of its rocks/beds (Visser & Botha, 1980; Bordy *et al*., 2004) lies below the Clarens Formation. The environment associated with this layer is that of an oxidising one evident through the red mudstones (De Decker, 1981; Botha & Singh, 2012; le Roux, 2012). Thus, the reddish colour is evident on the Formations's rocks/beds. This layer is composed of red and purple mudstone and subordinate lensoid medium-grained feldspathic sandstone beds that are not laterally persistent (le Roux, 2012). Distinctions between these two formations is problematic as both are characterised by flat-lying strata, making the contact disconformable (Bordy *et al*., 2005). Nevertheless, the Elliot layer can be up to 370 m thick (De Decker, 1981; le Roux, 2012).

Below the Elliot Formation lies the Molteno Formation, composed of red sedimentary rocks and glittering sandstones (course-grained). The sandstone bodies found in the upper regions of this formation are laterally extensive and sheet-like in nature, with sub-horizontal, sharp external erosion surfaces (Bordy *et al*., 2005). The formation's thickness ranges from approximately 15 m to roughly 200 m (Botha & Singh, 2012) and overlays the oldest layer (the Beaufort Group). The Molteno Formation is associated with seasonally warm and humid climate because the deposition of the layer occurred during the mid-Triassic Era (Bordy *et al*., 2005).

The Beaufort Group is the oldest layer and comprises the oldest land-living reptiles. An 80-million-year record of vertebrate evolution is preserved in this layer. This Group was deposited as fluvio-lacustrine sediments under semi-arid climatic conditions and is characterised by sandstones and mudstones that were all deposited during the late Triassic Era (Botha & Singh, 2012).

The geology map shown in Figure 3. 3 (pg. 44) illustrates a more specific geology which underlies the gullies identified within the study area. Red and greenish-grey mudstone of the Elliot Formation and fine- to medium-grained sandstone of the Clarens Formation underlie gully A, while gully D is underlain by a network of dolerite sills, sheets and dykes of the Drakensberg Formation (Rowntree *et al*., 2012). Gully B and C are underlain by heterogeneous geology of the Drakensberg Formation. A network of dolerite sills, sheets and dykes, mainly intrusive into the Karoo Supergroup, as well as mudrock and subordinate sandstone underlie gully B. In contrast, gully C is underlain by mudrock, subordinate sandstone and a network of dolerite sills, sheets and dykes.

Furthermore, soils present in the Lower Thina Catchment are mainly of a structureless nature (Figure 3. 4, pg. 44). The sedimentary rocks in the study area are generally shallow, poorly drained and sandy soils that are of poor quality (Hamann & Tuinder, 2012). Although the soils in this catchment are undifferentiated; poorly, freely and imperfectly drained, most of the catchment is characterised by undifferentiated soils. Gully A and B are underlain by undifferentiated shallow soils. Gully C on the other hand, is largely underlain by imperfectly drained soils, while gully D has structureless and poorly drained soils. As previously stated, gully A is found above the Elliot Formation. This implies that the soils around this gully system are dispersive and highly erodible (Rowntree *et al*., 2012). Furthermore, gully B, C and D are of the Drakensberg Formation and unlike gully A, they are found on less erodible soils. However, the steep slopes where these gullies are found increases the erosion potential in the area gretaly, thus resulting in great erosion rates (Rowntree *et al*., 2012).

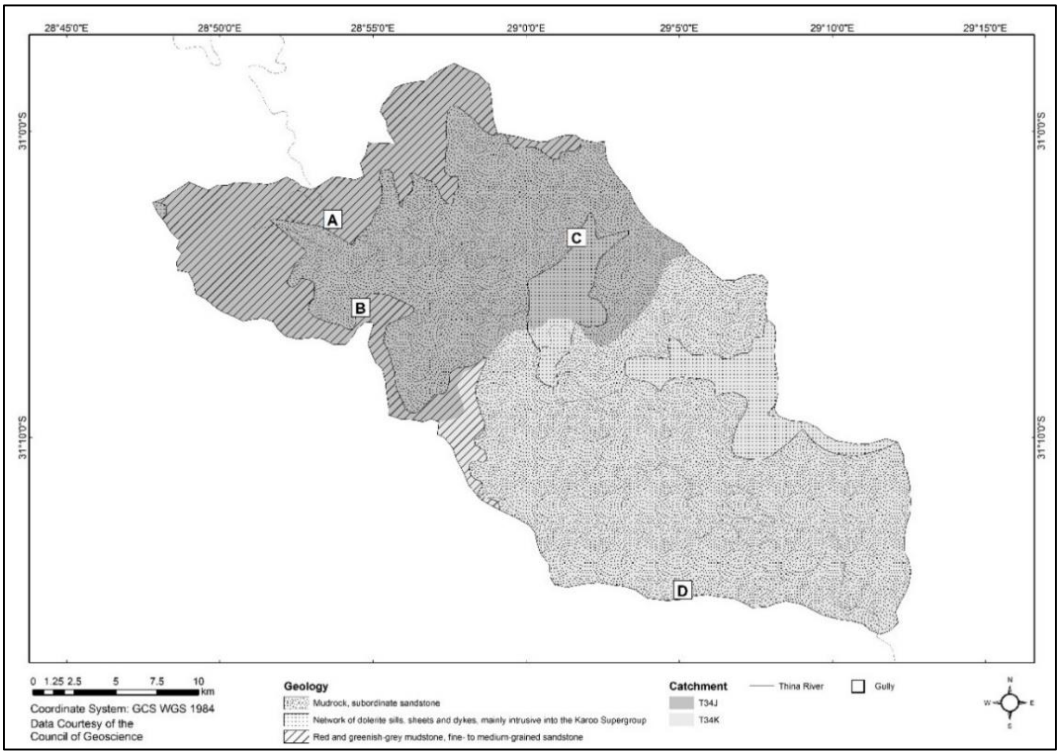


Figure 3. 3: Geology present in the Lower Thina Catchment. Gullies identified by labels A-D.

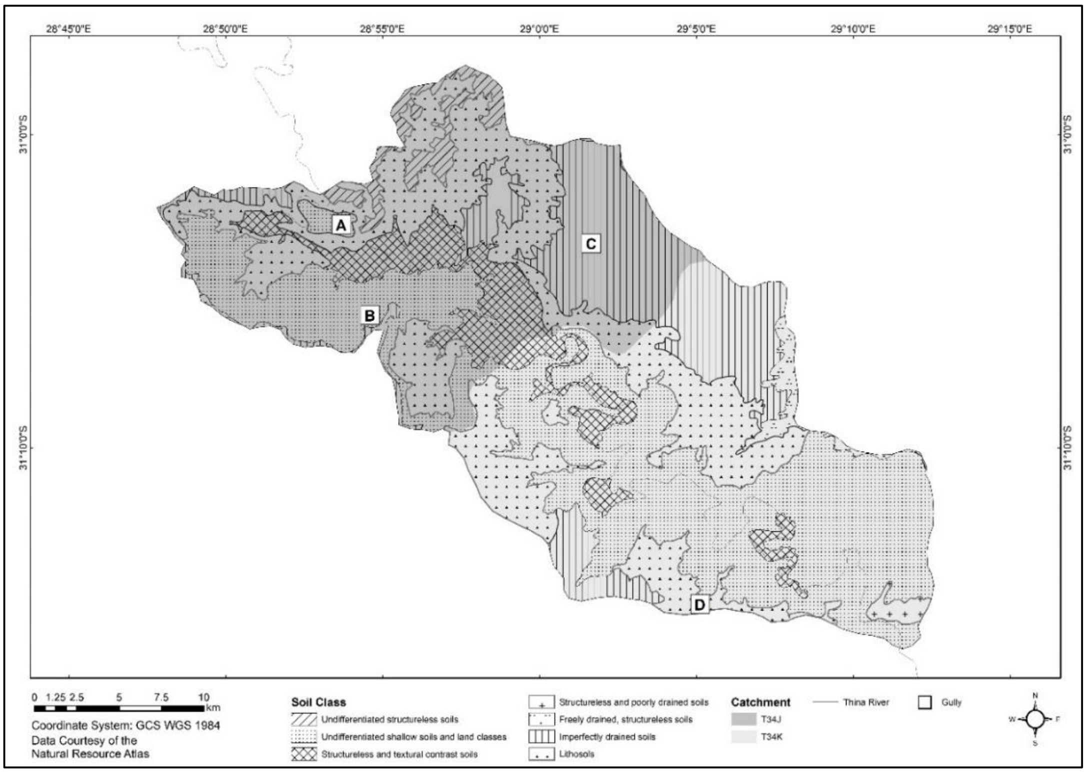


Figure 3. 4: Soil found within the study area. Gullies identified by labels A-D.

3.3. Topography

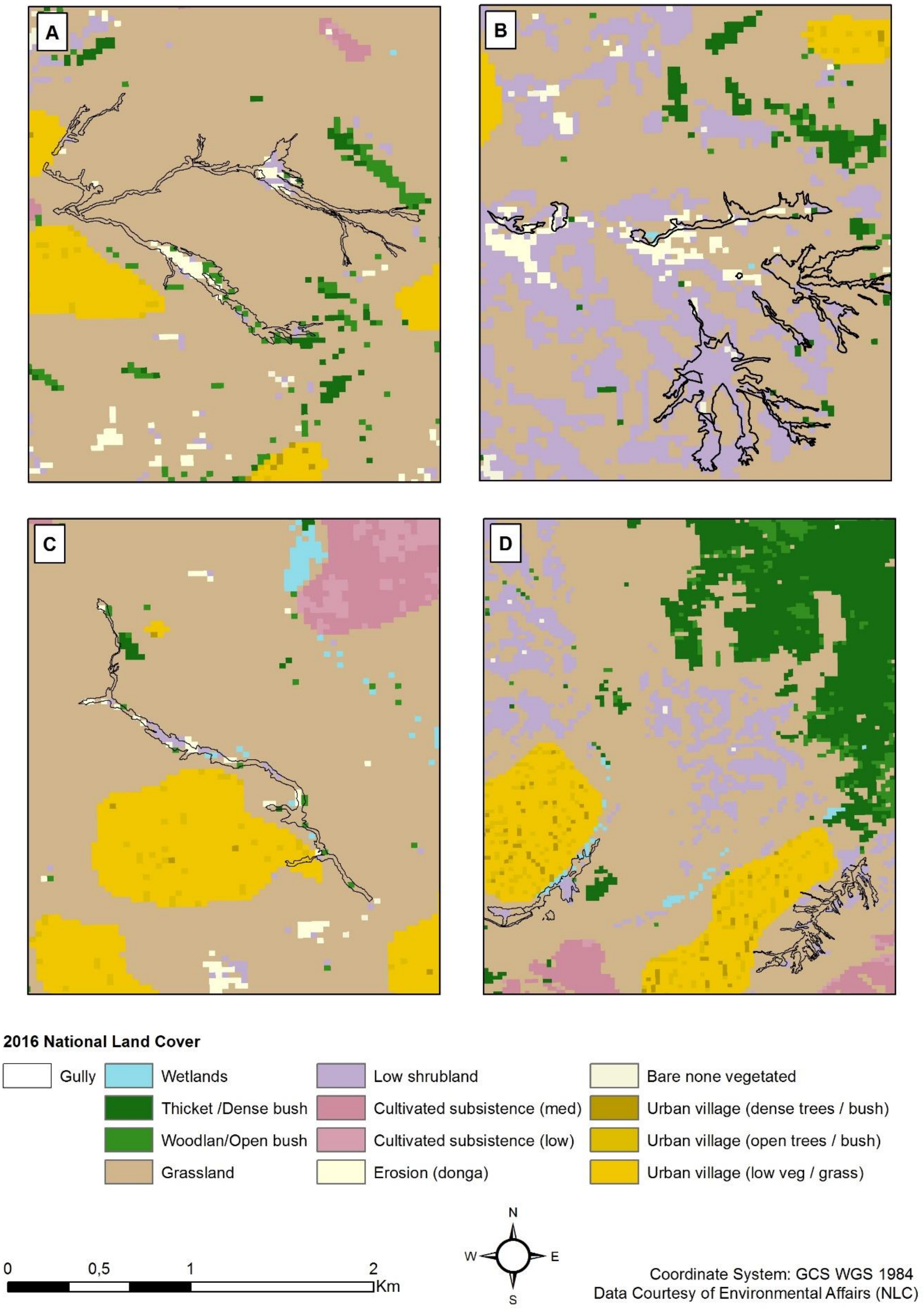
The study area is in the mountainous foothills of the Great Escarpment geomorphic province (Partridge *et al*., 2010), characterised by high relief and steep slopes as well as narrow steep valleys (van der Waal & Rowntree, 2017). The topographical gradient in the flood plains is much shallower than that of the mountain slopes. Many of the slopes in the Lower Thina Catchment are categorised as moderate to steep with hilly topography around both the coast and escarpment (Petty & van Dyk, 2018). The Drakensberg has long and narrow spurs that result in the creation of many ridges and plateaus that are separated by the presence of deep valleys (Mucina *et al*., 2006).

3.4. Climate

The climate of the Lower Thina Catchment is that of a sub-humid one (le Roux *et al*., 2015) that has temperatures ranging between 2º C and 30.6º C. A winter rainfall zone is evident in the west with a summer zone along the east (Hamann & Tuinder, 2012). The area experiences maximum rainfall during the summer period (Mucina *et al*., 2006; Pulley *et al*., 2017) with a mean annual rainfall of 668.05 mm – 918.02 mm. Nel (2009) and van der Waal (2015) note that high-intensity storms dominate the area during summer where precipitation reaches its peak. On the other hand, snow takes preference in winter months (Mucina *et al*., 2006). Approximately 625 mm of rainfall is evident (le Roux *et al*., 2015) in lower inland points and valley bottoms of Eastern Cape (Pulley *et al*., 2017), whereas an increased amount of rainfall of about 1,415 mm (le Roux *et al*., 2015) is evident for mountain chains at higher altitudes (Pulley *et al*., 2017). Due to varying topography, this catchment experiences spatio-temporal variability in rainfall (Bäse *et al*., 2006).

3.5. Land cover and land use

South Africa has nine biomes with Eastern Cape containing eight of these. Four biomes (Grassland, Nama Karoo, Thicket and Savanna) extend throughout the province with the Savana and Drakensberg grassland (Mucina *et al*., 2005; Hamann & Tuinder, 2012) the common ones in the Lower Thina Catchment (Hamann & Tuinder, 2012). From the land cover map created by le Roux *et al*. (2015), the lower parts of the Thina Catchment have bushland & forest, plantations, natural grassland and subsistence cultivation as common land cover classes. Nevertheless, three major land cover classes exist in the gullied areas. These are degraded land (erosion), cultivated land and natural grassland as evident from Figure 3. 5 (pg. 46).



Coordinate System: GCS WGS 1984
Data Courtesy of Environmental Affairs (NLC)

Figure 3. 5: Land cover evident in the study area. A-D indicate gullies A-D.

Like the studies performed in KwaZulu-Natal, gullied areas within this study occur on communal farms rather than commercial ones because of the informal and intensive crop agriculture present in the former (Meadows & Hoffman, 2003). According to le Roux *et al*. (2015), 72% of the major land cover classes present in the catchment are comprised of natural vegetation. However, much of the land use of the chosen study sites is degraded grassland that is often associated with subsistence grazing. Land use practices evident in the area are summarised in Table 3. 1 below and illustrate how such practices contribute towards gullying (pers. Comm, Ryan Anderson, 2019).

Table 3. 1: Land use practices and their corresponding contribution towards gullying (pers. Comm, Ryan Anderson, 2019).

Land use practices	Contribution towards gullying
Communal grazing/ overgrazing	Destroys protective vegetation cover
Animal tracks	Reduced infiltration rates and increased surface runoff
Seasonal fires	Dilution of soil nutrients resulting in less stable soils
Cultivated land	Poor land management
Residential areas	Alteration of drainage patterns

CHAPTER 4: METHODOLOGY

4.1. Overview

This chapter summarises the methods undertaken to ensure the completion of this project. The main aim of this study was to quantify the historical changes of gully erosion in the Lower Thina Catchment. The study entailed identifying and mapping gullies in the catchment (Aerial imagery), determining the land use activities in the area (National Land Cover (NLC) Data, pg. 50), and calculating the surface area growth of the gullies for six chosen time periods (Gully identification and classification

Gully identification from a map was done by analysing the obtained aerial images. According to Wang *et al*. (2016), this is one of the best techniques of mapping gully erosion over large areas. Gully classificataion was further done by evaluating the aerial imagery and applying the most suitable classification to each gully.The ephemeral and bank gully classification were ruled out because all the gullies present in the Lower Thina Catchment are not small/cannot be recovered through normal tillage and do not occur on or as a result of banks respectively. This suggests that all gullies present in the study site are permanent in nature.

Calculating surface area growth, pg. 51). Historical climate variability was also investigated and possible linkages made to the extent of gullying (Assessing rainfall erosivity pg. 52).

4.2. Mapping gully erosion

Historical tracking of gully development is a technique used to calculate the time span at which gullies are initiated (van der Waal & Rowntree, 2017). Additionally, this technique aids in calculating the rate of gully erosion within an area (*e.g.* Poesen *et al*., 2003; Nyssen *et al*., 2006; Frankl *et al*., 2012). In order to track gully development with time, Geographic Information systems (GIS) and remote sensing techniques were used to map gully erosion within the Lower Thina Catchment. This was achieved using aerial photographs as adapted from the work of Conforti *et al*. (2011), Igbokwe *et al*. (2008) and Taruvinga (2008). This study was solely desktop based, as a result, traditional methods of physically identifying gullies in the field (Jones & Keech, 1966; Morgan *et al*., 1997) were omitted and only remote sensing techniques were used to map gully erosion within the catchment.

4.2.1. Aerial imagery

Aerial photographs were obtained from the Department of Agriculture, Land Reform and Rural Development (DALRRD). These images were used to identify and map gullies within the

Lower Thina Catchment. Figure 4. 1 (pg. 50) illustrates a summary of the methodology applied across the study area to achieve all the desired objectives.

The obtained aerial images were for the following years: 1948-1950, 1969, 1974, 1995, 2003, and 2015. The selected years above, had images of varying scales while other years had no camera reports for the extraction of scale (Table 4. 1, pg. 49). As these images were not georeferenced, the first step was, therefore, to georeference the images according to the 50 cm Colour Imagery base map extracted from ArcGIS online (original source: NGI). This was followed by clipping black borders evident on the aerial images and mosaicking the photographs together in order to create one image per year.

Table 4. 1: Scale of aerial photographs used.

Aerial imagery used	Scale of photography
1948-1950	1:50000
1969	1:40000
1974	1:50000 - 1:60000
1995	No camera report
2003	1:32000
2015	No camera report

Table 4. 2 (pg. 50) summarises how the six time periods were determined. Nine year intervals were selected for this study, however, due to limited resources, the interval was not met for two time periods as seen on Table 4. 2 (pg.50) (*i.e.* 1975-1995 and 2004-2016).The aerial images used were either for the last year of each time period (*e.g.* 1995 for 1975-1995), the year before the last year of each time period (*e.g.* 2015 for 2004-2016) or the only available year within a 10 year range (*e.g.* 1969 for time period 1957-1966). Only one image at the beginning of each time period was mapped, along with the image of the last year of interrst (2016). This resulted in a total of seven images altogether. Two quaternary catchments (T34J and T34K) of the Lower Thina River were selected based on similar Groundwater Resource Unit (GRU), implying that the catchments have similar geohydrological properties, aquifer type and other physical management and/or functional criteria (Department of Water and Sanitation, 2017). These quaternary catchments were overlain onto the mosaicked aerial images and four of the largest gullies were identified and mapped (digitised) at a constant scale of 1:8 000 within the catchment. Buffers (1 km) were then inserted around the four gullies in order to ensure a constant area of interest (Mararakanye, 2015). The “buffer approach” was not used as an area influencing gullying. Instead, it was used as a tool that checks the cause and extent of gullying (Nwilo *et al*., 2011) as a result of any anthropogenic or natural activities occurring within the buffered area (Mararakanye, 2015; Dalil *et al*., 2016).

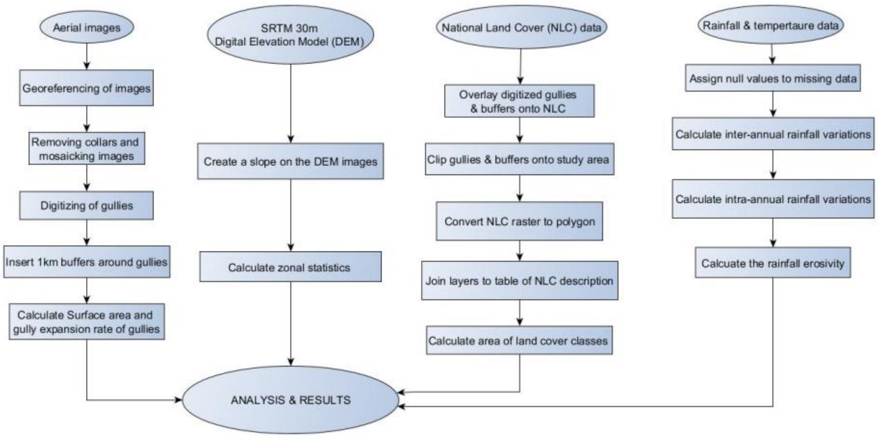


Figure 4. 1: Methodology used to achieve desired objectives.

Table 4. 2: Table showing which aerial images were obtained from Department of Agriculture, Land Reform and Rural Development (DALRRD) and how they were used for the selected time periods. *Aerial imagery is only available for 1969 and this year was thus used for the time period 1957-1966.

Determined six time periods of interest	Aerial imagery used
1948-1957	1948-1950
1957-1966	1969*
1966-1975	1974
1975-1995	1995
1995-2004	2003
2004-2016	2015

4.2.2. National Land Cover (NLC) Data

National Land Cover (NLC) Data of 30 m resolution were obtained from the National Geo-spatial Information (NGI) for the years 1990, 2000, and 2013-2014. Due to the limited availability of NLC data for the study area, no further land cover data were available. Of all the obtained NLC data, none aligned perfectly with any of the seven selected years of interest. As a result, the NLC closest to the year of interest was used for that particular year as seen from Table 4. 3 (pg.50).

Table 4. 3: Table showing which National Land Cover Data (NLC) was used and for which year respectively.

Seven discrete years of interest	NLC used for the respective years
1948	-
1957	-
1966	-
1975	-
1995	1990
2004	2000
2016	2013-2014

Buffers and digitised gullies were overlain onto the NLC data and the NLC layers clipped. The clipped NLC data were then converted to vector polygons, allowing for joining of grid codes with the NLC descriptions table. This also allowed for area calculations (in ha) of the land cover in and around the gully systems. Land cover present in the Lower Thina Catchment was represented in percentages, then tabulated. Only land cover classes greater than 1% were tabulated as part of the buffered area and were regarded as “major” land cover classes. However, all land cover classes within the gully systems were considered, irrespective of their percentage coverage.

4.2.3. Topographical maps

Like land cover data, the topographical maps were also obtained from the NGI. This dataset also had missing maps and only maps from the following years, 1980, 1982, 2003, and 2004 were present. All these maps were used to visually support data derived from aerial imagery, as well as land use data.

4.3. Detecting gully changes

Mapping gully erosion within the Lower Thina Catchment was coupled with calculating the surface area of gullies. Furthermore, the erosional rates of the gullies were also determined. These were done in order to determine whether the gullies in the area are active or not (Pretorius, 2016).

4.3.1. Gully identification and classification

Gully identification from a map was done by analysing the obtained aerial images. According to Wang *et al*. (2016), this is one of the best techniques of mapping gully erosion over large areas. Gully classificataion was further done by evaluating the aerial imagery and applying the most suitable classification to each gully.The ephemeral and bank gully classification were ruled out because all the gullies present in the Lower Thina Catchment are not small/cannot be recovered through normal tillage and do not occur on or as a result of banks respectively. This suggests that all gullies present in the study site are permanent in nature.

4.3.2. Calculating surface area growth

The seven images derived from the obtained aerial images, were used to calculate the area occupied by the gully using the Calculate Geometry tool in Esri ® ArcMap ™ software. Thereafter, the gully surface area growth was determined using Equation 4. 1 below. Only the lateral growth of the gullies was of concern because it was assumed that all active gullies had reached their bedrock level and were, thus, not increasing further in depth (le Roux *et al.,* 2015). The surface area growth results were then divided by the various time spans in order to determine how fast the gullies were expanding annually. The annual expansion was calculated using Equation 4.2 (Pretorius, 2016).

Equation 4. 1: Gully surface area growth equation, where y_a and y_b are the two years being compared.

$$Surface\ area\ growth = gully\ surface\ area\ (y_a) - gully\ surface\ area\ (y_b)$$

Equation 4. 2: Determining annual gully expansion.

$$Annual\ gully\ expansion = \frac{Surface\ Area\ growth}{Difference\ between\ the\ two\ years\ of\ interest}$$

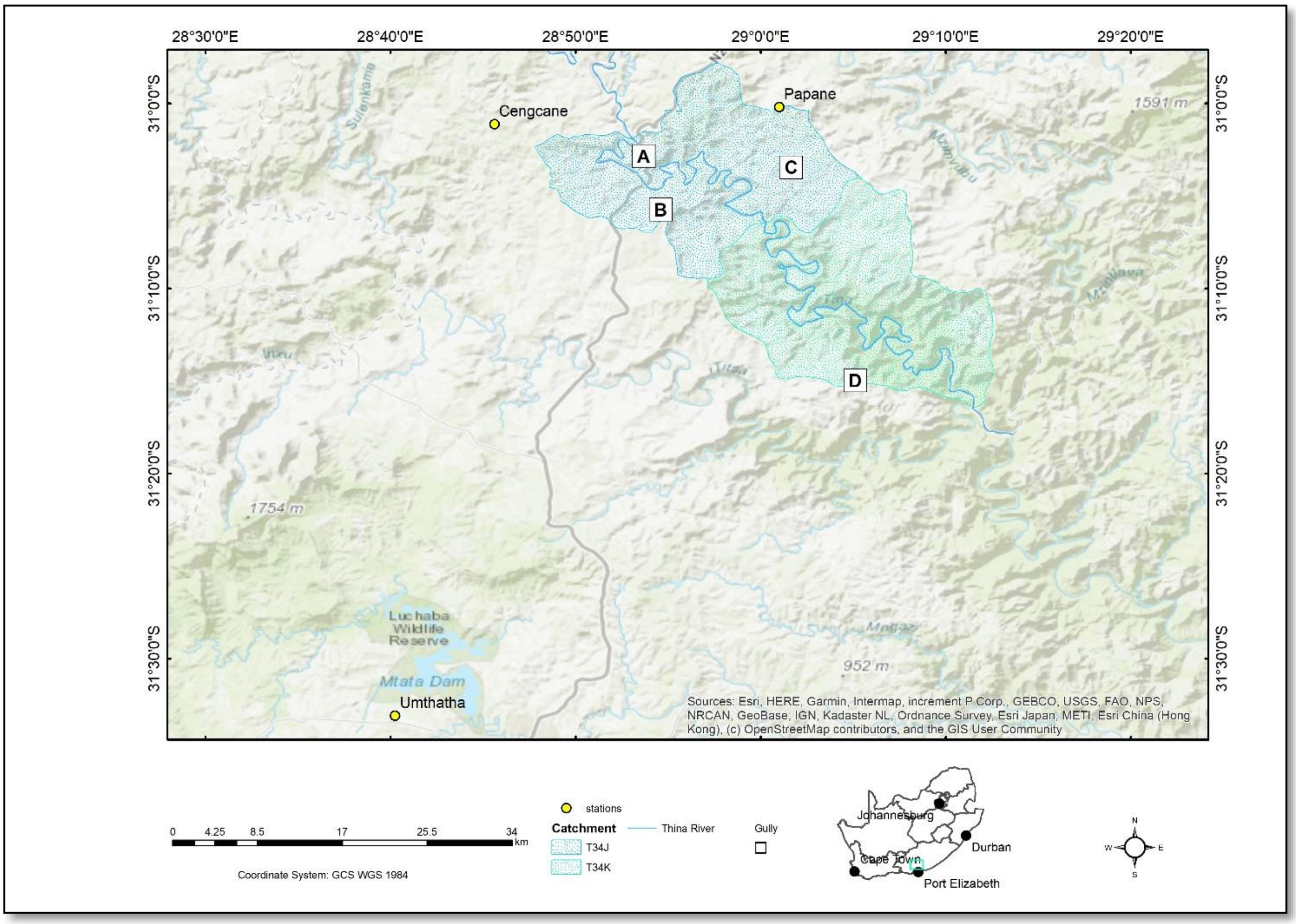
4.3.3. Steepness

Along with surface area, gully steepness was calculated for all years of interest. Two SRTM 30 m Digital Elevation Model (DEM) tiles were used to generate steepness values. Slopes (in degrees) were created from DEM images followed by the zonal statistics calculation, as accessible in ArcMap (*Zonal Statistics as Table*). This allowed for the assessment of the gullies' elevation and steepness at various times. Steepeness was then determined per gully system based on a relative assessment, *i.e.* each system's average slope was compared to the remaining gully systems. As such, steepness values of *steepest*, *steep*, *gentle*, and *gentlest* were assigned to the various gully systems. These descriptors are relative to each other, *i.e.* the steepest slope is assigned to the slope with the greatest gradient, whereas gentlest is assigned to the slope with the smallest gradient. Steepness values are thus based on a comparison between the various slopes of all four gullies of interest.

4.4. Assessing rainfall erosivity

4.4.1. Data

Rainfall and temperature data (measured at 08:00 daily) used in this study were obtained from three of the South African Weather Service (SAWS) stations. One of the stations (Papane at 31.00° S, 29.02° E) is found within the T34J catchment, with no weather station present within the T34K catchment (Figure 4. 2 on pg. 53). Two of the stations (Cengane at 31.02° S, 28.78° E and Umthatha at 31.58° S, 28.78° E) are found outside the catchment. Of the two weather stations found outside the catchment, the Cengcane is the one closest to the catchment, specifically the T34J catchment. On the otherhand, the Umthatha weather station is the furthest from the other two weather stations but yet the closest to the overall Lower Thina Catchment. This station has been moved twice geographically, however, in the absence of a better alternative, it remains the most suitable reference for temperature data considering that the other two stations lack temperature data for the selected years. All weather stations are located at different altitudes, this aided in determining the associated effect of altitude on rainfall erosivity.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 4. 2: Location of the three weather stations relative to the Lower Thina Catchemnt**.**

4.4.2. Unreliable data

The weather data contained incomplete records. These data are recorded by SAWS as missing data, data not yet available or unreliable monthly averages due to missing daily values. For the purpose of this study, these data were not corrected using extrapolation because the variable nature of rainfall is believed to alter results, thus, resulting in outcomes that are less accurate (Anderson, 2012). A null value was, therefore, assigned to missing data. This was done in order to indicate that no data at that specific day or month was recorded or available.

The table below (Table 4. 4) shows the percentage of missing rainfall data present for each weather station during each year of interest. Alongside this, is Table 4. 5, which shows the percentage of missing temperature data present at the Umthatha weather station (the only weather station that has temperature data). It is evident from Table 4. 5 below, that both the maximum and minimum temperatures are below the 10% mark usually set as a limit for a complete data set (Atkinson & Lee, 1992). However, all the rainfall data is beyond the 10% mark, implying that a limitation exists for the rainfall data used.

Table 4. 4: The percentage of missing rainfall data present in each weather station.

	1948	**1957**	**1966**	**1975**	**1995**	**2004**	**2016**
Umthatha	75	98	-	90	69	81	72
Cengcane	81	73	82	81	87	86	88
Papane	81	62	89	81	71	94	93

Table 4. 5: The percentage of missing temperature data present across the years.

	1975	**1995**	**2004**	**2016**
Maximum temperature	2	2	2	2
Minimum temperature	2	3	2	2

4.4.3. Data analysis

Separate Microsoft Excel spreadsheets containing temperature and rainfall data averages were generated for each year. The spreadsheets displayed daily average data on a monthly basis for all three weather stations. The data were re-arranged into separate Excel files where rainfall and temperature data for each weather station was recorded for the various years. This was done in order to ensure ease of use between various weather stations.

4.4.4. Determining rainfall erosivity

An Analysis of Variance (ANOVA) calculation was performed for the total rainfall data across all all three rainfall stations. Alongside this was the Levene's Homogeneity test and the Tukey HSD HSD test performed on the rainfall data. The selected confidence interval for the tests was 95% 95% (p < 0.05). Regression analysis was then done in order to determine the relationship between the annual rainfall within a particular weather station and the respective years. Following this were the rainfall parameter calculations, 1) inter-annual and 2) intra-annual rainfall variability, alongside 3) rainfall erosivity within the catchment. They were calculated using the coefficient of variation (CV), the Precipitation Concentration Index (PCI), and the

Modified Fournier Index (MFI) respectively. The equations used for these spatial and temporal variations were as per Equation 4. 3 (pg. 55) and Equation 4. 4 (pg. 55) respectively (Nel & Sumner, 2006). Table 4. 6 and

Table 4. 7 summarise the guidelines applied for both the CV and PCI values.

Equation 4. 3: Coefficient of variation equation, where σ= standard deviation, μ= mean of annual rainfall.

$$CV = 100 * \frac{\sigma}{\mu}$$

Table 4. 6: CV range and classification (Garcia, 1989).

CV range	Index
CV < μ - σ	Low
μ - σ < CV < μ + σ	Intermediate
μ + σ < CV < + 2 σ	High
CV > μ + 2 σ	Very high

Equation 4. 4: PCI equation where P_i= precipitation of month i.

$$PCI = 100 * \frac{\sum_{i=1}^{12} P_i}{\left(\sum_{i=1}^{12} P_i\right)^2}$$

Table 4. 7: PCI range and classification (Ezenwaji *et al*., 2017).

PCI Value	Significance (Temporal Distribution)
PCI ≤ 10	Uniform precipitation distribution (low precipitation concentration)
15 ≥ PCI >10	Moderate precipitation distribution
20 ≥ PCI >16	Irregular precipitation distribution
PCI >20	Strong irregularity of precipitation distribution

Rainfall erosivity was calculated using the Modified Fournier Index (MFI), as illustrated by Equation 4. 5. The commonly used rainfall erosivity (R-factor) equation expressed as the product of the storm rainfall energy (*E*) and the maximum 30 minute rainfall intensity (I30), Equation 4. 6 (pg. 56), (da Silva, 2004; Vreiling *et al*., 2010; Lee & Li, 2015), was not used in this study as it requires rainfall data at one-minute intervals alongside rainfall intensity data which is often rare and unavailable (Esther, 2009). Such high-resolution data is difficult to find when the required data spans over a long period of time. Furthermore, if the data is present, challenges regarding the cost and circulation of the data arise (Costea, 2012). Due to the scarcity of such data, it is problematic to calculate the R-factor as per its definition (Esther, 2009; De Luis *et al*., 2010). The mean annual rainfall is thus, used to determine rainfall erosivity (de Santos Loureiro & de Azevedo Coutinho, 2001). This alternative method (MFI) is derived and mostly applied to studies which focus on the aggressiveness of rainfall, enabling one to evaluate the probability of intense rainflall occurring in an area (Costea, 2012). MFI values range from 160<MFI< 60 and are summarised according to Table 4. 8 (pg.56). Furthermore, temperature data was used to generate a line graph incorporating both maximum and minimum temperatures. Regression lines were drawn on the line graphs and their equations were used to make an association with the rainfall data.

Equation 4. 5: MFI equation, where P = total annual precipitation, P_i= the monthly precipitation for month i.

$$MFI = \sum_{i=1}^{12} \frac{P_i^2}{P}$$

Equation 4. 6: R-factor equation, where E= storm rainfall energy, I_{30} = maximum 30-minute rainfall intensity.

$$R\text{-}factor = (E * I_{30})$$

Table 4. 8: MFI range and classification (Balogun *et al*., 2012).

MFI range	Erosion risk class
< 60	Very low
60-90	Low
90-120	Moderate
120-160	High
>160	Very high

CHAPTER 5: RESULTS

The desktop based methodology used within this study is supported by both primary and secondary data. GIS and remote sensing techniques were also used to generate results for all specified objectives as given in section 1.3 (pg. 15) and are, thus, presented below.

5.1. Objective 1

Map a selection of gullies found within the Lower Thina Catchment and determine their growth rate using seven discrete years (1948, 1957, 1966, 1975, 1995, 2004, and 2016).

Four of the largest gullies present within the Lower Thina Catchment were identified and mapped from the obtained aerial images. Three of these gullies (A, B and C) are in the T34J quaternary catchment, whereas one (D) is in the T34K quaternary catchment (Figure 5. 1).

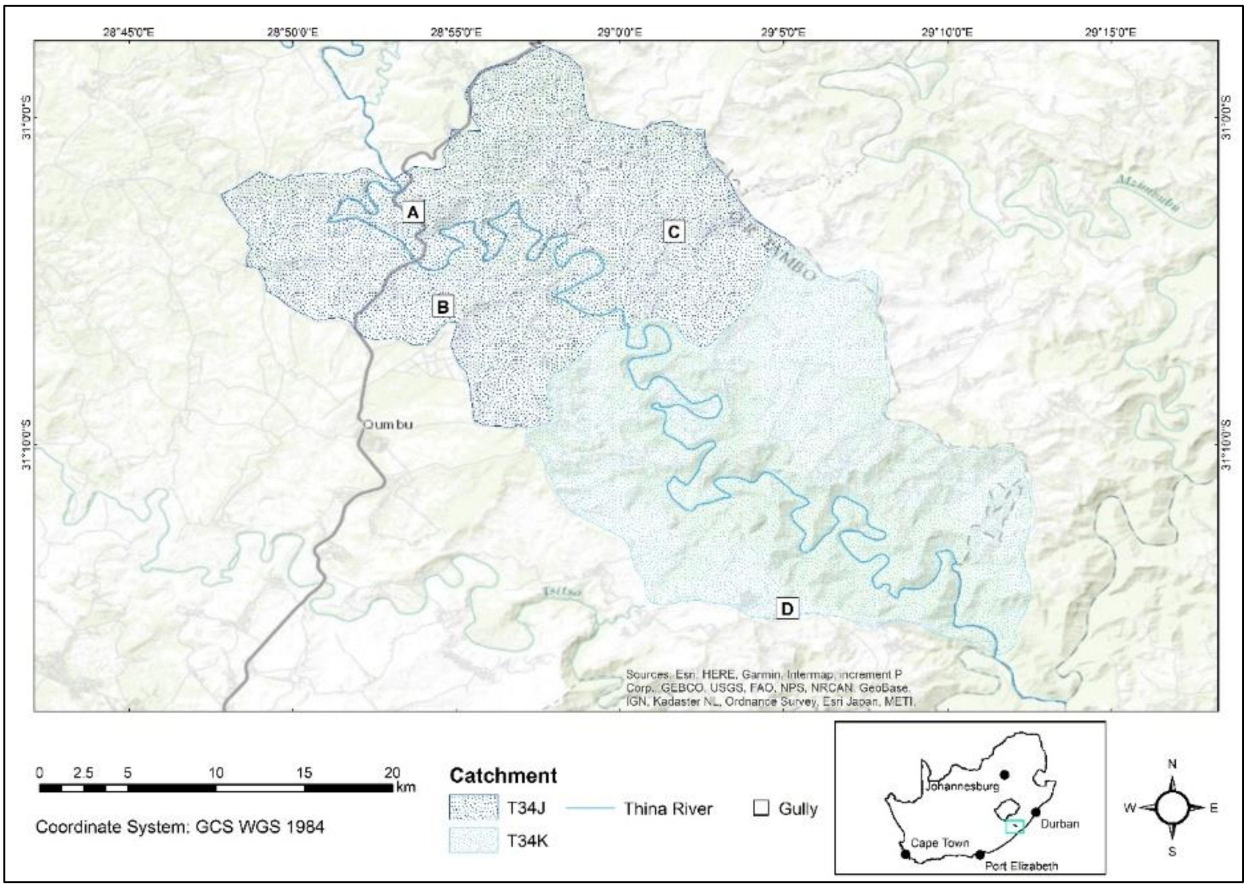


Figure 5. 1: Location of the four gullies mapped within the Lower Thina Catchment.

Figure 3. 5 (pg. 46), is a zoomed in section of the location map showing the pattern of the gullies in 2016 and the spatial region relative to their surrounding area. According to arial

images (Figure 5. 2, pg. 59 to Figure 5. 5, pg. 62), gullies A and D occur along a road and few residential blocks as well as abandoned land respectively. Furthermore, gully D is composed of two separate gullies. Both these gullies are found on either side of the mountain along a residential area. The area covered by housing near these gullies is greater compared to the ones on other gully systems. Gully B is the largest gully system and has many grazing tracks present alongside varying degree of settlements. Following this is gully C, which runs through a small cultivated land (farm) and a block of built-up areas. This gully system appears narrower and longer than the other gullies.

An assessment was done on the types of gullies each gully system falls within. From the drawn table below (Table 5. 1), it is evident that three different gully types exist, however, only one type (permanent) is relevant and applies to all the gullies across the various years.

Table 5. 1: The types of gullies present in the Lower Thina Catchment.

Types of gullies	**Gully**
Ephemeral	None
Bank	None
Permanent	A, B, C and D

Aerial imagery used was grouped into six time periods/categories as follows, 1948-1957, 1957-1966, 1966-1975, 1975-1995, 1995-2004 and 2004-2016. Gully maps of all four gullies were generated per time period and only the year at the beginning of each time period (1948, 1957, 1966, 1975, 1995, and 2004) together with the last (2016) was used to obtain such outputs. Figure 5. 2 (pg. 59), Figure 5. 3 (pg. 60), Figure 5. 4 (pg. 61) and Figure 5. 5 (pg. 62) display the surface area and changes occurring within the gully systems across the various time periods.

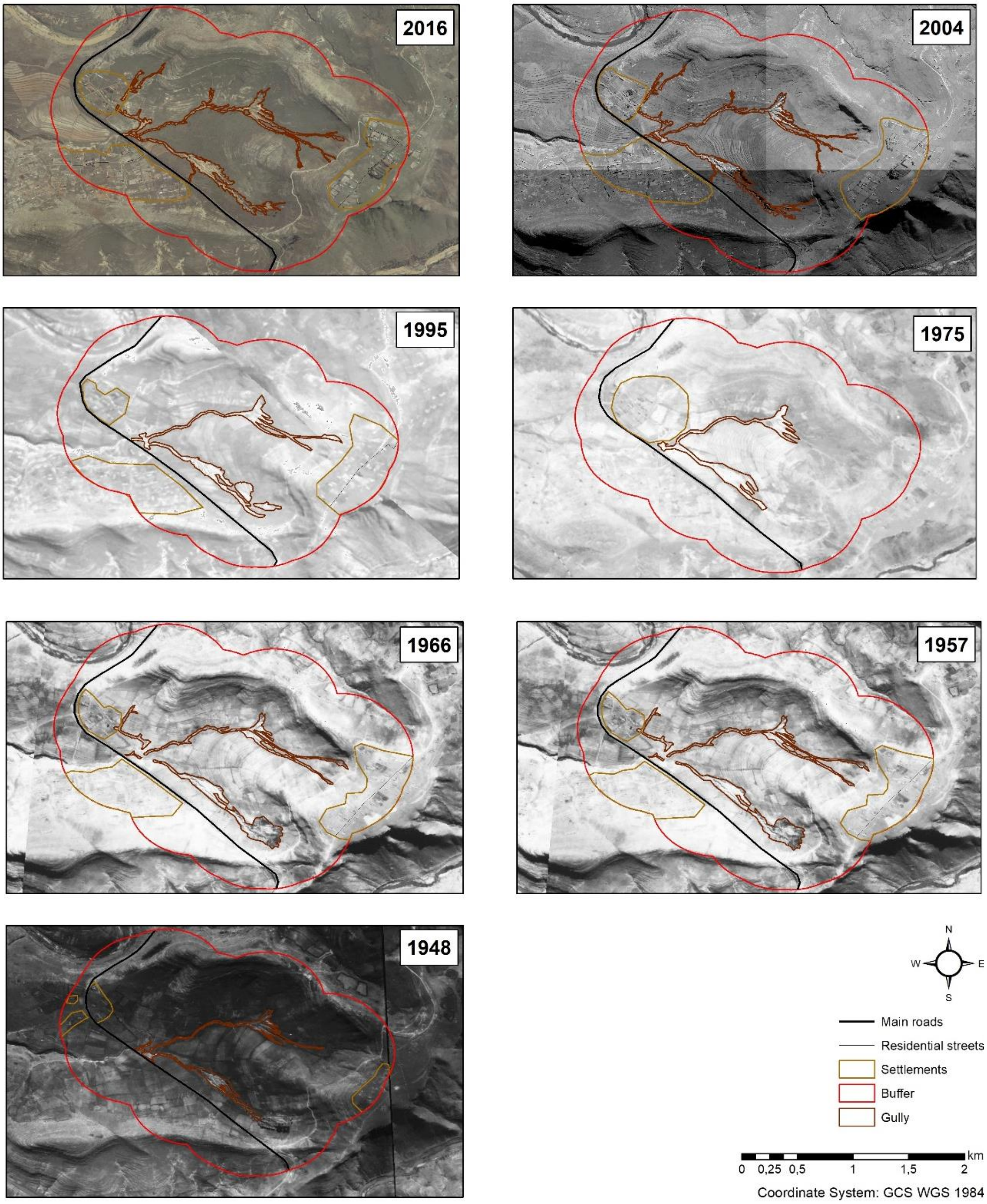


Figure 5. 2: Changes of gully A occurring over the six time periods.

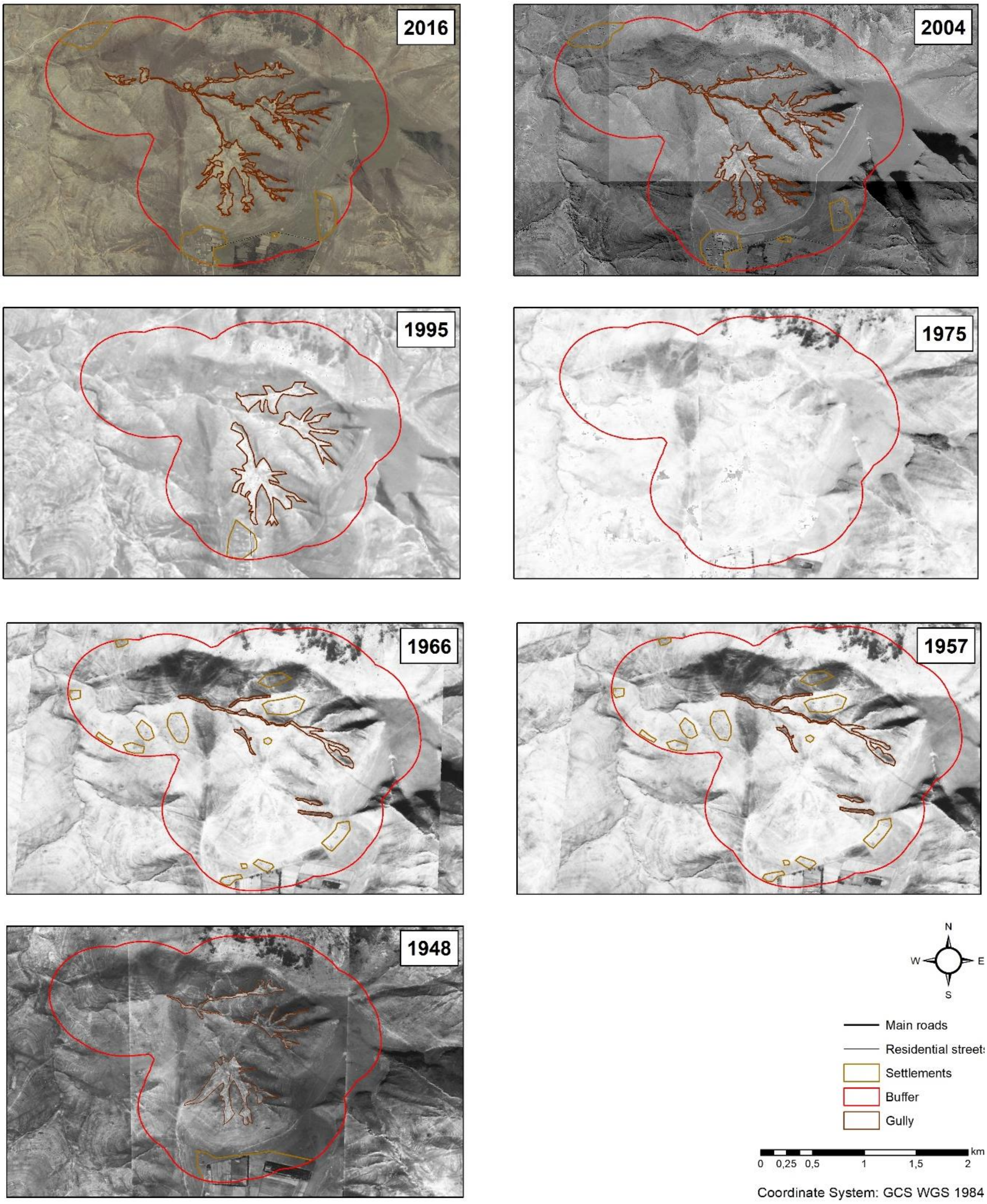


Figure 5. 3: Changes of gully B occurring over the six time periods.

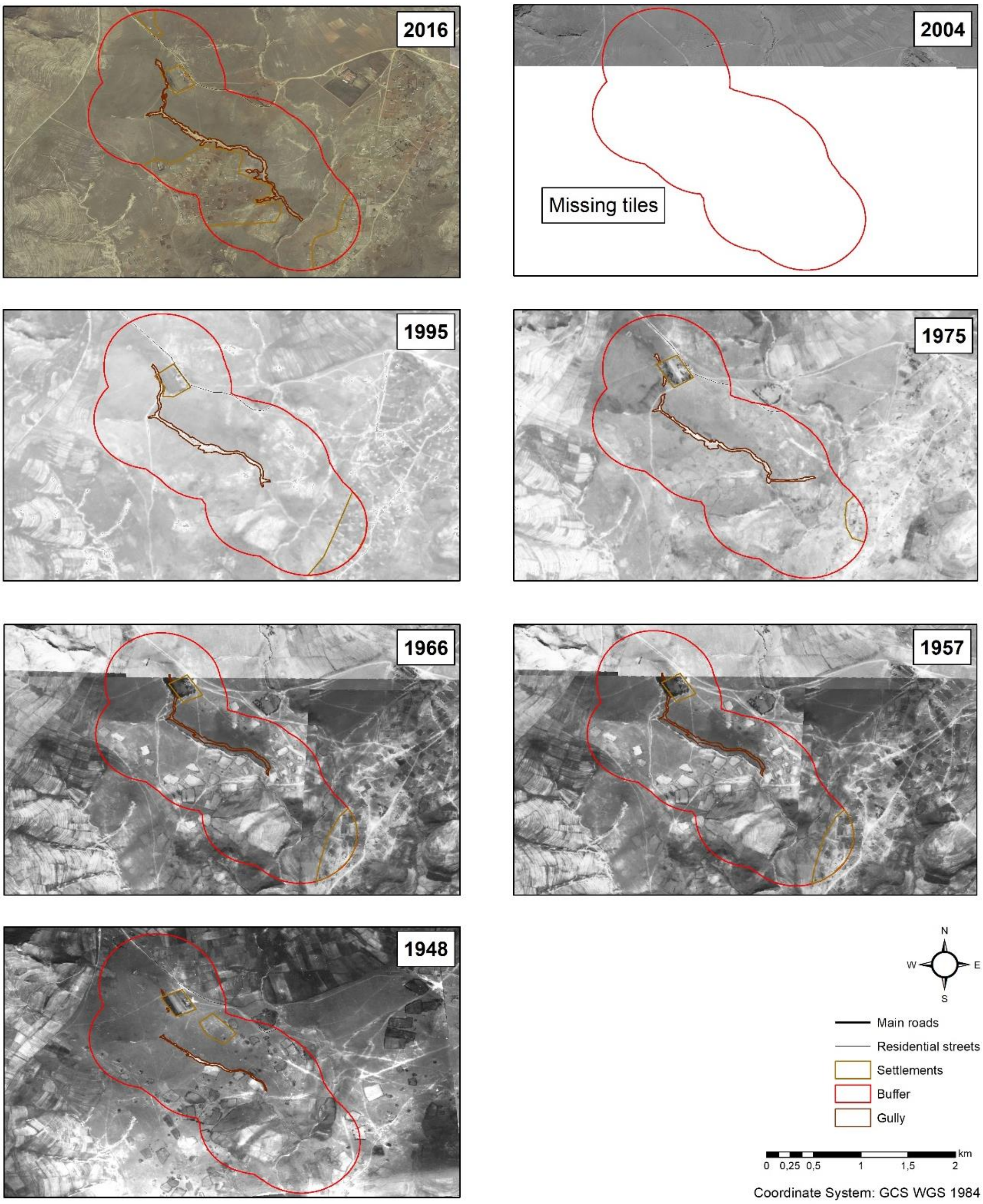


Figure 5. 4: Changes of gully C occurring over the six time periods.

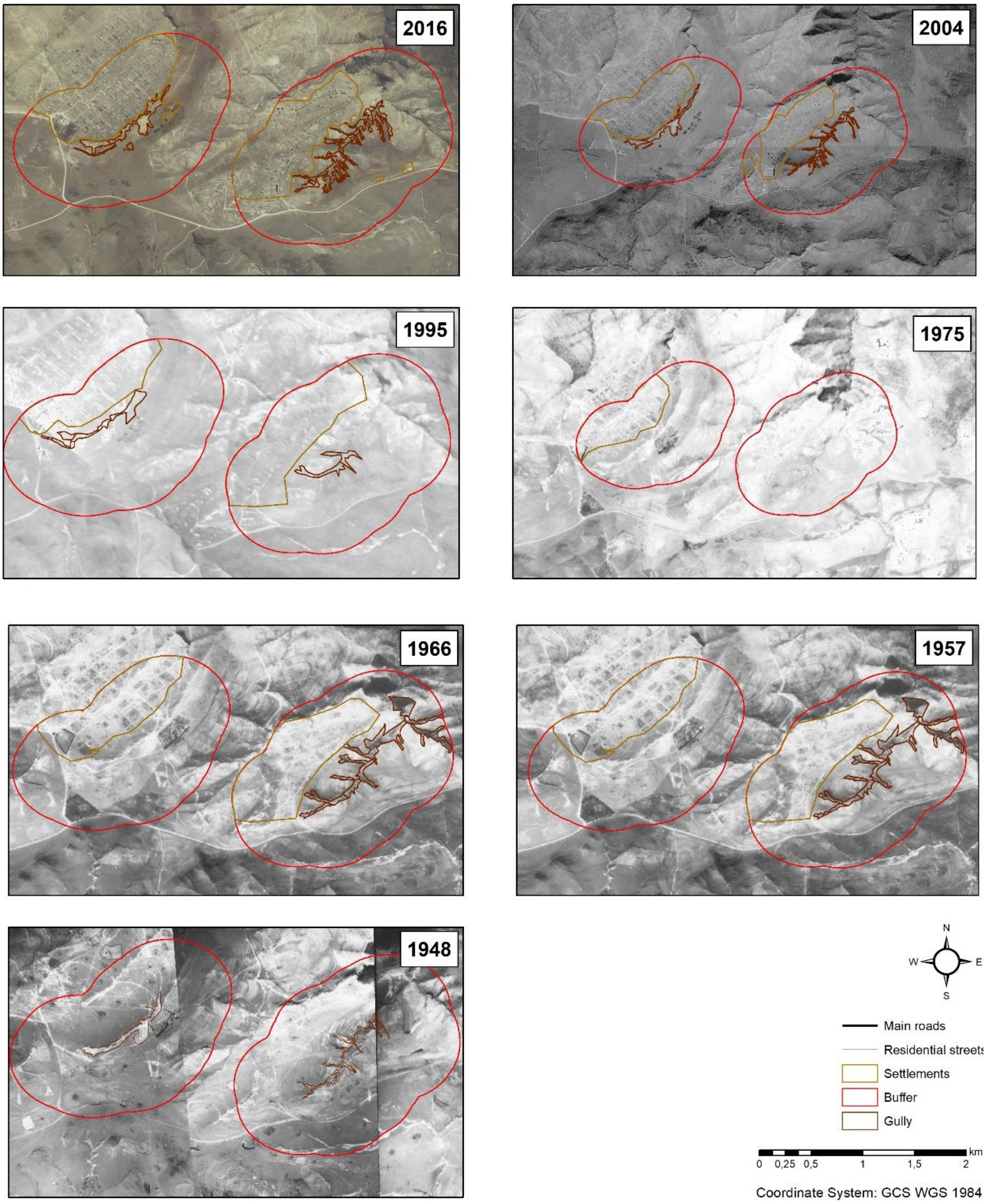


Figure 5. 5: Changes of gully D occurring over the six time periods.

Surface area calculations were performed and recorded in hectares for seven discrete years. The years used were the first year of each of the six time periods (1948, 1957, 1966, 1975, 1995 and 2004) together with the last year of interest (2016). Results were recorded in Table 5. 2 (pg. 63) as either whole numbers, “undefined” or “missing tiles”. Some years had results recorded as “undefined” due to subjective discrepancies such as unclear aerial imagery. Gully B and D were the two gullies which had “undefined” regions for some of the years. Alongside this were missing data from the Department of Agriculture, Land Reform and Rural Development (DALRRD) for gully C in 2004. Both these conditions lead to the inability to perform some statistical calculations for these gullies. However, general trends were determined. A general increase in surface area is noticed between the first (1948) and last year (2016) of interest. Stable conditions are present between 1957 and 1966, thereafter, an increase in surface area is evident.

Table 5. 2: Surface area (ha) of all four gullies for the selected years.

	1948	**1957**	**1966**	**1975**	**1995**	**2004**	**2016**
Gully A	10	18	18	13	16	16	17
Gully B	26	9	9	Undefined	35	29	31
Gully C	2	4	4	6	6	Missing tiles	8
Gully D	9	17	17	Undefined	8	12	16

Initially gully A only covered 10 ha. After nine years the size of the gully had increased to 18 ha. This gully extent stabilised for another nine years then decreased to 13 ha. After 20 years, the gully is seen to have increased again in size (16 ha) and goes through a second stage of stabilization for another nine years. A slight increase (17 ha) in size is then evident for 2016. Based on the drawn surface area graph (Figure 5. 6), a clear overall increase in surface area is evident from the late 1940s to 2016 as seen from the dotted trend lines.

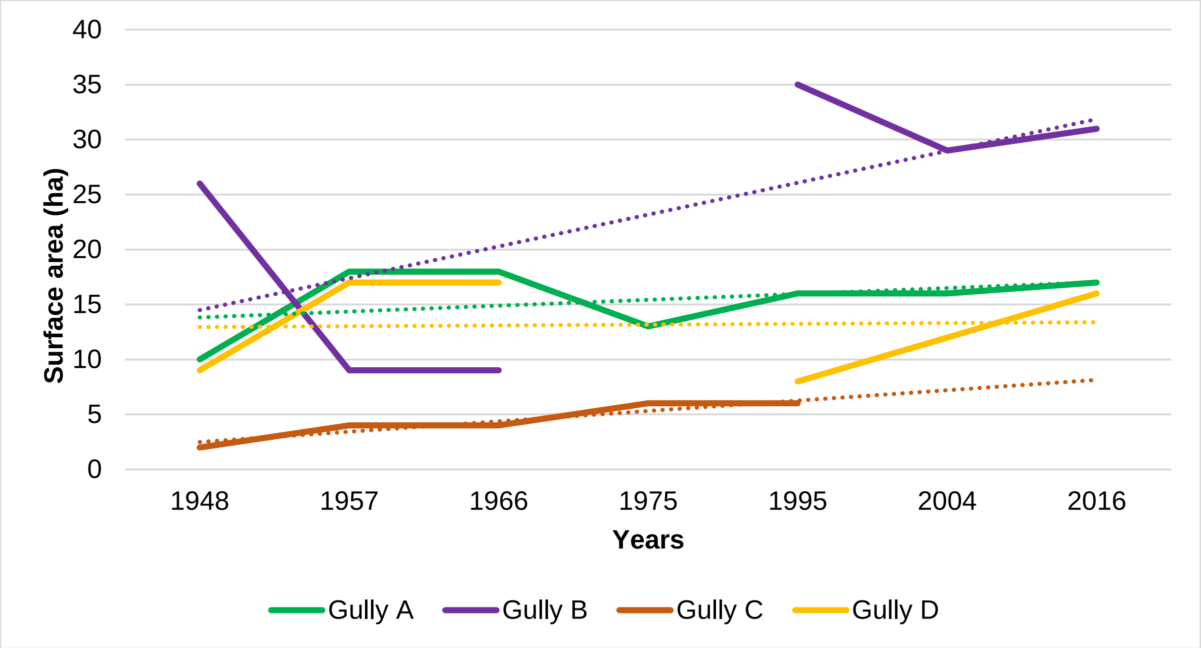


Figure 5. 6: Changes in gully surface area across the various years.

Gully expansion rates were calculated and presented in hectares per year for all four gullies (Table 5. 3). Annual gully expansion rates were affected by the calculated surface area results and missing values as already presented in Table 5. 2 (pg. 63). This resulted in expansion rates not calculated for those affected timespans. These timespans are indicated as “affected” in Table 5. 3 below. Gully A was the only gully that had complete calculations for all time periods due to the gully having no subjective discrepancies or missing data unlike gullies B, C and D. Additionally, gully B is the only gully system starting off on a negative rate of expansion. Furthermore, the second time period (1957-1966) show no increase in gully expansion rate as a result of constant surface areas present between 1957 and 1966. Nevertheless, data show that fluctuating gully expansion rates are apparent for the investigated gullies throughout the 68-year period within the Lower Thina Catchment.

Table 5. 3: Annual gully expansion rates of all four gullies in hectares per year for the selected time periods.

	1948-1957	**1957-1966**	**1966-1975**	**1975-1995**	**1995-2004**	**2004-2016**	**1948-2016**
Gully A	0.9	0	-0.6	0.2	0	0.1	0.1
Gully B	-1.9	0	Affected	Affected	0.7	-0.2	0.07
Gully C	0.2	0	0.2	0	Affected	Affected	0.09
Gully D	0.9	0	Affected	Affected	-0.4	0.3	0.1

During the mapping stage of these gullies, aerial images which had poor/low resolution were identified as this made it difficult to clearly see the pattern that the selected gullies followed (Figure 5. 7). These areas were ignored and not considered during analyses of results. It can be seen from Figure 5. 2 to Figure 5. 5 (pgs. 59-62) that settlements during 1948 were either absent or very few. Settlement density, alongside gullies, then increased as of 1948, occupying a greater density over the years. Main roads, residential streets and farms were predominant features evident within the 1 km buffer set around all four gullies.

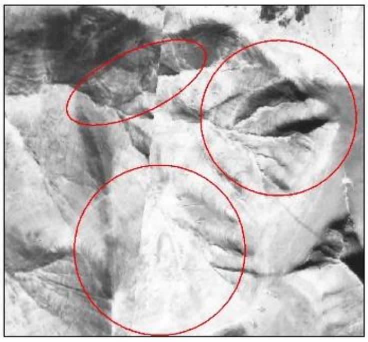


Figure 5. 7: Areas identified as having poor resolution for effective analysis.

In addition to these, some aerial image series obtained from the DALRRD had missing tiles, thus, affecting the statistical analysis of gullies. While three gullies remained unaffected, one gully (C) of the time period 2004-2016 was affected as seen from Figure 5. 4 (pg. 61) and Figure 5. 8 below. The steepness of the different gullies was also determined in this study (Table 5. 4), results show gully C as the gentlest gully while gully B is the steepest of all four gullies. Gully A is gentle in nature while gully D indicates a steep gully system.

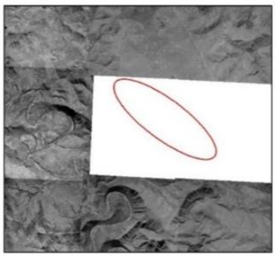


Figure 5. 8: Map showing a missing tile and an eclipse from 2004 where gully C was meant to be.

Table 5. 4: Various mean steepness and standard deviation values for all gullies across the selected time periods recorded in degrees.

Year	Gully	Mean $_{min}$ – Mean $_{max}$	STDEV $_{min}$ – STDEV $_{max}$
1948	A	4,80 – 8.22	4.41 – 2.03
	B	4.80 – 11.66	4.59 – 2.98
	C	2.70 – 10.62	1.36 – 5.00
	D	6.58 – 10.62	2.88 – 5.00
1957	A	4.92 – 10.95	1.64 – 7.96
	B	10.95 – 10.95	7.96 – 7.96
	C	11.16 –11.16	4.88 – 4. 88
	D	11.16 – 11.16	4.88 – 4.88
1966	A	4.92 – 10.95	1.64 – 7.96
	B	10.95 – 10.95	7.96 – 7.96
	C	11.16 –11.16	4.88 – 4.88
	D	11.16 – 11.16	4.88 – 4.88
1975	A	4.99 – 4.99	2.14 – 2.14
	B	N/A	N/A
	C	4.61 – 4.61	2.07 – 2.07
	D	N/A	N/A
1995	A	10.07 – 10.07	3.77 – 3.77
	B	10.07 – 10.07	6.74 – 5.77
	C	5.60 – 5.60	1.59 – 1.59
	D	10.62 – 8.56	4.50 – 0.21
2004	A	5.77 – 6.44	3.19 – 2.94
	B	6.44 – 12.72	6.88 – 2.44
	C	N/A	N/A
	D	8.58 – 8.58	4.27 -4.27
2016	A	5.64 – 6.77	3.53 – 1.60
	B	7.92 – 12.04	5.59 – 3.01
	C	3.32 – 3.32	1.56 -1.56
	D	9.44 -7.03	4.36 – 3.41

5.2. Objective 2

Establish whether there is any relationship between land use and gully growth.

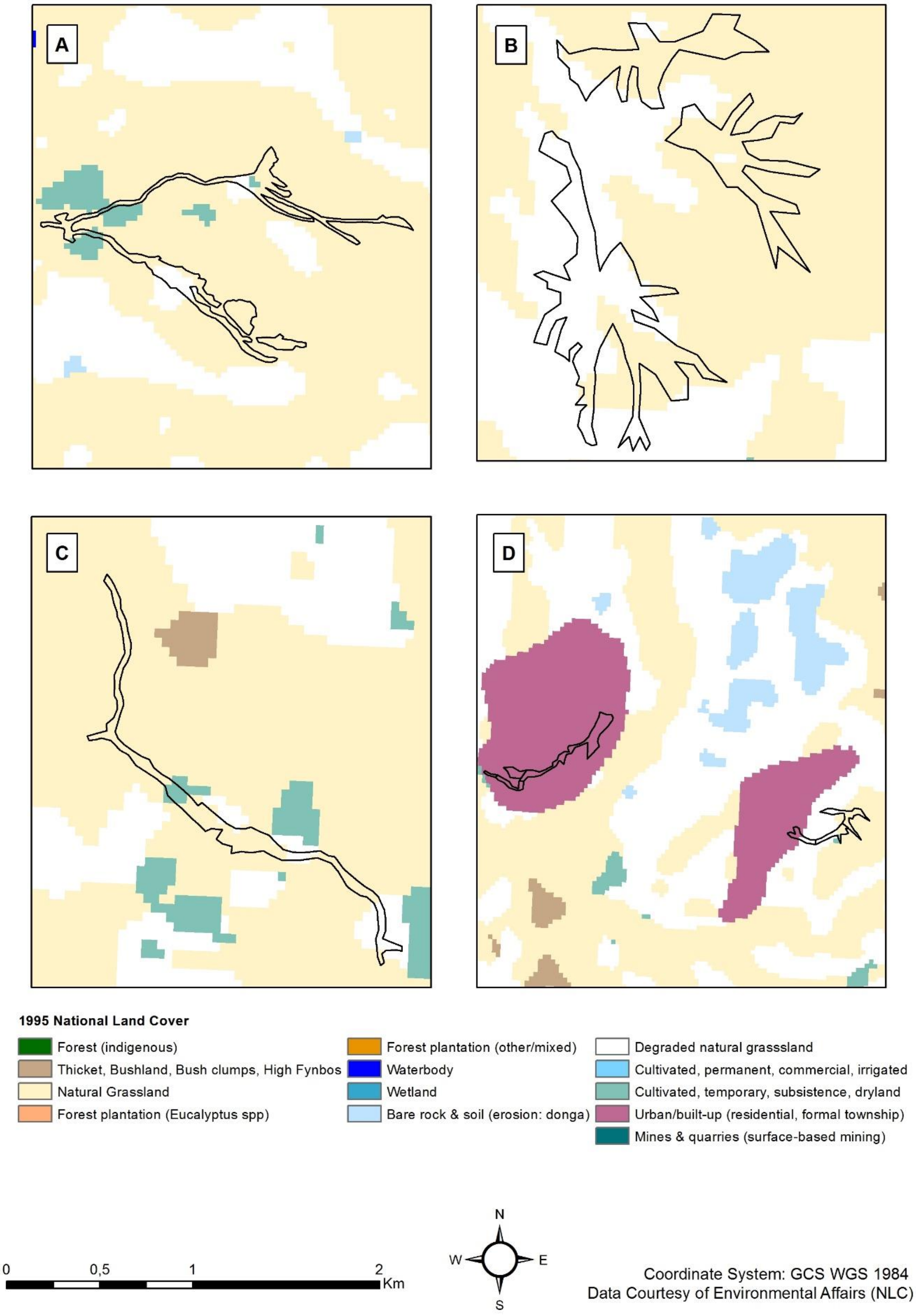
Based on the aerial images used for gully identification and historical land use data, three distinct land uses/activities, namely, 1) abandoned land, 2) cultivated land, as well as 3) grazing of many livestock, are dominant within the study area. The land use activities have been constant throughout the years. Some of the identified gullies cross through cultivated areas (small farms), while others follow the topography of roads or are simply found on abandoned land.

National land cover classes released by the South African National Biodiversity Institute (SANBI) further support the land use activities identified in this study. However, the common identified land cover classes vary throughout the years. Figure 5. 9 (pg. 68), Figure 5. 10 (pg. 69) and Figure 5. 11 (pg. 70) show the different land cover classes present during 1995, 2004 and 2016 respectively. Table 5. 6 (pg. 71) displays various land cover classes present within the four gullies as well as the buffered zone (1 km) for the years of interest, which were generated from the NLC maps. In bold are all the common land cover classes for that particular year across all four gullies. In 1995, *cultivated*, *permanent*, *commercial*, *sugarcane*, *improved grassland* and *forest plantation* were common land cover classes, while *natural grassland* and *degraded natural grassland* were the land cover classes common in 2004. Currently, the common land classes present are *grassland*, *cultivated subsistence, low shrubland* and *urban village*. Furthermore, Table 5. 7 (pg. 76) shows the common land cover classes within the gullies and the 1 km buffer expressed as percentage.

Based on the surface area and annual gully expansion calculations performed above (section 5.1, pg. 57 onward), it is evident that gully A, B and D show negative surface area growth. This can be ascribed to the specific land use (abandoned land) as well as the presence of a nearby road. This concept will further be discussed in CHAPTER 6: DISCUSSION (pg. 87). Furthermore, Table 5. 5 (pg. 67), summarises some of the additional factors which contribute towards gullying present within this catchment.

Table 5. 5: Additional factors seen to contribute towards gullying in the catchment.

Gully	Settlement Proximity	Road Proximity	Duplex Soils	Geology	Topography (slope)
A	Yes	Yes	Yes	Red and greenish-grey mudstone and fine- to medium-grained sandstone	Gentle
B	Yes	No	Yes	A network of dolerite sills, sheets and dykes, as well as mudrock and subordinate sandstone	Steepest
C	Yes	No	Yes	Mudrock, subordinate sandstone and a network of dolerite sills, sheets and dykes	Gentlest
D	Yes	Yes	Yes	A network of dolerite sills, sheets and dykes	Steep



Coordinate System: GCS WGS 1984
Data Courtesy of Environmental Affairs (NLC)

Figure 5. 9: National Land Cover for 1995.

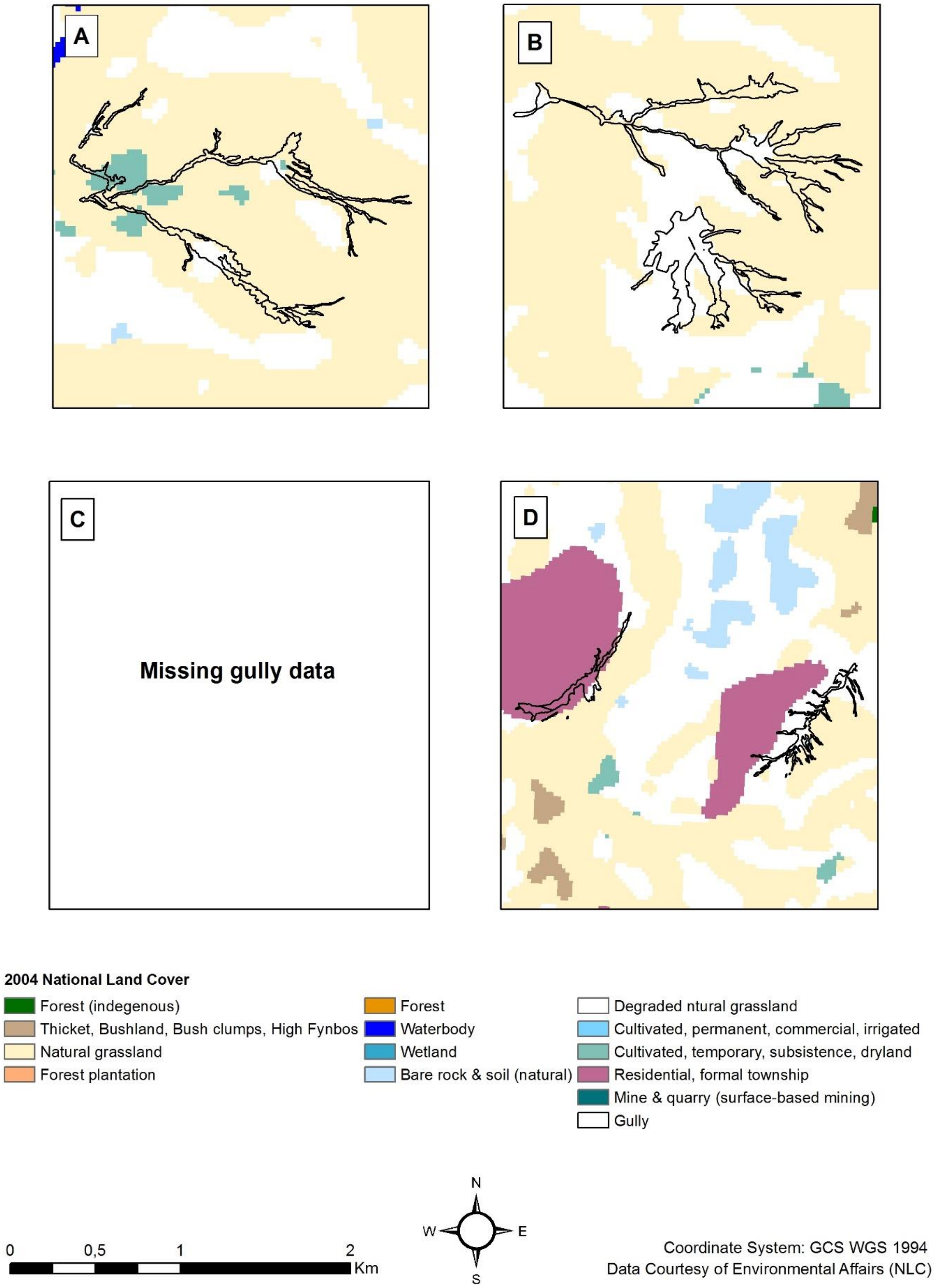
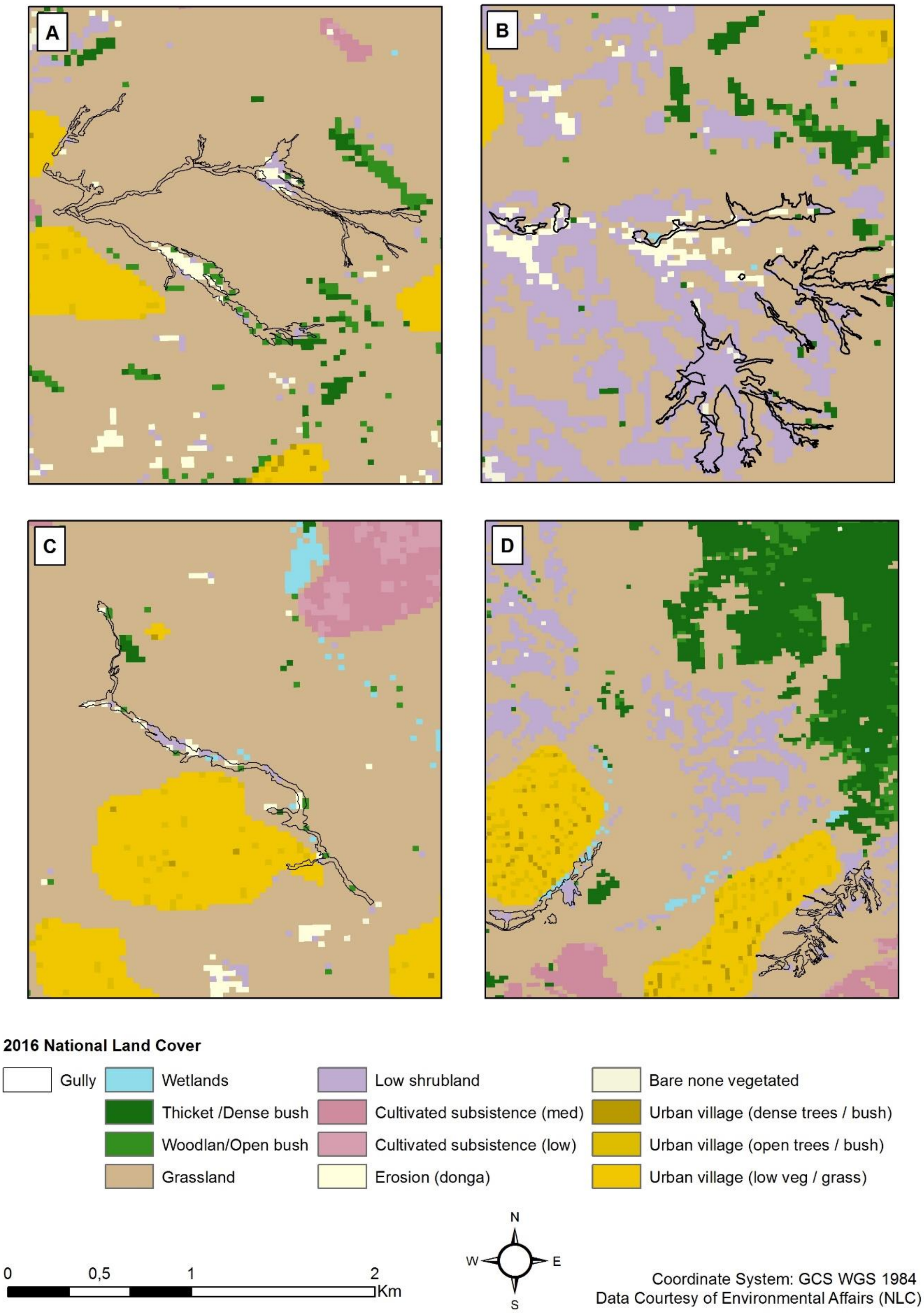


Figure 5. 10: National Land Cover for 2004.



Coordinate System: GCS WGS 1984
Data Courtesy of Environmental Affairs (NLC)

Figure 5. 11: National Land Cover for 2016.

Table 5. 6: Various land cover classes present within the four gullies and buffered zone (1 km) for the years of interest.

Year of interest	Gullies used from year X	Gully	NLC within the gully	Area (ha)	NLC (1km buffer)	Area (ha)
1995	1995	A	Unimproved (natural) grassland	13.43	Cultivated. permanent. commercial. dryland	0.06
			Degraded unimproved (natural) grassland	2.20	**Forest plantations**	**95.57**
			Cultivated. temporary. subsistence. dryland	0.79	Herbland	2.11
					Improved grassland	**502.41**
					Unimproved (natural) grassland	4.54
					Urban/build-up (residential. formal suburbs)	0.07
					Urban/build-up (smallholdings. thicket. bushland)	18.00
					Urban build-up	0.01
					Thicket. bushland. bush clumps. high fynbos	0.58
					Cultivated. permanent. commercial. sugarcane	37.13
		B	Unimproved (natural) grassland	20.28	Cultivated. permanent. commercial. sugarcane	3.29
			Degraded unimproved (natural) grassland	15.58	**Forest plantations**	**196.25**
					Herbland	3.345
					Improved grassland	**458.79**
					Unimproved (natural) grassland	2.19
					Urban/build-up (residential. formal suburbs)	0.40
					Urban/build-up (smallholdings. thicket. bushland)	19.15
					Urban build-up	71.12
					Thicket. bushland. bush clumps. high fynbos	0.30
					Cultivated. permanent. commercial. sugarcane	53.28

Year of interest	Gullies used from year X	Gully	NLC within the gully	Area (ha)	NLC (1km buffer)	Area (ha)
		C	Unimproved (natural) grassland	4.76	**Cultivated. permanent. commercial. sugarcane**	**79.37**
			Degraded unimproved (natural) grassland	0.89	Forest plantations	11.23
			Cultivated. temporary. subsistence. dryland	0.37	Herbland	0.61
					Improved grassland	**472.54**
					Unimproved (natural) grassland	1.17
					Urban build-up	14.63
					Thicket. bushland. bush clumps. high fynbos	4.30
		D	Unimproved (natural) grassland	1.44	Cultivated. permanent. commercial. dryland	1.49
			Degraded unimproved (natural) grassland	1.20	Forest plantations	105.28
			Cultivated. temporary. subsistence. Dryland	0.01	Herbland	13.95
			Urban / Built-up (residential. formal township)	5.52	**Improved grassland**	**405.79**
					Unimproved (natural) grassland	9.75
					Urban/build-up (smallholdings. thicket. bushland)	0.72
					Urban build-up	42.73
					Thicket. bushland. bush clumps. high fynbos	2.61
					Cultivated. permanent. commercial. sugarcane	**175.36**
2004	2004	A	Unimproved (natural) grassland	12.60	Cultivated. permanent. commercial. dryland	32.82

Year of interest	Gullies used from year X	Gully	NLC within the gully	Area (ha)	NLC (1km buffer)	Area (ha)
			Degraded unimproved (natural) grassland	2.27	**Degraded unimproved (natural) grassland**	**227.98**
			Cultivated. temporary. subsistence. dryland	1.27	Waterbodies	13.36
					Unimproved (natural) grassland	**640.89**
					Bare rock & soil (natural)	0.80
					Thicket. bushland. bush clumps. high fynbos	0.61
		B	Degraded unimproved (natural) grassland	13.56	Cultivated. permanent. commercial. dryland	26.59
			Unimproved (natural) grassland	14.64	**Degraded unimproved (natural) grassland**	**384.89**
					Unimproved (natural) grassland	**572.10**
					Bare rock & soil (natural)	4.55
					Thicket. bushland. bush clumps. high fynbos	2.40
		D	Unimproved (natural) grassland	1.67	Cultivated. permanent. commercial. dryland	9.85
			Degraded unimproved (natural) grassland	5.36	**Degraded unimproved (natural) grassland**	**351.15**
			Cultivated. temporary. subsistence. dryland	0.05	**Unimproved (natural) grassland**	**530.95**
			Urban/built-up (residential. formal township)	5.16	Bare rock & soil (natural)	32.54
					Thicket. bushland. bush clumps. high fynbos	10.69
					Urban/built-up (residential. formal township)	143.85
2016	2016	A	Thicket/dense bush	0.07	Cultivated subsistence (medium)	45.87
			Woodland/open bush	0.99	Cultivated subsistence (high)	0.40
			Grassland	12.23	Cultivated subsistence (low)	4.15

Year of interest	Gullies used from year X	Gully	NLC within the gully	Area (ha)	NLC (1km buffer)	Area (ha)
			Low shrubland	1.25	Low shrubland	11.44
			Erosion (donga)	2.49	**Grassland**	**690.13**
			Urban village (low veg / grass)	0.39	Woodland/open bush	18.39
					Thicket/dense bush	10.07
					Plantation/woodlots young	0.26
					Plantation/woodlots mature	0.23
					Bare none-vegetated	7.35
					Erosion (donga)	9.05
					Water seasonal	0.29
					Wetlands	0.55
					Urban village (open trees/bush)	2.62
					Urban village (dense trees/bush)	2.44
					Urban village (low vegetation/grass)	**122.91**
					Water permanent	0.19
		B	Wetlands	0.06	Cultivated subsistence (medium)	36.43
			Thicket/dense bush	0.29	Cultivated subsistence (high)	0.68
			Woodland/open bush	0.04	Cultivated subsistence (low)	6.17
			Grassland	14.74	**Low shrubland**	**237.89**
			Low shrubland	13.24	**Grassland**	**605.89**
			Erosion (donga)	1.98	Woodland/open bush	9.92
			Bare none vegetated	0.28	Thicket/dense bush	20.59
					Plantation/woodlots young	2.54
					Plantation/woodlots mature	4.94
					Bare none-vegetated	10.04
					Erosion (donga)	27.87
					Wetlands	0.55
					Urban village (open trees/bush)	1.97

Year of interest	Gullies used from year X	Gully	NLC within the gully	Area (ha)	NLC (1km buffer)	Area (ha)
					Urban village (dense trees/bush)	0.91
		C			Urban village (low vegetation/grass)	62.94
			Wetlands	0.06	Cultivated subsistence (medium)	65.47
			Thicket/dense bush	0.31	Cultivated subsistence (high)	3.42
			Woodland/open bush	0.86	Cultivated subsistence (low)	15.63
			Grassland	19.96	Low shrubland	3.79
			Low shrubland	11.97	**Grassland**	**562.58**
			Erosion (donga)	3.67	Woodland/open bush	2.54
			Bare none vegetated	0.27	Thicket/dense bush	1.46
			Urban village (low veg / grass)	0.30	Bare none-vegetated	0.57
					Erosion (donga)	6.88
					Wetlands	4.22
					Urban village (open trees/bush)	4.29
					Urban village (dense trees/bush)	0.82
					Urban village (low vegetation/grass	**135.63**
		D	Wetlands	0.14	**Cultivated subsistence (medium)**	**158.95**
			Woodland/open bush	0.07	Cultivated subsistence (high)	6.51
			Grassland	12.13	Cultivated subsistence (low)	39.10
			Low shrubland	3.30	Low shrubland	54.57
			Urban village (low veg / grass)	0.02	**Grassland**	576.94
					Woodland/open bush	20.91
					Thicket/dense bush	42.05
					Wetlands	4.99
					Urban village (open trees/bush)	14.15
					Urban village (dense trees/bush)	5.83
					Urban village (low vegetation/grass	134.36

Table 5. 7: Land cover classes within the gully and the 1 km buffer presented in percentages.

Year of interest	Gully present	NLC inside gully	NLC coverage (%)	NLC within 1 km buffer	NLC coverage (%)
1995	A	Unimproved (natural) grassland	81.79	**Improved grassland**	**76.07**
		Degraded unimproved (natural) grassland	13.41	**Forest plantations**	**14.47**
		Cultivated. temporary. subsistence. dryland	4.79	Cultivated. permanent. commercial. sugarcane	5.62
				Urban/build-up (smallholdings. thicket. bushland)	2.73
	B	Unimproved (natural) grassland	56.56	**Improved grassland**	**56.77**
		Degraded unimproved (natural) grassland	43.44	**Forest plantations**	**24.29**
				Urban build-up	8.80
				Cultivated. permanent. commercial. sugarcane	6.59
				Urban/build-up (smallholdings. thicket. bushland)	2.37
	C	Unimproved (natural) grassland	79.10	**Improved grassland**	**80.94**
		Degraded unimproved (natural) grassland	14.75	**Cultivated. permanent. commercial. sugarcane**	**13.59**
		Cultivated. temporary. subsistence. dryland	6.15	Urban build-up	2.50
				Forest plantations	1.92
	D	Urban / Built-up (residential. formal township	67.61	**Improved grassland**	**53.56**
		Unimproved (natural) grassland	17.64	**Cultivated. permanent. commercial. sugarcane**	**23.14**
		Degraded unimproved (natural) grassland	8.17	Forest plantations	13.90
		Cultivated. temporary. subsistence. dryland	0.06	Urban build-up	5.64
				Unimproved (natural) grassland	1.29
2004	A	Unimproved (natural) grassland	77.94	**Unimproved (natural) grassland**	**69.93**
		Degraded unimproved (natural) grassland	14.02	**Degraded unimproved (natural) grassland**	**24.88**
		Cultivated. temporary. subsistence. dryland	7.83	Cultivated. permanent. commercial. dryland	3.58
				Waterbodies	1.46
	B	Unimproved (natural) grassland	51.92	**Degraded unimproved (natural) grassland**	**57.76**
		Degraded unimproved (natural) grassland	48.08	**Unimproved (natural) grassland**	**38.86**

Year of interest	Gully present	NLC inside gully	NLC coverage (%)	NLC within 1 km buffer	NLC coverage (%)
				Cultivated. permanent. commercial. dryland	2.68
	D	Unimproved (natural) grassland	43.79	**Unimproved (natural) grassland**	**49.21**
		Urban/built-up (residential. formal township)	42.19	**Degraded unimproved (natural) grassland**	**32.54**
		Degraded unimproved (natural) grassland	13.63	Urban/built-up (residential. formal township)	13.33
		Cultivated. temporary. subsistence. dryland	0.39	Bare rock & soil (natural)	3.02
2016	A	Grassland	70.00	**Grassland**	**74.50**
		Erosion (donga)	14.31	**Urban village (low vegetation/grass)**	**13.27**
		Low shrubland	7.16	Cultivated subsistence (medium)	4.95
		Thicket/dense bush	5.67	Woodland/open bush	1.98
		Woodland/open bush	2.24	Thicket/dense bush	1.09
		Urban village (low veg / grass)			
	B	Grassland	48.13	**Grassland**	**58.86**
		Low shrubland	43.25	**Low shrubland**	**23.11**
		Erosion (donga)	6.46	Urban village (low vegetation/grass)	6.11
		Thicket/dense bush	0.93	Cultivated subsistence (medium)	3.54
		Bare none vegetated	0.90	Erosion (donga)	2.71
		Wetlands	0.19	Thicket/dense bush	2.00
		Woodland/open bush	0.13		
	C	Grassland	52.67	**Grassland**	**69.69**
		Low shrubland	32.00	**Urban village (low vegetation/grass)**	**16.80**
		Erosion (donga)	9.81	Cultivated subsistence (medium)	8.11
		Woodland/open bush	2.30	Cultivated subsistence (low)	1.94
		Thicket/dense bush	0.82		
		Urban village (low veg / grass)	0.80		
		Bare none vegetated	0.72		
		Wetlands	0.15		

Year of interest	**Gully present**	**NLC inside gully**	**NLC coverage (%)**	**NLC within 1 km buffer**	**NLC coverage (%)**
	D	Grassland	77.48	**Grassland**	**63.82**
		Low shrubland	21.11	**Cultivated subsistence (medium)**	**17.58**
		Wetlands	0.88	Low shrubland	6.04
		Woodland/open bush	0.44	Thicket/dense bush	4.65
		Urban village (low veg / grass)	0.10	Cultivated subsistence (low)	4.32

5.3. Objective 3

Investigate historical climate variability and relate it to the gully growth occurring over the various time periods.

The data analysis performed for this objective was based on raw rainfall and temperature data obtained from the South African Weather Service (SAWS). A mean annual rainfall graph incorporating all three weather stations was generated (Figure 5. 12 below) in order to visually illustrate the overall rainfall patterns that occurred during the various time periods across the years.

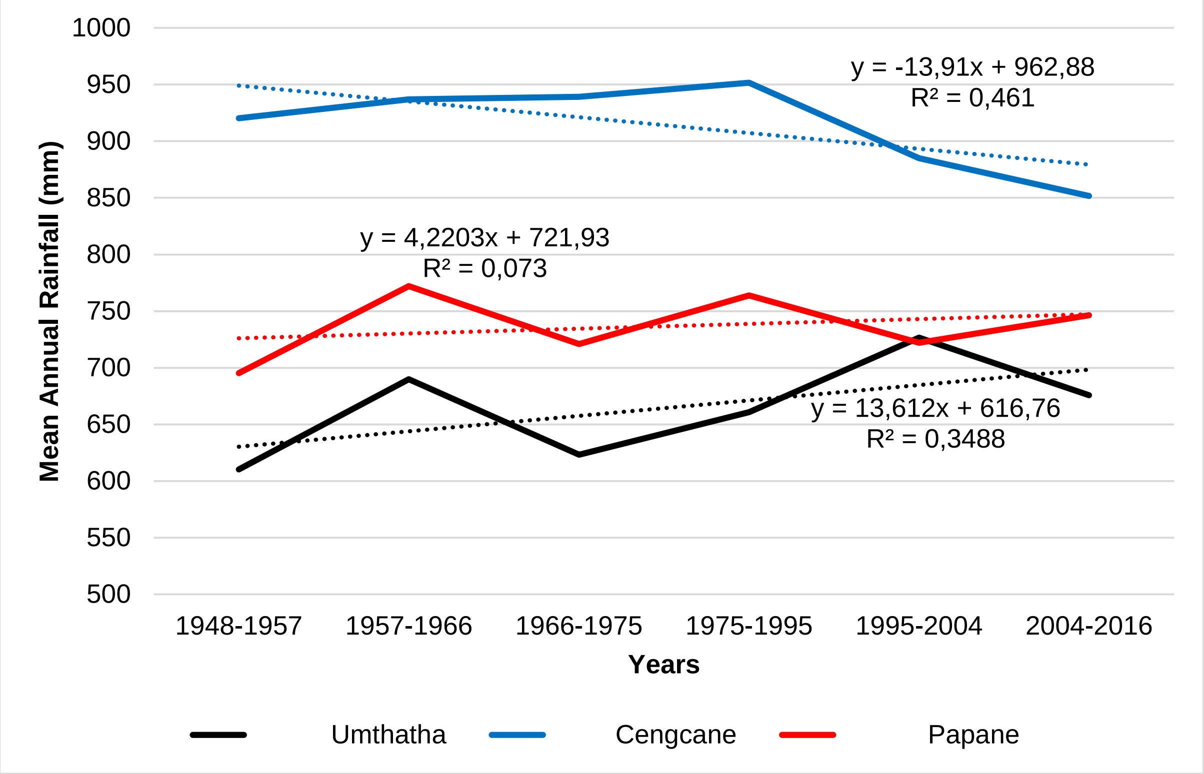


Figure 5. 12: Mean annual rainfall of all three rainfall stations occurring over the six time periods. A linear trend line is indicated by the dashed lines.

5.3.1. Rainfall data

Umthatha rainfall station

All three weather stations had a similar pattern in rainfall occurrence across the six time periods as seen on Figure 5. 12 above. Rainfall within the Umthatha rainfall station quickly increased during the first time period (1948-1957). The rainfall trend between 1948 and 2016 alternated between high and low annual rainfalls with a few peaks, in between the years, which vary per weather station. Two distinct rainfall peaks were evident for Umthatha and occurred during the second (1957-1966) and fifth (1995-2004) time periods. The rainfall over these two time periods was 689.77 mm and 726.58 mm respectively with the lowest mean annual rainfall present during the first time period (1948-1957) at only 610.18 mm. Umthatha has an increasing rainfall pattern across the years.

Cengcane rainfall station

Contrary to the Umthatha rainfall station on Figure 5. 12 (pg. 79), Cengcane, had its highest annual rainfall during the fourth time period (1975-1995) at 951.70 mm rainfall while 2016 had the lowest rainfall at only 851.78 mm. Unlike the Umthatha rainfall station, Cengcane station shows a decreasing pattern in rainfall across the time periods. The rainfall station showed a high initial rainfall that steadily increased until 1975-1995, following this was a drop in annual rainfall till the last time period 2004-2016.

Papane rainfall station

According to Figure 5. 12 (pg. 79) Papane rainfall station is the third and last rainfall station of interest. Like the Umthatha rainfall station, this station had an initial peak in annual rainfall (772.11 mm) during the second time period (1957-1966). Another peak (763.74 mm) was evident during the fourth time period (1975-1995). Parallel to the Umthatha rainfall station, the Papane rainfall station received its lowest rainfall during the first time period (1948-1957) followed by a quick increase in rainfall and a steady drop in rainfall after the first peak.

5.3.1.1. Regression analysis

A regression analysis was performed and a null hypothesis (H_0) was set as follows: there is no significant difference of annual rainfall within the three rainfall stations across the years. On the other hand, an alternative hypothesis (H_a) was set such that a statistically significant relationship between the annual rainfall and the years exists among the three rainfall stations. Alongside this was an alpha (α) value of 0.05. Figure 5. 12 (pg. 79), shows the mean annual rainfall for the three rainfall stations whereas Figure 5. 13 (pg. 81) to Figure 5. 15 (pg. 82) illustrate regression analysis of the various rainfall stations together with their respective *p*-values. All *p*-values for the rainfall stations were above the set alpha (α) value of $\alpha=0.05$, which indicate that there is not enough information or data present to allow one to reject the null hypothesis. Although the linear trends show both an increase and decrease in the rainfall patterns for various rainfall stations, there is no statistically significant difference between the annual rainfall occurring within the various rainfall stations and the years in which the rainfall occurs. Although this is the case, the *R*-squared values are close to zero, implying that other tests should be run to further explain rainfall variability within stations. The ANOVA test was thus, run and its results (Table 5. 8, pg. 82) further confirmed that rainfall received within each rainfall station is homogeneous ($p=0.238$). Alongside this is the heterogenous rainfall (*p*-value

~ 0.000) present between some of the rainfall stations. Furthermore, Table 5. 9 on pg. 82 shows for which of these weather stations a significant difference exists, and for which the difference is not significant.

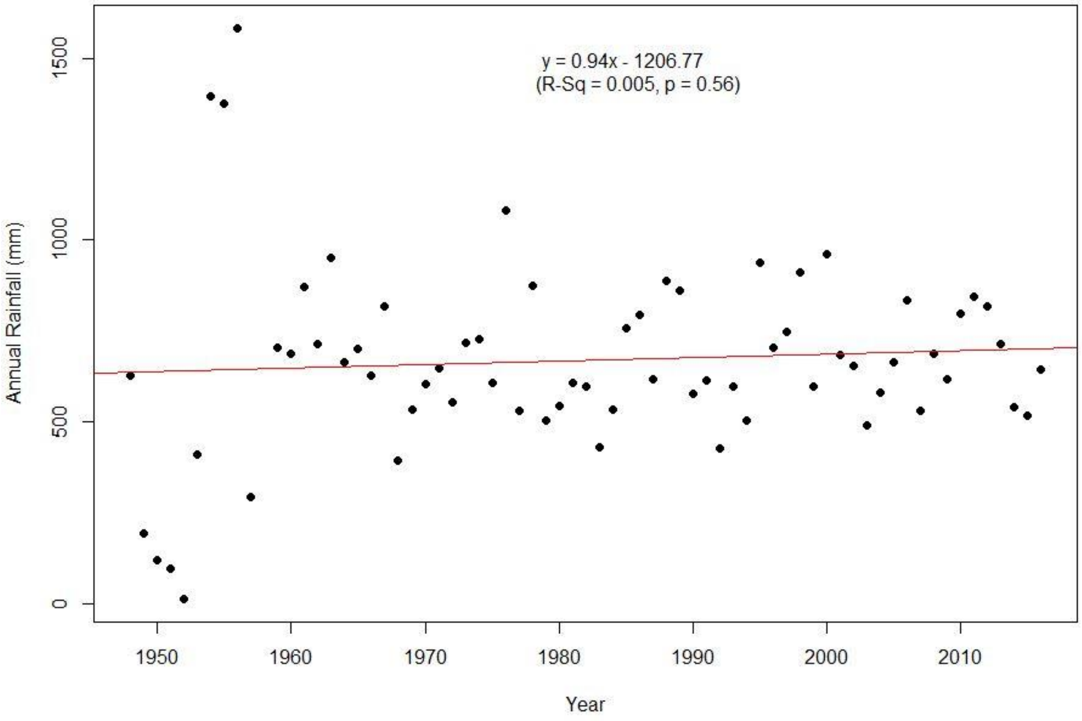


Figure 5. 13: Total annual rainfall received at the Umthatha rainfall station.

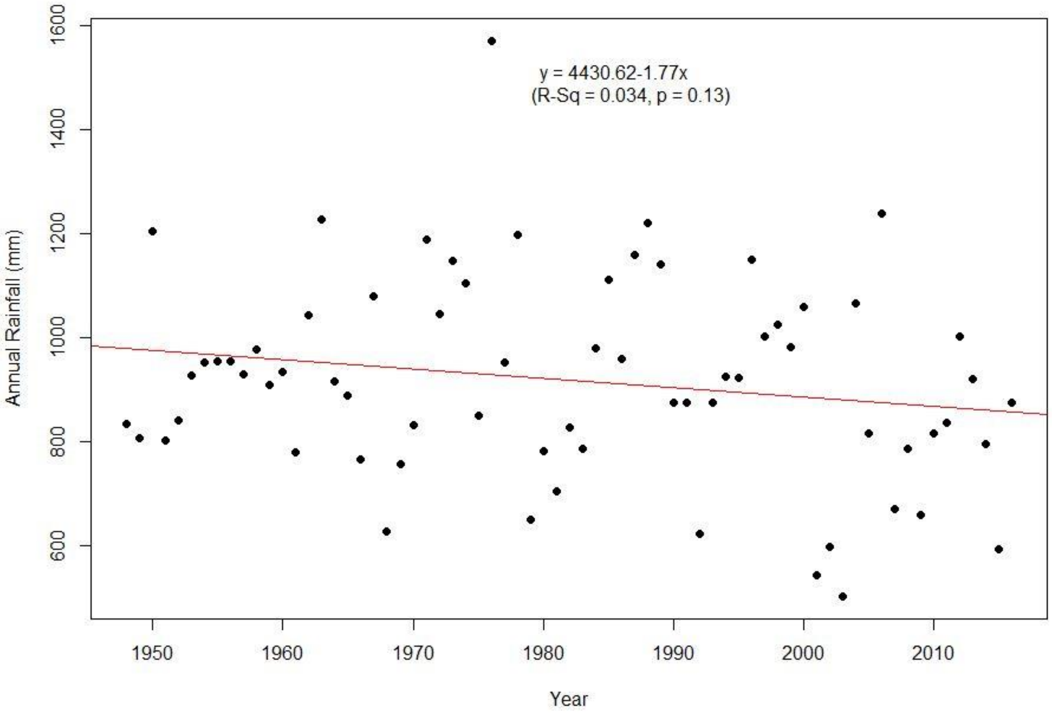


Figure 5. 14: Total annual rainfall received at the Cengcane rainfall station.

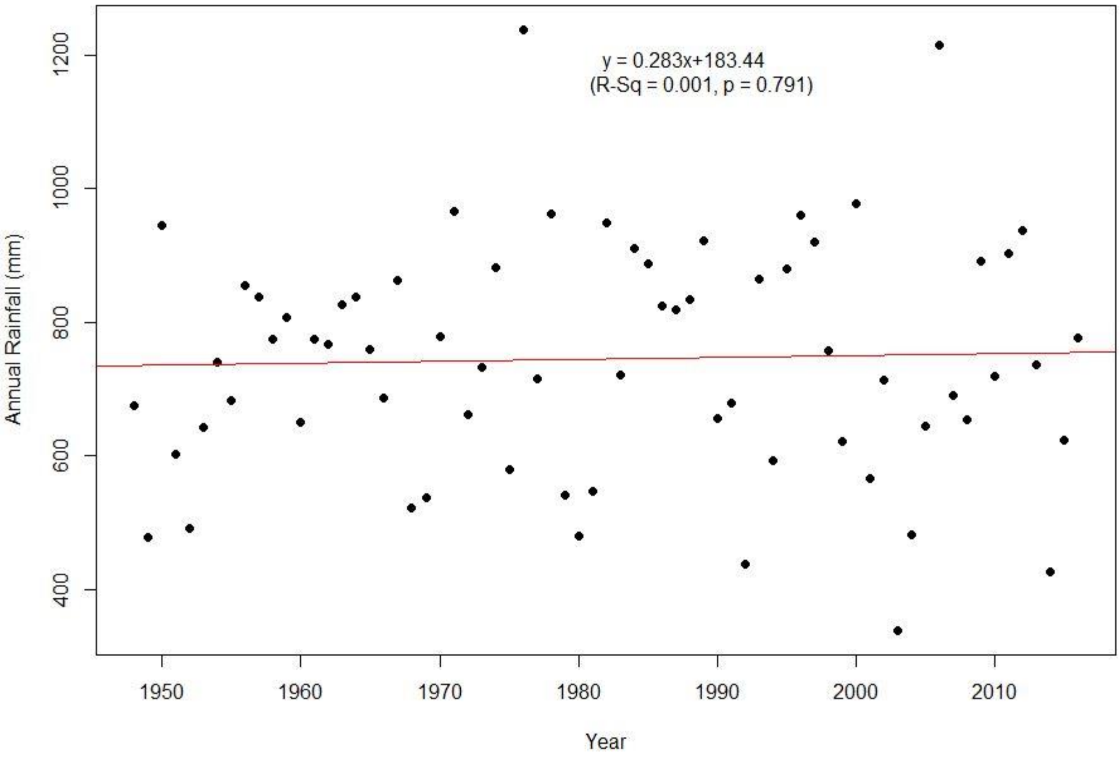


Figure 5. 15: Total annual rainfall received at the Papane rainfall station.

Table 5. 8: Rainfall results from the ANOVA test.

ANOVA test	***p*-values**
Levene's Homogeneity test based on means	0.238
ANOVA test between groups	~ 0.000

Table 5. 9: Tukey HSD multiple comparison test.

Tukey HSD comparison test	***p*-values**
Umthatha and Cengcane	$p < 0.05$
Umthatha and Papane	$p > 0.05$
Papane and Cengcane	$p < 0.05$

Table 5. 10 shows the summarised mean annual rainfall present over the 68-year time period per weather station. Alongside this, was the inter- and intra-annual rainfall values (CV and PCI respectively) together with rainfall erosivity values (MFI). Cengcane has the highest mean rainfall over all six time periods, followed by the Papane rainfall station and the Umthatha rainfall station.

Table 5. 10: Temporal distribution of selected rainfall stations in the Lower Thina Catchment.

Station	**Time Period**	**Mean**	**Standard Deviation**	**CV**	**PCI**	**MFI**
Umthatha	1948-2016	668.05	262.75	39.33	17.98	100.20
Cengcane	1948-2016	918.02	193.83	21.11	14.73	134.89
Papane	1948-2016	774.57	174.96	22.59	14.64	86.43

5.3.1.2. Inter- and intra- annual rainfall variability

Rainfall variability for the Lower Thina Catchment was evaluated inter- and intra- annually, between rainfall stations. Table 5. 10 (pg. 82) summarises inter-annual rainfall variability using the Coefficient of Variation (CV). All three rainfall stations reflect low CV values (CV < μ - σ). This implies a low variation in rainfall from one year to the other within the catchment. The Precipitation Coefficient Index (PCI) was used to calculate the intra-annual rainfall variability within the catchment (Table 5. 10, pg. 82). Of the three rainfall stations, one station (Umthatha) reflects an irregular precipitation distribution (20 ≥PCI>16) while two (Cengcane and Papane), reflect a moderate precipitation distribution (15 ≥PCI>10).

5.3.1.3. Modified Fournier Index (rainfall erosivity)

The Modified Fournier Index (MFI) was used to calculate rainfall erosivity within the catchment. As previously discussed, this index was mainly used as a result of the lack of one-minute interval rainfall data for the study area. Table 5. 10 (pg. 82) shows the various degree of rainfall erosivity among the three rainfall stations while Figure 5. 16 (pg. 84) displays the visual representation of the various MFI values present across the different time periods. The degree of erosivity may further be related to the annual mean rainfall, which occurred at the respective rainfall stations. The Umthatha station had rainfall erosivity ranging from 89.49 to 127.87. Nonetheless, the values alternate between low (60<MFI<90), moderate (90<MFI<120) and high (120<MFI<160) rainfall erosivity.

Unlike the Umthatha rainfall station, which exhibit three different erosivity classes (Table 5. 11, pg. 84), Cengcane rainfall station only has one erosivity class (high erosivity, 120<MFI<160). On the otherhand, the Papane rainfall station has two erosivity classes, the low (60<MFI<90) and moderate class (90<MFI<120). The rainfall station with an overall high rainfall erosivity is Cengcane, while Umthatha and Papane have moderate and low rainfall erosivity values respectively (Table 5. 11, pg. 84).

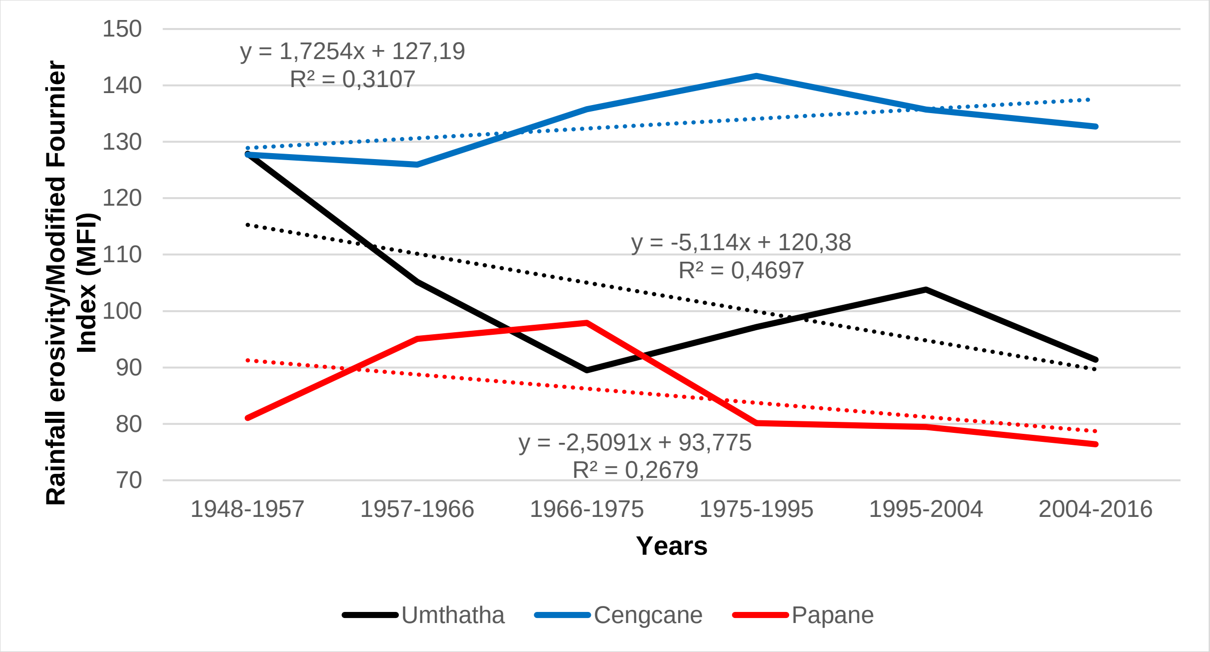


Figure 5. 16: Modified Fournier Index across the time periods of interest.

Table 5. 11: Modified Fournier Index for all three weather stations across all the different time periods of interest. Low values are in **bold**, high values are underlined.

Time period	Umthatha	Cengcane	Papane
1948-1957	127.87	127.68	**81.05**
1957-1966	105.17	125.92	95.06
1966-1975	**89.49**	135.74	97.88
1975-1995	97.18	141.65	**80.11**
1995-2004	103.81	135.68	**79.46**
2004-2016	91.35	132.72	**76.40**

5.3.2. Temperature data

Climate variability does not only occur as a result of variation in precipitation but also as a result of global air temperature fluctuations (Nearing, 2001). According to the IPCC (1995), warmer atmospheric temperatures are predicted to lead to vigorous hydrological cycles, as well as extreme rainfall events. This may lead to intense rainfall events in the coming decades (Mondal *et al*., 2015). Temperature data was thus used to derive the annual maximum and minimum temperatures in order to make this association.

Unlike the rainfall data obtained from three stations, only one station (Umthatha) had data for both maximum and minimum temperatures. Rainfall data began in 1959 (Figure 5. 17, pg. 85). Trend lines were drawn on the temperature graph generated (Figure 5. 17, pg. 85) and although small, incements in both maximum and minimum temperatures are evident throughout the years, agreeing to global trends (Nearing, 2001).

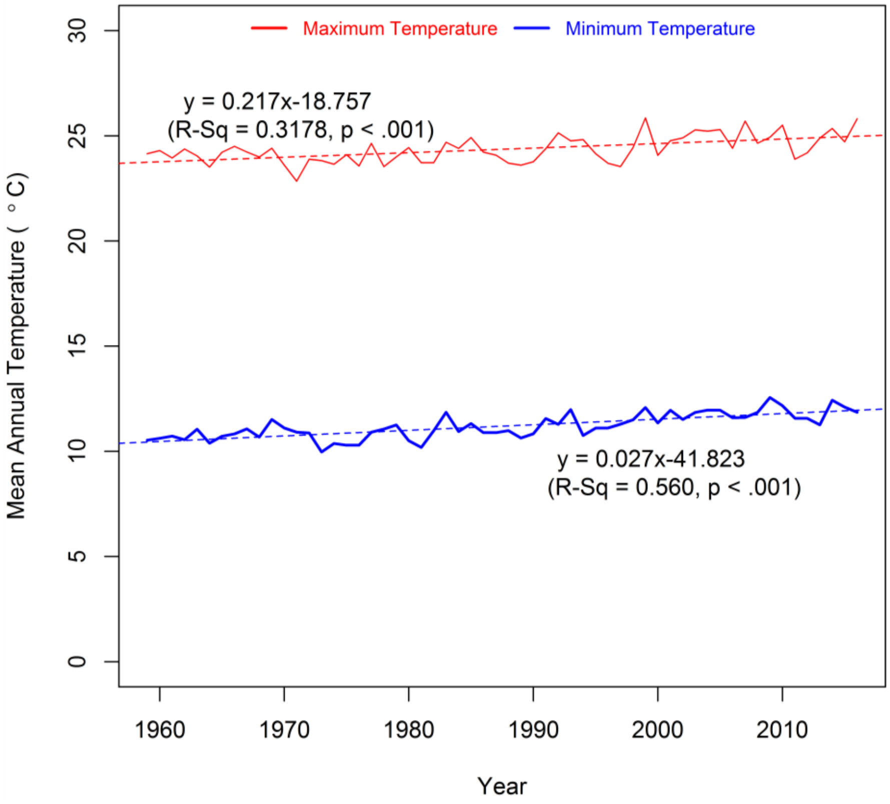


Figure 5. 17: Maximum and minimum temperatures for Umthatha.

5.3.3. Limitations and delimitations

Gully development usually has no time frame but instead depends on favourable conditions. Once gullies have developed, the growth process and further development is slow (Malik, 2005). For this reason, only six time periods were chosen for the duration of the study. Furthermore, although the years inbetween the time periods are not consistent, the various time periods are used to fully understand the erosional dynamics within the catchment. Images from these time periods were selected based on availability and map resolution. There was a limited number of aerial images available, this however, did not hinder with the success in generating images for analysis. Only one gully (gully C in 2004) resulted in a break in or discountious trend in information. This may have hindered with the outcomes obtained regarding the gully system analysis. Furthermore, difference in the scale of the aerial photos resulted in a coarse resolution for some of these images. Additionally, the absence of colour information for these images made digitizing a difficult process. Moreover, errors associated with digitising features may have lead to erroneous calculations of gully surface change. However, such errors were minimised by digitising at a constant scale.

The National Land Cover (NLC) data used were of the same resolution, however, there was a difference in the classes used. Alongside this, was the varying technique used to collect the

NLC data. This made comparison of land cover classes among various years difficult but feasible. Furthermore, the NLC data was consistant between 1995 and 2004, making it feasible for comparison purposes, however, the NLC data changed in 2016. This made comparison impossible, therefore NLC data for this year was merely used as reference for the current NLC condition.

The number of rainfall stations present within the study area together with the available rainfall and temperature data, pose further limitations to this study. Only the T34J catchment had a weather station (Papane) present while the T34K had none. Furthermore, two weather stations found outside the Lower Thina Catchment, Cengcane and Umthatha, were used because they are the closest to the Lower Thina Catchment and only one with temperature data respectively. Alongside this, was the missing rainfall data which was way beyond the 10% mark together with anomalously low or high values which could skew and alter results, therefore, producing inaccurate outcomes. This can be linked to the rainfall erosivity being a calculated average (Anderson, 2012). However, for this study none of the values were removed due to the dataset having limited readings. Absence of one-minute interval rainfall data made it impossible to calculate rainfall erosivity using the commonly used R-factor technique. Instead, the Modified Fournier Index (MFI) was used. Along with these were the chosen delimitations for this study, which were gully surface area, continuity of the gully, variation in topography, and the extent of gully erosion (not active, moderately active, active and very active). Irrespective of the limitations and delimitations discussed, the study is not flawed.

CHAPTER 6: DISCUSSION

6.1. Aerial images, surface areas and annual gully growth rate

After an analysis of all the four gullies present within the study area, it is evident that the gullies cannot be ephemeral nor bank in nature. This is because gullies occur at large time scales, cannot be removed through tillage and do not occur on the banks of rivers (as discussed in section 2.2.2, pg. 20 onward). As a result, all gullies are characterised as permanent in nature as they visually appear deeper than 0.5 m and cannot be managed nor rehabilitated through normal tillage (Poesen *et al*., 2003; Capra, 2013). Furthermore, the gullies present in this study are all assumed to be U-shaped due to the slowed down rate of runoff flow and the assumption that the gullies have all reached their gully floor. As a result, only lateral changes (surface coverage change as calculated from aerial imagery) were recorded.

6.1.1. Gully A

Gully A has an overall annual gully expansion rate of 0.1 ha.yr^{-1}. It is evident from the mapped gullies, that gully A is the closest gully to the Thina River. Nonetheless, the river may have contributed in the initiation of the gully (Shellberg *et al*., 2013), but not on the further development/growth of the gully. This is seen from the size and growth rate of the gully system, which behaves like the other gullies in the catchment. The gully system is found above fine to medium grained sandstone and undifferentiated shallow soils. According to Scotney & Dijhuis (1990), all South African soil is characterised by very low organic matter, resulting in unstable soils. Such evidence is seen through gullying within the Lower Thina Catchment. Furthermore, 90% of soils found in the Eastern Cape are duplex in nature, making them highly sensitive to erosion (Parwada & van Tol, 2016). As a result, severe gully erosion is present not only in the Lower Thina Catchment but across the Eastern Cape province at large.

The surface area making up gully A increases over the years. This increase in surface area may be associated with underlying geology, topography and rainfall erosivity within the area. However, the main reason for an increase in the size of gully A, is the road along which the gully is found. In West Pokot, Kenya, Jungerius *et al*. (2002), observed no gully erosion before the construction of a road. Over time, gullying occurred along the roadside. The results from the current study can be related to that of Jungerius *et al*. (2002). It may be assumed that no gully or very little gullying was evident pre-1948. After the construction of the road, gullies developed and the smaller, already existing ones (if present before the road construction) increased in size. An assumption can be made that the road engineering becomes inadequate with time because of the human settlement attracted by the road. As a result, surface drainage deteriorates, and erosion occurs at unpredicted points (Jungerius *et al.,* 2002).

Construction of roads affects the extent of erosion both positively and negatively. Roads are commonly known to increase the size of or initiate gullies. However, a study in the Northern Ethiopian Highlands, reveals that roads can also cause gullies to be inactive (Nyssen *et al.,* 2002). This is due to the position in which the road is constructed. Gullies are likely to initiate where roads intercept and concentrate runoff from slopes. Roads which are constructed such that insufficient runoff is concentrated, do not initiate or extend gullies, instead, they cause the inactivity of gullies (Nyssen *et al.,* 2002). This supports the presence of gully A occurring and extending only along one side of the road although settlements occur along both sides of the road.

Furthermore, the underlying geology also affects the development and growth of gully A. Sandstone, the underlying geology for gully A, is an easily erodible geological layer prone to gully erosion (Fadul *et al*., 1999; Taruvinga, 2008; le Roux & Sumner, 2012; Parwada & van Tol, 2016). Moreover, from the obtained aerial images, and calculated slopes for all gullies, gully A occurs along gentle regions and follows the topography of the area. The gentle topography along which the gully is found, contributes less towards surface area expansion and erosion. El-Swaify (1997) confirms that soil loss increases with slope steepness; this is due to hilly or mountainous slopes being highly favoured for gully development (Valentin *et al.,* 2005). Alongside this is the high energy that eroding agents (usually water) have in conjunction with slope steepness (Renard & Foster, 1983). The rate of surface runoff is affected by the steep slopes which in return, affect the development and growth of gullies (Shit *et al.,* 2013; Mararakanye, 2015).

Gully A exhibits fluctuating annual expansion rates across the six selected time periods. The rate of gully expansion for both gully A and D was the greatest during the first time period and decreased right through to the current time period (2004-2016), an association may be made to gully filling (Kropáček *et al*., 2016). Like the soil erosion study conducted in the Herschel District (Eastern Cape) by Vetter (2007), the current study reflects a soil erosion rate of change that differs considerably across time intervals. Soil erosion rates are commonly known to increase with time as a result of the various land use changes or betterment measures present in an area (Vetter, 2007). Nonetheless, expansion rates of gully A in the Lower Thina Catchment show a different trend. The gully erosion rate initially decreases, then remains constant. With time, a further decrease in the rate of gully erosion occurs. This may be linked to open bushes evident in the catchment alongside absent shrubland in the area. Furthermore, vegetation cover is reduced as a result of overgrazing and human settlement evident from aerial images (Kakembo *et al.,* 2009). This is a conducive condition for gully initiation or expansion and permits detrimental effects from rainfall events. Kakembo *et al*. (2009) also supports the formation and expansion of gullies along such abandoned and/or less vegetated areas (Rienks *et al.,* 2000; le Roux & Sumner, 2012).

6.1.2. Gully B

Gully B has an overall annual gully expansion rate of 0.07 ha.yr^{-1}. Contrary to the first gully system, which is located near a main road, gully B is not near nor along a road. Instead, only steep topography along with residential areas are evident. Like gully A, gully B is underlain by fine to medium grained sandstone, together with undifferentiated shallow soils. These are duplex conditions, and thus, conducive for erosion in the area (van Zijl *et al*., 2013; van der Waal, 2015; Parwada & van Tol, 2016). Gully B occupies the greatest surface area among all four gullies of interest. Nevertheless, its growth rate is not necessarily the greatest among the other three gullies. Unlike gully A, which has an initial increase in surface area followed by a stagnant surface area due to zero expansion rate, the surface area for gully B initially decreases then remains stagnant. This gully system is the largest of all four gullies and has many grazing tracks, which may have formed over time as a result of high volume of trampling (Rowntree *et al*., 2004). This implies intense grazing activity around the gully, which can be related to a reduction in vegetation. During the early years in the catchment, little grazing was evident. However, with time, the degree of livestock grazing increased (van der Waal, 2015). This is associated with the isolated vegetation cover present, later affecting the rate of gully expansion. Evans (1998) states that the growth rate of vegetal cover is impeded by constant grazing and that loss of vegetation cover is directly proportional to the severe effect of erosion. Furthermore, Evans (1998) and Hall *et al.* (1999), note that grazing animals are mostly responsible for the global degradation of land. Even so, animals have an even greater effect if the area undergoes various land uses as compared to when the land is in its natural state. The effects of grazing, alongside winter burning and abandonment of land, aggravates the formation of extensive gullies in the catchment as a result of severe degradation of vegetation (van der Waal, 2015; Bannatyne *et al*., 2017).

Unlike some research (*e.g.* Evans, 1998; Lasanta *et al.,* 2001), which found steep slopes as areas seldom associated with grazing, the Lower Thina Catchment also has grazing evident in steeper areas. This implies that gully formation on steep slopes can be attributed to contemporary land use. Gully B is the largest and steepest of all four gullies, this agrees with other research (*e.g*. Tyson *et al*., 1976; Schulze, 1979; El-Swaify's, 1997; Nel & Sumner, 2006; Schulze, 2010), which state that soil loss increases with slope steepness. Nonetheless, as already stated, gullies in the Lower Thina Catchment are not solely related to the steepening of slopes.

As already shown in Figure 5. 7 (pg. 64), some of the used aerial images have poor resolution. As a result, gully B aerial images for the year 1975 were not used because these were not clear. This undefined surface area affected the calculation for determining annual expansion rate for two consecutive time periods (1966-1975 and 1975-1995). Gully B is the only gully starting off on a negative rate of expansion. This is due to the degraded land coupled with surface loosening as a result of low rainfall during this time. Nonetheless, a linear extrapolation shows the surface area of gully B increasing with time.

6.1.3. Gully C

Gully C has an overall annual gully expansion rate of 0.09 ha.yr^{-1}. It is evident from the mapped gullies that gully C is the narrowest and longest yet smallest gully among all four gullies. The gully system is found above mudrock subordinate sandstone and poorly drained soils. It runs through a small farm as well as blocks of residential areas. Also, the gully occurs along the gentlest topography of all four gully systems.

Alongside this, is the eroded land occupying the smallest surface area among the four gullies. This gully system has no road present within its vicinity; only settlement areas are present. In the early years few settlement areas were evident, as the years progressed, the settlements that were initially present, became absent. Reasons for this may be due to the fear of the gully growing and expanding further into the residential area. This is possible as most gullies start off small and expand with time, displacing residents (Ezezika & Adetona, 2011). Nonetheless, the overall area occupied by residential blocks increased. An association between settlements and gully expansion is thus, present. The cultivated land seems to have predated part of the gully system and is seen to have triggered further expansion of the gully system. This can be supported by Jahantigh & Pessarakli (2011), who indicate that agricultural activities play a role in gully initiation. Furthermore, gully C is a unique gully system since it has rates which alternate between 0.2 and 0 ha.yr^{-1}, showing the least variation of gully erosion expansion and/or contraction among all gullies investigated.

6.1.4. Gully D

Gully D has an overall annual gully expansion rate of 0.1 ha.yr^{-1}. It is the only gully system located in the T34K quaternary catchment and the only one comprised of two separate gullies.

Like gully C, this gully system is found above mudrock subordinate sandstones. In addition, lithosols are present within the gully system further making the soil susceptible to erosion.

The calculated surface area reveals a pattern evident for all four gully systems. Gully D initially begins with a small surface area that then increases with time and stabilises between 1957 and 1966. Thereafter, a pattern like gully B is evident where the system experiences a decrease in surface area but further increases in the last year, exceeding the surface area calculated in the first time period of interest. Residential areas are visible only for five time periods. The year 1948 reflects no residential areas. This implies that the gully system predates residential areas present in the catchment as per the work of Temme *et al*. (2008), who stated that some gullies predate human occupancy. Settlements are only evident from 1957. During this year, the gully system was also seen to have grown further in comparison to when it was initially identified, when no residential area was present. In 1975, the resolution of the aerial images used was not ideal. Consequently, the gully system was not clear and was thus not identified, however, some residential areas were clearly recognised. In 2004 and 2016, greater development took place and tarred roads were now evident, as well as a greatly expanded gully system.

The low vegetal cover may have contributed to the increment in gully size. This is so, because decreased vegetation is known to increase both surface and subsurface runoff resulting in increased flow velocity. Low and/or poor vegetation implies that few plant roots are present to restrain or hold soil particles together (De Baets *et al.,* 2006; Tebebu *et al.,* 2010), thus increasing the extent of erosion (Tamene *et al*., 2006; le Roux & Sumner, 2012). Even so, anthropogenic factors contribute greatly to the expansion of gullies. It is suggested that both settlement areas and the present main road, surpass the influence of vegetal cover because, although the degree of vegetal cover is unknown across the years, the extent of settlements and roads present is known. The increase of surface area covered by the gully may be related to poorly drained soils undergoing great compaction (during animal grazing) over time together with the constructed roads. These both contribute to the poor drainage system in the area, which may initiate and expand the size of gullies in the area (Evans, 1998; Lasanta *et al.,* 2001; Ezezika & Adetona, 2011; le Roux & Sumner, 2012).

The expansion rate of gully D is identical to that of gully A during the first time periods. With time, the annual rate of gully expansion decreases. This may be associated with the varying degree of vegetation cover, various land use activities and climatic parameters to be discussed towards the end of this chapter.

Overall, the gullies' steepness varies per year as a result of natural vegetation encroachment and rehabilitation, thus, reducing the extent in which gullies are found. Furthermore, the gullies could still be active, thus, the lateral increase in gully size upslope. Moreover, the subjectivity associated with gully digitisation alongside the bare soil in which the gullies are embedded on, could be an additional reason for the variation of gully steepness.

6.2. Land use

Gullies within the catchment have varying land cover across the years. Nonetheless, natural grassland is the dominating land cover for the years which land cover data were available (Table 5. 6, pg. 71). The grassland cover across the catchment decreased from 1995 till 2004 followed by an increase thereafter. This reduction in grassland may be associated with the farming practices that initially began as permanent and commercial in nature and later changed to subsistence farming. Changes in land use cover activities within and around the gullies cause varying extents of erosion that may be reduced through widespread revegetation, as roots are known to bind surface soil, thus, improving its structural stability (Valentin *et al.,* 2015). It was thus assumed that grassland in the area was also used as part of the rehabilitation strategies in place. This agrees with the works of De Baets *et al*. (2009), Ayele *et al*. (2016) and Talema *et al.* (2017). However, this only temporarily stabilises gullies as they increase again in size over time. Shellberg & Brooks (2013) support this by stating that not all ground cover is equally effective in reducing soil erosion. Effective stability, thus, depends on the stage of the gully, where initial stages are more preferred for successful rehabilitation (Ayele *et al*., 2016). Grassland is, furthermore, used as feed for livestock in the area.

Based on the analysed aerial photographs, it is evident that urban built-up (residential areas) as well as a main road, are present across the history of gully A. However, the two land cover classes are not always dominant across the years. This implies that other factors dominate and contribute more to the reduction and enlargement of the gully. An interesting aspect is seen during 2016: residential areas are identified within the actual gully system. Two reasons may exist for this phenomenon. First, the gully may have spread in size, engulfing some of the residential areas within the actual gully. Second, the mapped gullies do not align with the NLC data. The first reason was disregarded based on the analysed aerial images that show an absence of houses within the gully system. The second reason is thus, favoured as the NLC data used for the various years is not for that particular year of interest. Due to availability, all the years used preceded the year of interest (refer toTable 4. 3, pg.50). Furthermore, gullies were mapped from aerial photographs having a higher resolution than the NLC dataset. This illustrates that care must be taken when using secondary data for gully development and growth determination.

Like gully A, the largest gully system (gully B) also has grassland as the common land cover occurring across the years. A study by Nyessen *et al*. (2006), where gully erosion rates were assessed through interviews and measurements, revealed that various land uses in and around the gully system result in changes both in the rate and size of gullies. Similarly, Garcia-Ruiz (2010), further supports the above statement. This is revealed through his study aimed at determining the effects of various land uses on soil erosion in Spain. Some of his results showed that expansion of cereal episodes relates to extensive soil erosion. Sheet erosion, piping and gullying also affected abandoned fields in the area. Varying extents of erosion were thus, evident due to the varying land uses present. The work of Gutierrez *et al*. (2009b) explored the effects of land use and topographic thresholds on gullying. A clear trend between land use and gully evolution was evident, favouring an increase in erosion as a result of extensive and varying land uses present within the catchment. According to these studies, varying land uses are attributed to influence an increase in the surface area of gullies in the Lower Thina Catchment. It can therefore be deduced that the surface area of gullies is more dependent on the surrounding land use changes than on the interior changes within the gully itself (Collins *et al*., 2000). Substantiating this, are the few land cover classes present within gully B (during 1995 and 2004) as opposed to other gullies, yet, gully B is still the largest in size.

Throughout the years, residential areas decreased in size around gully B and increased in size for gullies A, C and D. Nonetheless, gully B was still the largest among all gullies. This supports the notion that settlements and their associated human activities cannot solely result in gully expansion, instead, they form part of other contributing factors. The study of Jahantigh & Pessarakli (2011) is in line with this, demonstrating that various factors lead and contribute to gully erosion. Among human activities is land use change, decrease in soil surface resistance, increase in erosive forces, overgrazing, intensive, and short-period rainfall and agricultural activities. Similarly, Abdulfatai *et al*. (2014), reviewed causes, impacts and possible solutions to gully erosion. In their findings, they revealed that causes of gully erosion cannot be pinned onto one factor but many combined factors such as geology, natural causes (*e.g*. tectonism, climatic factors, geotechnical properties of soil), and anthropogenic effects.

Farming practices date as far back as the 1930s, this is seen from various aerial images covering different parts of South Africa (Vetter, 2003). Farming has long been a common practice in the communal lands of Eastern Cape. Alongside this, are associated extensive overgrazing practices (Rowntree *et al.,* 2004). Valentin *et al. (*2005), further reiterate this by stating that farming enhances gullying and causes gullies to form perpendicular to farm contours. Furthermore, van der Waal (2015) and van Dijk *et al*. (2017) observed that subsistence farming negatively affects soil erosion within an area and that rills tend to expand further and develop into gullies as a result of poor farming practices (De Baets & Poesen, 2005; Desta & Adugna, 2012; Mararakanye, 2015). Overall, the effect of poor farming practices leads to severe erosion such as gully initiation and enlargement (Rowntree *et al*., 2004). Conversely, lack of severe erosion in an area is present where land is undergrazed (Rowntree *et al*., 2004).

Environmental changes (including climate factors) are equally as important for soil erosion and should, thus, not be disregarded. Nonetheless, according to most studies (*e.g.* Vandekerchove *et al*., 2000; Poesen *et al*., 2003; Kropacek *et al*., 2016) climatic conditions have a lower effect on soil erosion than vegetation cover. Similarly, climatic conditions have a lower ranking in the Lower Thina Catchment compared to land use and vegetation cover. Furthermore, Kabanda & Palamuleni (2013) demonstrate that although climate and land use/land cover affect major hydrological processes, a non-climatic, time-dependent factor affects discharge fluctuations more than climate itself. Thus, changes in discharge coincide more with land cover/land use changes. This is supported by Garcia-Ruiz (2010), who states that many scientific studies have demonstrated close relationships between land use/land cover changes and soil erosion and that this is sometimes masked or enhanced by climatic fluctuations. Moreover, Evans (1998) proved that climate change cannot solely be responsible for widespread erosion, rather, erosion is linked to overgrazing, winter fires, drought and climate variabilities in an area. However, Nyssen *et al*. (2006), show that a positive evolution of climatic conditions improves gullying. This is further supported by Kavian *et al*. (2017), who state that climate change results in degradation of land.

Droughts occurred in Eastern Cape between 1940 and 1970 (Nearing *et al*., 2005; Zhang, 2007; Mararakanye, 2015). These events may have to some extent contributed to the land degradation and erosion in the Lower Thina Catchment. Droughts are known to reduce vegetation cover of an area, leaving the area unprotected from rain-splash, thus, increasing the levels of runoff that promote gullying (Mararakanye, 2015). Furthermore, an increase in gully size could be related to the extensive rainfall received following the droughts in the area (Kosmas *et al*., 1997; Collins *et al*., 2000; Nearing *et al*., 2005; Nyssen *et al*., 2006; Zhang, 2007; Mararakanye, 2015). During the mid-1970s, extreme rainfall occurred in the Eastern Cape (Nearing *et al*., 2005; Zhang, 2007; Mararakanye, 2015) and may be attributed to the El Niño and La Niña events (Azmoodehfar & Azarmsa, 2013) which occurred during this time. Further affecting temperatures within the catchment along with the extent of gullying. The intensity of the rain following the drought period was unknown, as a result, the raindrop sizes (Nyssen *et al*., 2006) were attributed to the great erosivity potential within the area. In addition to the drought and rainfall, which both affected gulling in the catchment, the Lower Thina Catchment could also be affected by poor land management strategies further adding to the soil erosion evident (Evans, 1998; Kakembo, 2001). A study conducted in Spain, showed erosion problems to have resulted due to fires conduced to remove thorny shrubs and improve the quality of grassland (Gracia-Ruiz, 2010). Likewise, Lasanta *et al*. (2001), showed seriously damaged areas to be due to cropping and previously frequent fires.

The discussion on land use clarifies to one that the 1km buffer used thoughout the study cannot be the cause/hindrance of gullying, however, the activities occurring within the buffer (*e.g*. increase in settlements) are the ones contributing to greater run-off, thus, resulting in greater erosion potential together with the steep slopes and hilly topography present within the catchment (Petty & van Dyk, 2018). Furthermore, varying land uses within the catchment not only result in varying surface areas of gullies but also in erosion rate variations. Across the years, the gullies experienced fluctuating erosion rates between negative and positive values. Although uncommon, negative rates of gullying may be related to the different land uses that do not remain the same and continue to change with time. As already implied, some land use cover improves erosion while others hinder it (Kakembo, 2001). Couper (2002) mentions and discusses few factors that may be related to negative erosion values within a study area. These include deposition of sediment during high flows, loosening of surface soil and human interferences such as rehabilitation measures. Positive values on the other hand, show and increase in the erosional rates of gullies due to various natural and human-induced reasons.

6.3. Climate parameters

It is clear from the analysis performed that all gully surface areas increase with time. Factors such as underlying geology, soils, agricultural practices, roads, residential areas and topography have been identified as the main causes to such increases. However, climatic and land use parameters also play a role in gullying and erosion (Poesen *et al*., 2003; Valentin *et al.,* 2005; Frankl *et al.,* 2012; Mararakanye, 2015).

Overall rainfall for the three rainfall stations shows an alternating pattern between highs and lows. The rainfall received may result in Hortonian overland flow within the area even during low intensity rainfall (Sami & Hughes, 1996). The total rainfall received within the catchment is less than that outside the catchment. This is deduced from the comparison of rainfall received at the rainfall station within and outside the catchment. Furthermore, a relationship is present between rainfall and altitude. Rainfall measured at the various rainfall stations increases directly proportional to an increase in altitude. This agrees with several studies (*e.g.* Tyson *et al*., 1976; Schulze, 1979; El-Swaify, 1997; Schulze, 2010; Nel & Sumner, 2006), that show a direct correlation between attitude and rainfall received.

Regarding the mean annual rainfall, the Cengcane rainfall station has the highest altitude (1,280 m a.s.l), highest mean annual rainfall (918.02 mm) received and highest erosivity within the catchment. Similarly, the Papane and Umthatha stations have moderate (1,125 m a.s.l.) and low (742 m a.s.l.) altitudes, which correspond to their respective moderate (774.57 mm) and low (668.05 mm) mean annual rainfall received alongside decreasing erosivity. This aligns with the common trend evident for the Drakensberg where below 2,100 m a.s.l. mean annual rainfall is strongly related to altitude (Nel & Sumner, 2006; Nel & Sumner, 2007). Although mean annual rainfall correlates with altitude, in this study, the phenomenon applies more to higher altitudes as opposed to at lower altitudes where the phenomenon does not always hold. This is seen through gully B, which is at the highest altitude (1,005 m a.s.l) and is also the largest in size, implying greater erosivity within the gully system. However, a different pattern is sometimes evident for the lower reaches. This can be seen from gully D which is the lowest in altitude (902 m a.s.l) but does not undergo the least erosion, as a result, the gully system is not the smallest in size. As such, altitude is an important driver regarding rainfall and rainfall erosivity. However, gully size (and the implied scale of erosion) is not correlated to altitude, illustrating the multiple factors (not only rainfall) at play in gully erosion.

The extent of erosivity is also related to the amount of rainfall received. Results show that the greater the rainfall received in an area, the greater the values for erosivity calculated. This is clearly seen from the three weather stations where the one receiving the most rainfall has the greatest erosivity. The IPCC (1995) further state that an increase in temperature results in changes in hydrological cycles and may lead to extreme rainfall. Results in the Lower Thina Catchment confirm this through an increase in both maximum and minimum temperatures with time. While these temperatures are heterogeneous and support the irregular and moderate intra-annual rainfall present within the study, these increasing temperatures, due to El Niño and La Niña events (Azmoodehfar & Azarmsa, 2013), have contributed to extreme rainfall recorded across the various stations as of the mid-1970s. In agreement to this is Nearing *et al*. (2005), Zhang, (2007) and Mararakanye (2015) who iterate the presence of extreme rainfall during the 1970s in the Eastern Cape. Moreover, the work of Marengo (2004) further shows a relationship between the inter-annual variations and the El Niño and La Niña events occurring in an area.

The regression graphs drawn (Figure 5. 13, pg. 81; Figure 5. 14, pg. 81; and Figure 5. 15, pg. 82) all indicate that a non-significant difference among total annual rainfall exists within rainfall stations. This was seen through high *p*-values as well as *R*-squared values, which are close to zero. This trend implies a homogeneous rainfall distribution within the dataset of each rainfall station. The performed Levene homogeneity test further supports this. However, the ANOVA test shows that a significant difference exists between groups. The performed Tukey test confirms that the difference is only between the Umthatha and Cengcane and the the Papane and Cengcane stations. Nonetheless, irregular and moderate precipitation distributions are present for Umthatha, Papane and Cengcane stations respectively. These results suggest moderate and concentrated seasonality across the rainfall stations, implying a moderate and an intense rainfall erosivity potential across the seasons respectively. Depending on the rainfall frequency, quantity, intensity (Kakembo, 2000; Vetter, 2007) and raindrop sizes (Frankl *et al*., 2012) the rainfall received is likely to result in an increase in the size of the gullies present within the catchment. As a result, intra-annual rainfall distribution across the study area is highly influenced by seasonal rainfall (Apaydin *et al*., 2006; Nel & Sumner, 2006; Nel, 2009). This suggests an increase in summer rainfall and a decrease in winter rainfall (Nel, 2009), implying greater runoff and erosivity (gullying) in summer than in winter (Nearing *et al*., 2004; Scholz *et al*., 2008). However, the results are contradictory to those of Nel's (2009), which only showed seasonal rainfall (11<PCI<20). Regarding inter-annual rainfall variability, historical records indicate an increase in inter-annual variability in South Africa but show a non-significant change in variability in the Drakensberg. This agrees with this study as the CV results reflect low rainfall variation year on year. While the calculated CV values for this study (ranging between 21.11 and 39.33%) are not in complete agreement with those of Nel & Sumner (2006), the values are, nonetheless, similar. Both PCI and CV values measure the risk associated with erosion within the area. The higher the values/classes, the greater the risk of gullying. As a result, based on PCI and CV values the risk of gullying in the Lower Thina Catchment across the 68-year period is low to moderate.

Variation in rainfall across the catchment has minimal effect on the rate of gully expansion. This is evident through active gullying occurring throughout the entire study period, as a result, rainfall cannot solely be responsible for the increment in gully size across the years. Additionally, the method used to select "driver" rainfall stations, shows a low reliability of rainfall data across the Drakensburg area (Schulze, 2006). An additional variable, or variables must be responsible for such growths. Confirming this is Gully B which is found at the steepest topography and is the largest in size but exhibits the slowest erosional rate. Similarly, gully A and D are found at a gentle and steep topography respectively but have the greatest erosional rate of 0.1 ha.y $^{-1}$. Moreover, gully C undergoes a different pattern of erosion rate, which alternates between 0.2 ha.y $^{-1}$ and 0 ha.y $^{-1}$. In addition, warming temperatures for this catchment may result in future changes of the hydrological cycle as well as lead to extreme rainfalls in the catchment (IPCC, 1995; Mondal *et al*., 2015). From the discussed rainfall parameters, it is evident that, although minimal, climate variability contributes towards the gullying within the catchment. Nonetheless, this contribution is not of a greater erosion agent/factor compared to the overall land use in the area.

CHAPTER 7: CONCLUSION AND RECOMMENDATIONS

Gully erosion is a serious problem evident across the Lower Thina Catchment. Various studies demonstrate that several factors contribute to and/or result in gully erosion. However, little effort in South Africa has been made to highlight the rate of historical climate and land use change. The importance of historical land use and climate variations on gullying is, thus, highlighted in this study.

Throughout the years, gullies A, B and D showed fluctuating surface area results, which also affected the annual growth rate of these gullies. Gully C on the other hand, is the only gully showing an increase in surface area irrespective of its missing aerial image tile in 1948. Previous studies (*e.g*. Sonneveld *et al*., 2005; Mararakanye, 2015) demonstrate that no two areas have the same contributing factors to gullying due to the associated spatial and temporal variations that exist. The unique behaviour of gully C reiterates these findings. Furthermore, negative growth rates exist across the years which are related to deposition of sediment during high flows, loosening of surface soil and human interferences such as rehabilitation measures. Regardless of the varying changes of surface area and gully growth rates, an overall increase in surface area is evident since 1948 to date (2016). The common belief is that the development and growth of gullies is governed by various biophysical and land use factors. However, few studies have considered the role of historical land use on gully erosion.

Various land uses present in the catchment result in gully erosion across all time periods of interest. The derived National Land Cover maps show grassland to be a common land use for all years, followed by *cultivated commercial lands* in 1995, *degraded grassland* in 2004 and *urban village* alongside *cultivated subsistence land* in 2016. Reduction in grassland across the study area is due to farming, rehabilitation practices and feed for livestock. Varying land uses in the catchment can be related to the gullying evident in the catchment. The obtained NLC results support Weepener *et al.,* (2015), who state that some parts of the Eastern Cape Province are suitable for cultivation. Most of these cultivated areas experience poor farming practices that result in overgrazing and trampling by livestock, disturbing the sensitive soil present in the catchment. Furthermore, a reduction in vegetation results in the area becoming more prone to gullying. Alongside this, is the disturbance of vegetation further associated with abandonment of land, attributed to both improper cultivation and poor management practices.

Climate parameters used to determine climate variability within this study, show that erosivity is directly proportional to altitude and an increase in soil loss occurs with steepness. However, gullies found on gentle topography do not always abide to this phenomenon. Not all the gullies undergo the least erosion although they are found on gentle topography. Gully erosion occurring on steep topography in the Lower Thina Catchment results due to contemporary land uses such as farming, abandoned land, grazing, constructed roads, settlements and managerial strategies. Moreover, the degree of erosivity is related to rainfall received in the area. Although unknown in this study, rainfall frequency and intensity also contribute to the erosivity present within a catchment. The study area has irregular and moderate intra-annual rainfall patterns, which iterate seasonality of monthly rainfall. Temperature data in the Lower Thina Catchment is, further, heterogeneous across the years and the minimum and maximum temperatures support the irregular and moderate intra-annual rainfall present within the study area. Furthermore, gullying in the catchment is greatest during summer as this is the high rainfall season. However, this study indicates a low inter-annual rainfall variability across rainfall stations, implying that based on rainfall erovisty alone the risk of gullying in the Lower Thina Catchment is low to moderate. As such, although climate affects gully erosion in the catchment, it ranks lower compared to land use/land cover and anthropogenic factors.

Gullying present in this study is governed by various factors such as land use, anthropogenic practices (farming, abandoned land, grazing, constructed roads, settlements and managerial strategies), and natural factors (geology, topography and climatic parameters). However, it is evident that among these, land use and anthropogenic factors surrounding gully systems contribute more towards gullying in the Lower Thina Catchment. Nonetheless, no factor can solely contribute to gully erosion, instead, it is influenced by other factors too.

Performing this study highlighted the historical changes of gully erosion present across the 68-year time period. Additionally, this study is of importance because of the following reasons:

i. The study applies a novel desktop approach, combining GIS and remote sensing.
ii. No gully erosion study has been done before in the Lower Thina Catchment.
iii. The resuts of the study show similar results to other gully erosion studies which involve fieldwork.
iv. Few studies consider historical land use of an area.
v. To know how different time scales influence erosion.
vi. To further contribute to already existing knowledge of gully erosion within this catchment, as well as for gullying in general.
vii. Farmers and residents in the study area can be educated on measures to take or avoid in order to reduce the risks of erosion.

However, further refinement in gully erosion research is advised with the aid of the following recommendations for additional research hereafter.

i. Topographical maps

Aerial photographs have been used in many studies and were deemed fit and effective. In this study, however, guidance from topographical maps was seen to be effective. It is thus, suggested that these maps be consulted alongside aerial images during analysis.

ii. Rehabilitation

Vegetation can result either in an enhancement or a hindrance of erosion (Kakembo, 2001). As a result, when rehabilitating an eroded catchment, one should ensure that they know the impact of the plant to be used on an area because it may increase the existing gully system (Nyssen *et al*., 2006). Suitable vegetation should, therefore, be used for the re-establishment of the land. Furthermore, the government could investigate more financially costly methods such as drop structures, stone bund terraces, reshaping of gullies, microbasins and trenches in order to halt and rehabilitate the gully systems.

iii. Managerial strategies

Much of the soil present in the Eastern Cape is duplex in nature (Parwada & van Tol, 2016). Additionally, the underlying sedimentary rock in the Lower Thina Catchment generates shallow, poorly drained and sandy soils known to be poor in quality (Hamann &Tuinder, 2012). This implies that the catchment should be monitored, avoiding continued gullying because this could ultimately result in local climate changes (Abdulfatai *et al*., 2014). Above all, land management strategies (*e.g*. rotational grazing and seasonal burning of land) and regulatory policies should be implemented to control the extent of erosion within the catchment.

iv. Availability and reliability of data

Aerial photographs, topographical maps, land use data and temperature and rainfall data were all used in this study. However, none of the data required, for all the above-mentioned aspects, were readily available. For future studies, one could use more gullies in the catchment in order to provide a greater spectrum of factors resulting in the initiation, hindrance and expansion of gullies in a catchment. High resolution imagery (satellite images) could also be used to extract erosional features.

v. Rainfall data

For future studies, it is recommended that rainfall calculations be done on a seasonal basis in order to know the seasonality of erosive events and relate them to the source of precipitation. However, this will only be effective if the seasonal data can be related to seasonal gully extent data, which was not available in the current study.

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