SEDIMENT LINKAGES IN A SMALL CATCHMENT IN THE MOUNT FLETCHER SOUTHERN DRAKENSBERG REGION, SOUTH AFRICA

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ABSTRACT

Soil erosion is a persistent problem that requires continued control efforts as agricultural land loses productivity and communities dependent on the land become increasingly vulnerable to decreased food security. The negative effects of soil erosion in Khamopele River catchment, in the Mount Fletcher southern Drakensberg region of South Africa, are manifest in extensive gullying and wetland loss. Soil erosion has resulted in siltation in a recently constructed dam and the alteration of aquatic habitats. This research was undertaken to identify the sources of eroded sediment in the small upper catchments of the Mzimvubu River catchment to inform broader catchment management strategies.

The scale of erosion was quantified using field surveys of gully extent and form. Environmental magnetic tracing techniques were used to determine the sources of eroded sediment in Khamopele River and upper Tina River catchments. The radionuclide ^{137}Cs was used to determine soil loss over a 55 year period in Khamopele River catchment. The Landscape Connectivity framework was used to describe the sediment source, pathway and sink interactions at sample area level.

Results indicated that historical and contemporary land management practices such as uncontrolled grazing, grassland burning and furrows promoted soil erosion in the catchment. Soil erosion was most pronounced in the Taung sample area where there was extensive gullying, tunnelling and subsurface erosion. Environmental magnetic tracing results indicated that there were clear differences in source areas. Despite its prevalence in the area, gully erosion was not shown to be a major source of sediment to downstream sinks. Topsoil and hillslope derived sediment were shown to be mobile in the catchment, suggesting that sheet erosion processes were dominant in the catchment. Radionuclide tracing studies showed that at least 20 cm of soil had been eroded from the Khamopele River catchment surface since 1956.

This research has shown that it is possible to distinguish source areas of erosion in the catchment by matching catchment mineral magnetic signatures to those in sink areas. This means that rehabilitation projects can use resources efficiently as the areas needing the most attention can be identified.

341 words

Keywords: degradation, soil erosion, environmental tracing, magnetic susceptibility, sediment connectivity

DECLARATION

I have read an understood the Rhodes University plagiarism policy. This study presents original work by the author and has not plagiarized the works of others. Where use has been made of the work of other authors it is acknowledged in the text accordingly.

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

Environmentally we are faced with two problems, one of diminishing natural resources and the second of deteriorating quality of natural resources. Consequences resulting from the loss of natural resources are often underappreciated. Land degradation, a global reality and representation of diminishing and deteriorating quality of soil and vegetation, threatens ecological sustainability and human livelihoods worldwide. In some countries pressing developmental and social issues take priority in government and planning sectors, meaning that action to conserve and rehabilitate land is left until there is manifestation of exceeded thresholds in natural ecosystems e.g. vegetation loss, sedimentation and gullies. The delayed response to this degradation prolongs the loss of ecosystem services and decreases food security in vulnerable communities.

The challenge of protecting natural resources remains in society even with increased awareness campaigns. Perhaps, conservation is spurred by the foreseeable threat to human infrastructure and economy. A good example is sedimentation. When large amounts of soil are transported, sedimentation occurs in the river channel, often affecting regulating infrastructure such as dams. Irrigation agriculture is most affected by high sediment yields as it decreases water availability, silts up abstraction infrastructure and irrigation drains (Morgan, 2005). Shongweni and Hazelmere Dams in KwaZulu-Natal, South Africa are prime examples of the negative consequences that siltation has in impoundments as their water storage capacities have been decreased by 100 % and 19.6 %, respectively (Russell, 1999). However, sedimentation is a symptom of underlying process at the catchment level linked to soil erosion; maybe the best response is to work from the receiving end of the system and determine the root cause of the problem which not only affects anthropogenic activities but the aquatic ecosystem too.

In South Africa, a country where the unequal distribution of natural resources (particularly in the communal lands) produces greater dependence on the natural environment, there is an ever increasing urgency to quantify and understand the processes that underpin land degradation and desertification.

The Department of Environmental Affairs and Tourism (2007) estimated that 20 % of South Africa's surface area has been transformed by degradation. Le Roux *et al*. (2007) approximate this value to be closer to 70 %. Beckedahl *et al*. (1988) and Huntley *et al*. (1989) estimated that 360 to 400 million tonnes of soil was lost in South Africa annually. The Eastern Cape, KwaZulu-Natal and Limpopo provinces have the highest soil and vegetation degradation indices in South Africa (Hoffman and Todd, 2000). Le Roux *et al.* (2008) also found that the three aforementioned provinces were more susceptible to erosion when compared to the rest of the provinces in the country. Reasons for the high degradation rates in these provinces involve a complex interplay of historical, socio-economic and environmental factors that will be elaborated upon in this study.

It is clear that the manner in which science responds to diminishing and deteriorating natural resources sets a standard for the short and long term management of our natural resources. By working to ensure that water and soil are retained in the landscape, ecosystem services such as water, biodiversity and aesthetics are preserved (de Groot *et al*., 2010). However, this begins with a quantification of the loss that currently exists and the assessment of the quality of our natural resources.

1.2. MOTIVATION

There are two factors that have driven this study. The first is the 2012 State of the Nation Address where the president of South Africa announced that the construction of uMzimvubu Dam (600 Mm^3) would commence to harness water in the uMzimvubu primary catchment (The Presidency, 2012). The aim of this project is to increase water availability in this Water Management Area (WMA). Authors such as Laker (2010) view the area as a viable option for a water transfer scheme because of the high water potential at the headwaters of the uMzimvubu River. This is because, in stark contrast to most of the country, the uMzimvubu to Keiskamma WMA has no inter-basin transfer scheme (Blackhurst *et al.*, 2002).

Even in its early stages the venture seems doomed to suffer the fate of dams that have silted up and lost their storage capacity. Firstly, Transkei rivers are known to have high sediment loads, reflected by their turbidity (Mbande, 2003; Scherman, 2007). Secondly, evidence of sedimentation/siltation is present in tributaries of the uMzimvubu River. Mount Fletcher Dam (500 000 m^3), constructed in 2008, lying just below the confluence of the Tina and Tinana Rivers which feed the uMzimvubu River, has lost 70% of its capacity due to siltation (Naude *pers.comm*, 2011). This increase in sediment load had water managers worried about the lifespan of the dam and the amount of degradation taking place in the upper Tina and Tinana River catchments (Naude *pers.comm*, 2011). In light of this, the questions surrounding the dam's long term functionality should address whether similar processes in the Tsitsa River catchment are likely to cause a siltation/sedimentation problem in the new dam.

The second motivator was the Maloti Drakensberg Transfrontier Project which undertook feasibility study of a hydrological payment for ecosystem services (PES) model in the Mzimvubu River catchment (Maloti Drakensberg Transfrontier Project, 2007). An outcome of the study was the selection of catchments that needed natural capital restored due to the negative effects of land degradation. Based on the findings of the Maloti Drakensberg Transfrontier Project (2007) report, the Department of Water Affairs (DWA), Working for Water, Working for Wetlands and the Joe Gqabi District collaborated to initiate a pilot project called the Watershed Services Project (WSP). The WSP aims to increase livelihood security and decrease vulnerability by restoring natural capital in Mount Fletcher.

One of the ways that the WSP aims to restore natural capital is by undertaking rehabilitation projects in the rural areas of Mount Fletcher. Some of the WSP aims include re-establishing degraded landscapes, improving winter flows and increasing the biodiversity in the region (WSP, 2010). This research project is aligned with one of their outcomes: to rehabilitate degraded landscapes (WSP, 2010:4).

One of the many ways in which degradation has manifested itself in a rural catchment in Mount Fletcher is through wetland loss and gully erosion. The Khamopele River catchment has experienced wetland loss and some areas in the catchment have been eroded. While Dlamini *et al*. (2011) and Le Roux (2007) point out that erosion by water (wind and ice) is a natural and necessary process for landscape development e.g. river courses, cause for concern arises when degradation rates exceed biotic and abiotic thresholds (Hobbs, 2007; Vetter, 2009). Once thresholds are exceeded severe damage occurs in the ecosystem, often making it difficult for the environment to return to equilibrium conditions and for communities to use what was once fertile soil. Soil erosion studies therefore need to better identify, quantify and predict sources of erosion to protect natural ecosystems and livelihoods.

The Khamopele River catchment typifies a number of sub-catchments in the upper Mzimvubu river catchment that are badly eroded and contribute to the high sediment yields observed in the region. The Khamopele River catchment was selected as the study site for this research as it provided an opportunity to investigate the underlying causes of soil erosion in the Eastern Cape southern Drakensberg region. However, to begin to address the problem of land degradation in these catchments, there must to be a better understanding of the extent of soil erosion and the sediment source areas in such catchments.

1.3. RESEARCH AIM

The aim of the study is to assess the extent of erosion in the Khamopele River catchment and determine whether sediment derived from the Khamopele River catchment contributes to sedimentation in Mount Fletcher Dam and the upper Tina River.

1.4. RESEARCH OBJECTIVES

a) To investigate anthropogenic factors that promote soil degradation in the Khamopele River catchment.

b) To assess the physical factors promoting soil erosion (soil, gully morphology, connectivity, geomorphic controls) and;

c) To employ environmental magnetism and gamma spectroscopy techniques to identify sediment source areas matched to data from sink zones.

1.7. RESEARCH APPROACH

There are generally two ways in which degraded landscapes can be restored - by natural methods (succession) or by human intervention (rehabilitation). This study feeds in to the latter, particularly as this is in line with the proposed implementation of the PES model in the region. One of the ways to achieve this in the Khamopele River catchment is to understand the process of sediment delivery to the Tina River and the linkages that exist within the catchment because if rehabilitation seeks to achieve long term functionality of the ecosystem, root causes of the problem must be identified.

Field surveys were undertaken to characterise and understand the morphology and extent of gullies in the catchment. The selection of gullies was motivated by the concerns of the community members and district planners. Gullies are a pervasive symptom of the soil erosion problem in this region. By understanding their form, extent and contribution to the degradation process, rehabilitation efforts can be strategically directed to areas needing the most attention.

Advances in the field of environmental magnetism have allowed Earth scientists to better understand source areas of eroded sediment by matching sediment to other catchment source areas. When environmental magnetism techniques are applied in conjunction with radionuclide tracing techniques, the reconstruction of catchment dynamics is strengthened. These methods, environmental magnetism and radionuclide tracing, were used in Khamopele River catchment to understand the erosion, transport and deposition processes in the catchment. Radionuclide dating and environmental magnetic techniques are robust and provide a complementary scientific explanation for the observed degradation in the catchment.

In the greater systems theory context, this research uses the Landscape Connectivity Framework, which is outlined further in Chapter 3, to understand and explain interactions in Khamopele River catchment. The framework is used as a guide for catchment interactions as landscape connectivity allows researchers to better grasp the behaviour of systems and (or) catchments and quantify them in detail (Brierley *et al.*, 2006).

1.8. CHAPTER OUTLINE

The dissertation structure that is adopted is one that considers objectives *a, b* and *c* as standalone chapters. Therefore, each a chapter contains a full dissertation structure (introduction, literature review, methods etc.). This structure is adopted to provide a comprehensive and logical understanding of the addressed objective. The first objective is included in the study area chapter as there were a number of overlaps between the study area, socio-economic factors and land use. The structure of the dissertation follows the outline below.

Chapter 2: This chapter presents the study area in considering both the physical environment and the anthropogenic factors that have shaped the present state of the catchment.

Chapter 3: This chapter presents the physical factors responsible for the observed soil degradation in Khamopele River catchment.

Chapter 4: This chapter presents the sediment tracing techniques used in the catchment and their application to identify the sources of erosion.

Chapter 5: This chapter presents a general discussion of the findings of the study and the interpretation of the results in the context of the catchment and the upper Tina River catchments.

Chapter 6: This chapter provides the conclusion and way forward using the findings of the study.

1.9. CONCLUSION

It is widely acknowledged that rehabilitation efforts are needed to restore natural capital in degraded catchments in the country, but more so in places deemed as vulnerable. Even though most restoration efforts are socially inclusive, there is a strong push for degradation to be quantified and the root causes addressed (DEAT, 2007). This research is aligned to meet those needs as the quantity and quality of water resources is a concern in South Africa. Rehabilitation of degraded land has been proposed in the upper Tina River catchment. To achieve this it is important that the underlying catchment dynamics, particularly those relating to sources, transport and sinks in the catchment are understood.

CHAPTER 2

STUDY AREA

2.1. INTRODUCTION

In 2010, the Working for Wetlands officials in the Joe Gqabi District Municipality expressed interest in reclaiming a drained valley bottom wetland in Khamopele River catchment. The wetland had undergone significant degradation as a result of water table lowering and ancillary erosion. Furthermore, soil erosion in the form of sheet and gully erosion was further cited as a persistent problem in the catchment (Naude *pers comm*, 2010). These factors contributed to the selection of Khamopele River catchment as the study area for this research.

Khamopele River catchment lies in what is termed *communal land* in South Africa. The term describes land that is “occupied or used by members of a community subject to rules or custom of that community” (Department of Land Affairs, 2004: 6). Makhoaseng village, which is found in Khamopele River catchment, formed the base for the research as it was in close proximity to footpaths leading to the former valley bottom wetland and access roads. Makhoaseng village derives its name from southern seSotho word meaning *place of Lekhoasa* (Setloboko *pers comm.*, 2011) who was its first chief. His (Lekhoasa) seSotho descendants oversee the villages of Makhoaseng, Bethania, Zwetlitsha and Taung to this day.

Khamopele River catchment is located approximately 27 km North West of Mount Fletcher, a rural service node in the Eastern Cape Province, South Africa. The catchment lies in quaternary T34A and has an area of 46.58 km^2. Catchment T34A falls within the uMzimvubu River primary catchment in the Eastern Cape (see Figure 2.1) which a strategic water area in the country (Umzimvubu Catchment Partnership Programme, 2012). This catchment has also been considered by the Maloti Drakensberg Transfrontier Project (2007) for hydrological ecosystem services trading due to the high amount of mean annual runoff available in the upper uMzimvubu River catchments.

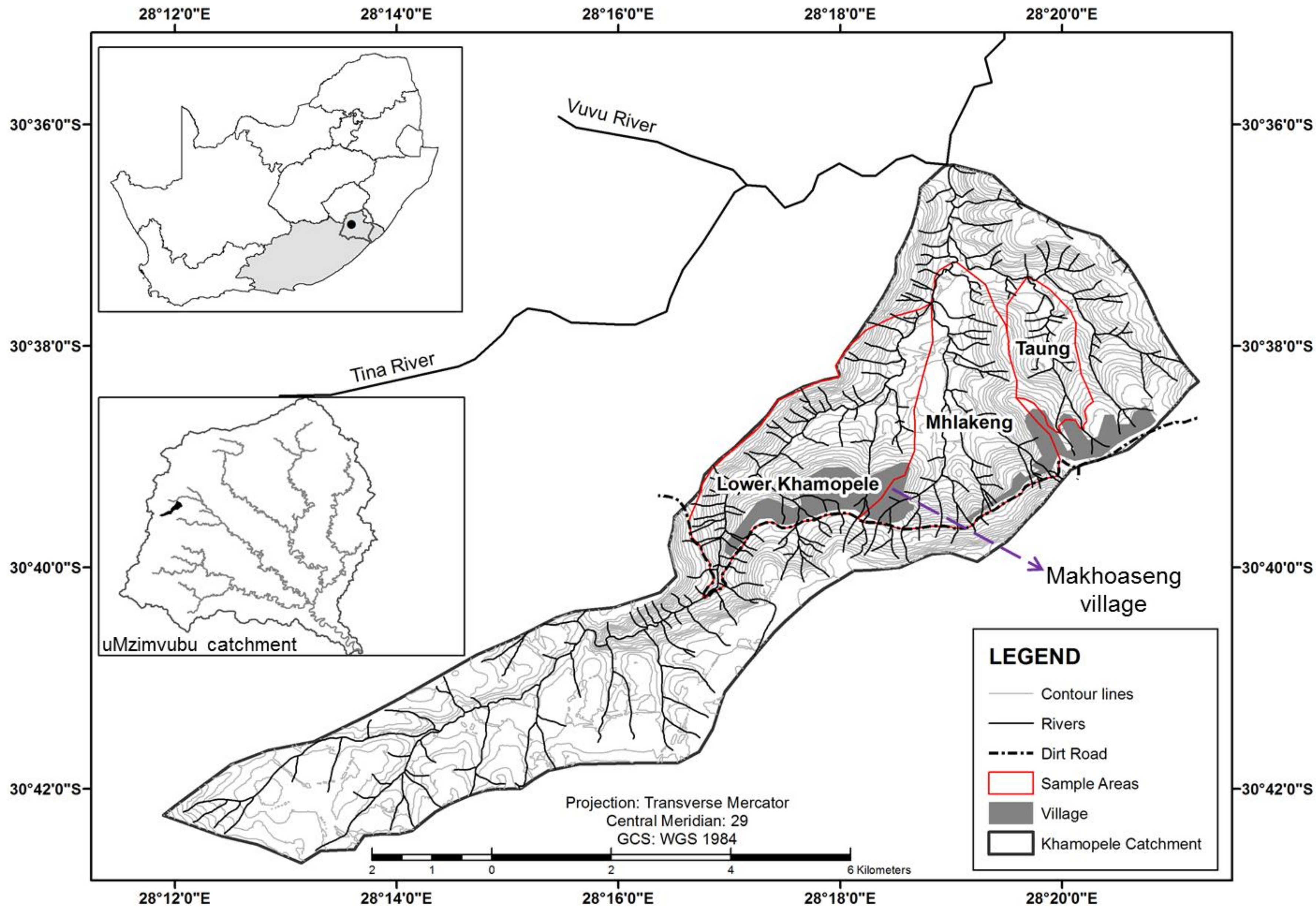


Figure 2.1: Khamopele River catchment locality map.

This chapter presents the attributes of Khamopele River catchment. The chapter is divided into two sections, the first provides a description of the physical attributes and the second provides the social background of the study area. The social aspect of the study was incorporated into the study as the researcher had engaged with the community during a questionnaire session in the pilot study phase. This approach was adopted as it was complementary to the physical description of the catchment, considering that soil erosion is a result of both physical and anthropogenic activities and (or) processes.

Due to the size and relief of the catchment the researcher was unable to sample the whole catchment; therefore, sample areas were delineated in Makhoaseng catchment (see Figure 2.1). The term "Makhoaseng catchment" was used to indicate the village closest to sampling areas and has no geographic significance. Makhoaseng catchment describes the area north of the dirt road and its east-west extent to the confluence of Khamopele and Tina Rivers. The three sample areas, Lower Khamopele, Mhlakeng and Taung, fall within Makhoaseng catchment. Khamopele River catchment therefore describes the sub-quaternary catchment within quaternary catchment T34A.

2.2. PHYSICAL CHARACTERISTICS

This section presents aspects that relate to the structure and function of Khamopele River catchment. Factors that are considered include, geomorphology, rainfall, climate, geology, soils and vegetation.

2.2.1. GEOMORPHOLOGY

Khamopele River catchment lies on the Eastern Escarpment Mountains Eco-region which is a high altitude region marked by closed hills and mountains with moderate and high relief (Kleynhans *et al.*, 2005). The catchment is found in the southern Drakensberg lowlands (1440 m - 2180 m) on the unmodified African Surface (Dardis and Moon, 1988). Hillslopes in the catchment are often bench-like due to the underlying geology and form steps (described in section 2.2.3).

According to Kruger's (1983) terrain morphology, the catchment is found in high mountains which can be characterised by concave, convex and straight slopes. Kleynhans *et al.* (2005) estimated that 80% of slopes in the catchment have an inclination greater than 5 %. This has significance, particularly in erosion studies, as Meyer and Harmon (1985) found that soil loss increases significantly for slopes of 6.5 % or more.

The Tina River, which runs WSW to E in Figure 2.1, is a confined second order (on the 1:500 000 DWA rivers coverage) stream that lacks a well-defined floodplain in this region (DWA, 2012). At the confluence of the Khamopele, the Tina River drains a 227.23 km^2 catchment. The characteristics of the Tina River in this reach adhere to Rowntree and Wadeson's (1999) Transitional Zone in the geomorphological zonation classification system for rivers in South Africa.

2.2.2. RAINFALL AND CLIMATE

Khamopele River catchment lies in a humid region of South Africa and, like most regions east of the Great Escarpment, it has a distinct wet season that occurs between December and February (Schulze, 1997). Blackhurst *et al.* (2002) estimate that 534.57 million m^3 of water is made available in cumulative natural mean annual rainfall in the Tina River catchment alone. The mean annual precipitation in the Khamopele River catchment is estimated to lie between 800 mm and 1000 mm (ENPAT, 1999).

Annual Precipitation records

Archival rainfall data for quaternary catchment T34A was difficult to source. Therefore, the nearest Department of Water Affairs (DWA) verified meteorological station was used to ascertain the rainfall trends in the area as shown Figure 2.2.

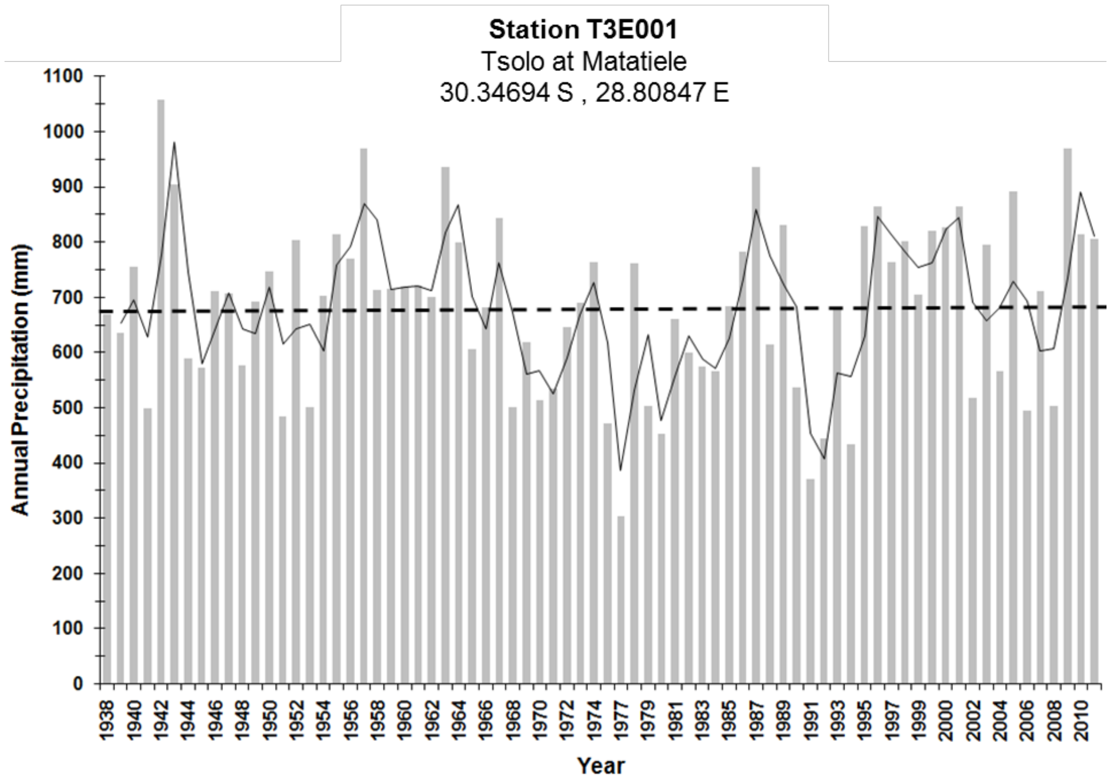


Figure 2.2: Rainfall record at station T3E001 from year 1938 to 2011 (DWA, 2011).

The rainfall record spans 72 years (1976 has no record). The average precipitation over seventy two years is 681 mm. Furthermore, the rainfall trend shows a cyclical distribution of wet and dry periods. Wet periods lie above the average (dashed line) and dry periods lie below the average. The longest of the wet periods occurred between 1954 and 1964 followed by that of 1995 and 2001. During the study period the region was experiencing a wet period as the years 2009 to 2011 show above average rainfall conditions.

Monthly Precipitation records

Additional archival data was gathered from a guest house and farm that lie in the adjacent Bell River catchment (D13B). This data was used as a surrogate of the monthly distribution of rainfall in the Khamopele River catchment. The monthly distribution of rainfall from these stations is shown in Figure 2.3.

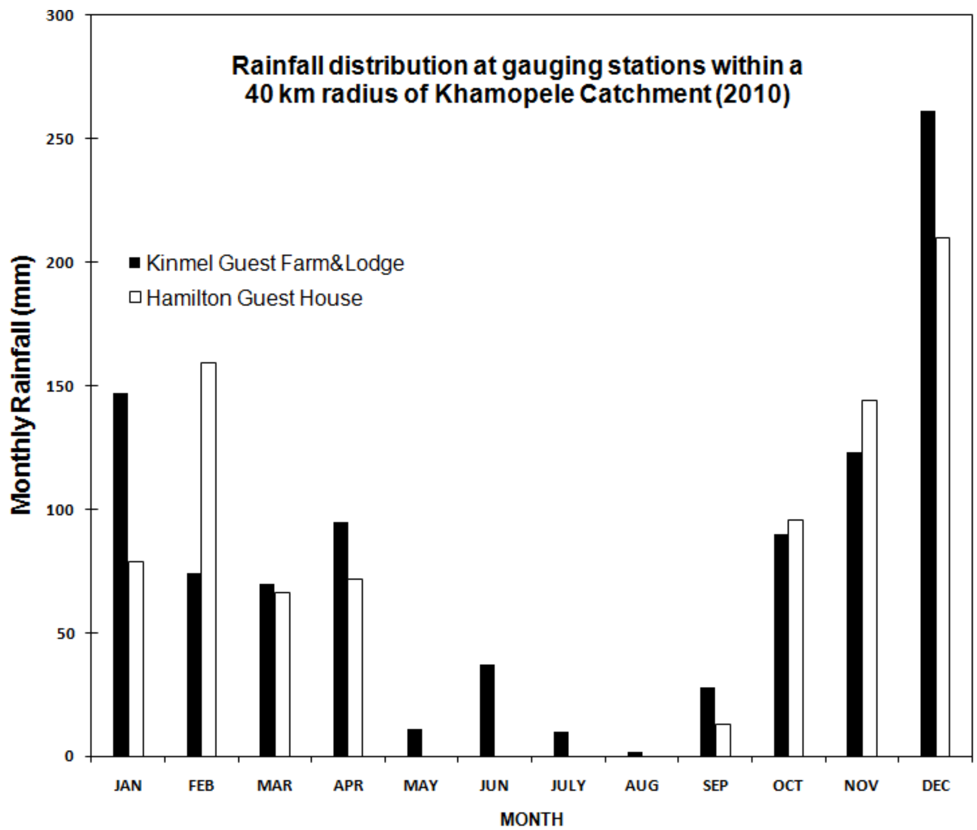


Figure 2.3: Rainfall distribution within a 40 km radius of the catchment.

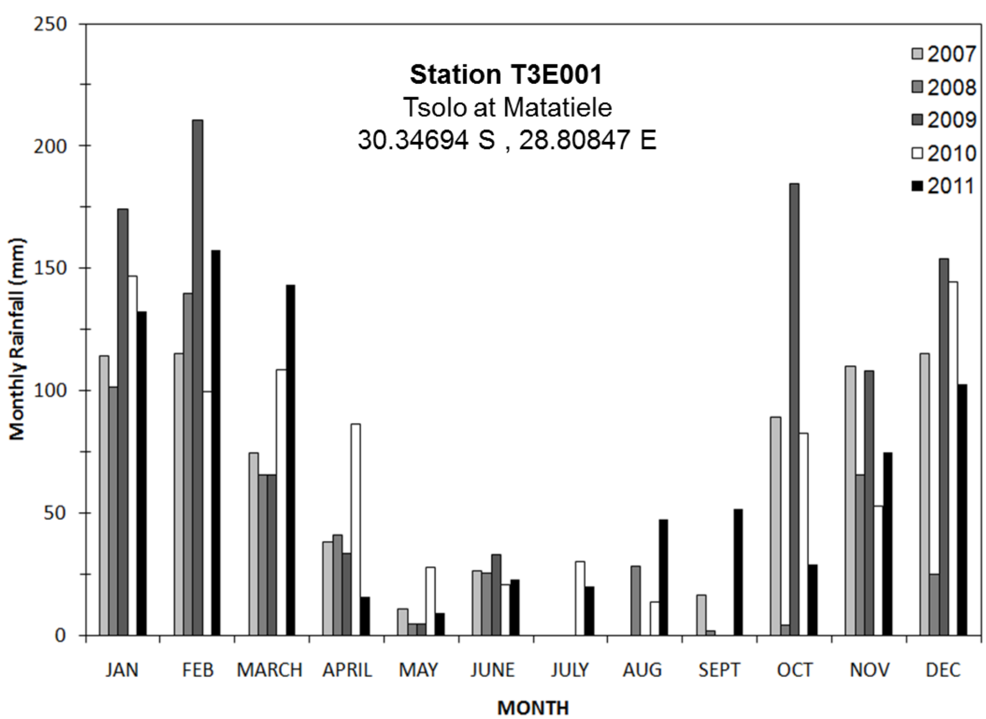


Figure 2.4: Five year rainfall distribution at station T3E001 (DWA, 2011).

To compare the monthly rainfall distribution trends, data sourced from the nearest Department of Water Affairs verified meteorological station was used for the 2007 – 2011 rainfall period. Figure 2.4 above shows the results of the rainfall distribution at station TE3001.

The results indicated that there were distinct differences in the rainfall records captured by the DWA and local farms. For the 2010 period, the DWA station indicated that monthly rainfall did not exceed 250 mm.

In general, the graphs show a U-shaped rainfall pattern for both sets of data with the lowest rainfall observed during the winter months (June, July and August) at both stations. The pattern is fairly consistent except in 2008, 2010 and 2011 when most of the rain occurred in late summer and early autumn (see Fig 2.4). The wettest year in the five year record was 2009 with 968.6 mm annual precipitation recorded.

To verify the observed rainfall trends at the stations, verified flow data was obtained from the DWA Mahlungulu gauging station on the Tina River (T3H005). The data was used to assess whether the wet periods occurred at the same time as the guest farm and DWA stations (see Figure 2.5). In theory, the high periods of rainfall should coincide with increased flow due to increased runoff into the river channel. Therefore, flow peaks should be indicative of the erosive and transport phases, whereas troughs should represent waning energy and the deposition phase.

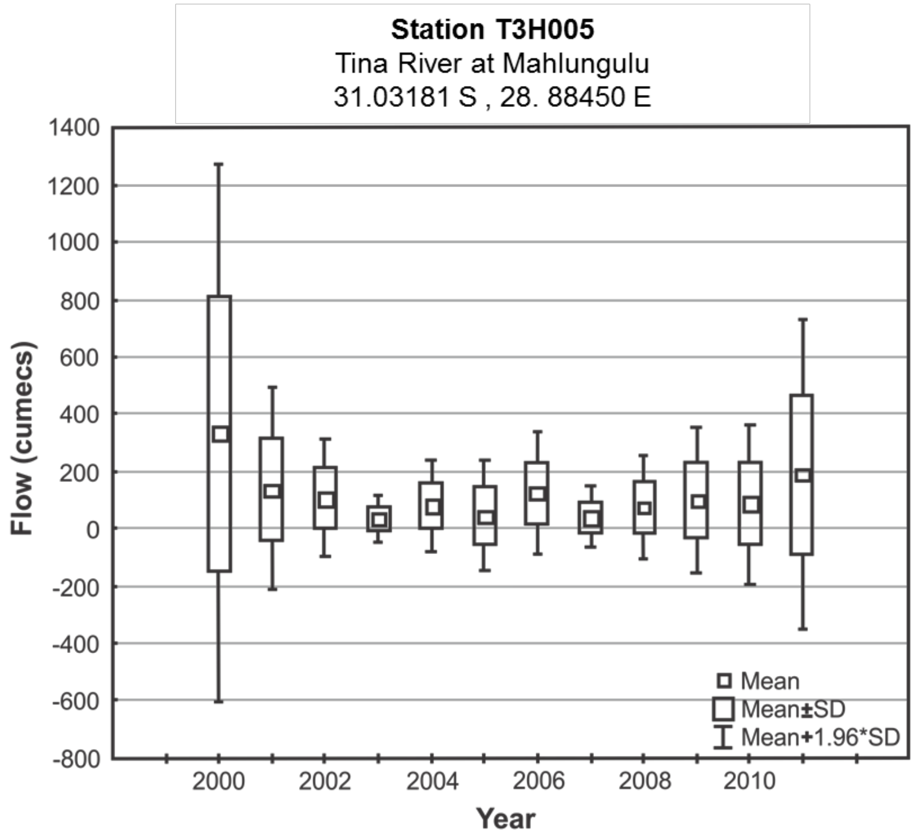


Figure 2.5: Mean Monthly Flood Peaks at Mahlungulu station 2001 – 2011 (DWA, 2011).

The highest flow at station T3H005 coincides with years that experienced greater than 800 mm annual rainfall at station T3E001 i.e. years 2000, 2001, 2006, 2009, 2010 and 2011. The results show that the 2009 to 2011 rainfall period exhibits conditions favourable for soil detachment and transport.

According to the Department of Health (n.d.) temperatures can reach a minimum of -11 °C in winter and rise to 42 °C in summer. Frost and snow are common occurrences during the winter months, particularly in higher lying areas of Khamopele River catchment (DoH, n.d; Bredenkamp *et al.*, 1996). Evaporation rates of less than 1400 mm per year are experienced in the catchment; this is a low value for South Africa (Shulze, 1997; ENPAT, 1999).

2.2.3. GEOLOGY

The Khamopele River catchment geology is that of the upper Karoo Supergroup (Late Triassic – Early Jurassic). The successive geological units exposed in the catchment are as follows: Molteno Formation, Elliot Formation, Clarens Formation and Drakensberg Group. The Molteno Formation consists of sandstones inter-bedded with mudstone in an alternating fining upward sequence (Johnson, 1976; Johnson *et al*., 2006). The Elliot Formation is typified by its red and (or) purple colour and a fining upward sequence (Bordy *et al*., 2004). The Elliot Formation adheres to a general red bed deposit classification (Johnson, 1976). The thin Clarens Formation outcrop in the catchment consists of fine grained sandstone indicative of the aeolian palaeo-depositional environment (Johnson *et al*., 2006). The Clarens (sandstone) and Elliot (mudstone and siltstone) Formations are horizontally bedded in the catchment and where the stratum dips, it seldom exceeds two degrees (Department of Minerals and Energy Affairs, 1981). The Drakensberg Group, emplaced between 190 Ma and 150 Ma and composed of flood basalts (Duncan and Marsh, 2006), caps the sequence and is found at the catchment divide and higher lying areas in the study area as shown in Figure 2.6 and 2.7.

The Karoo Dolerite Suite is represented in the catchment by the two dykes traversing the study area. The geological cross section indicates that valley bottom areas in all three sample areas consist of rocks of the Molteno Formation. Alluvium is found at the three major confluences in the catchment.

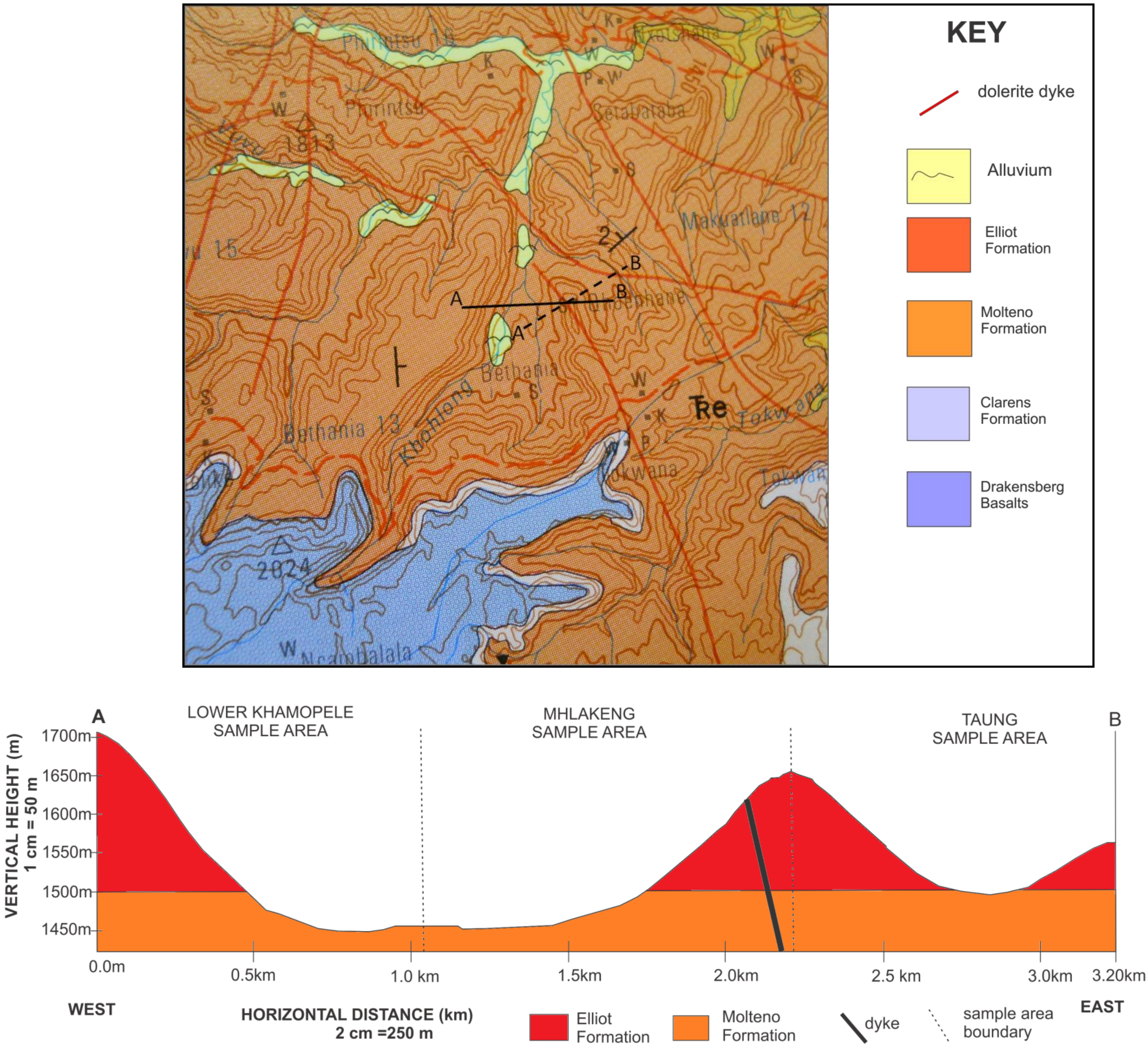


Figure 2.6: Geological Map of the Khamopele River Catchment and the cross section AB (solid line) (*Source*: Chief Directorate Surveys and Mapping, 2004).

2.2.4. SOILS

The Mount Fletcher magisterial district was identified by Hoffman and Ashwell (1997) as having severe veld and soil degradation levels. The soil degradation problem has not diminished in recent years. Rehabilitation works in the nearby Sterkspruit (Herschel) settlement, which is severely degraded, provide some evidence of the extent of the soil erosion problem in this region (Vetter, 2009).

According to Laker (2000), soils in Khamopele River catchment are moderate to highly weathered. Land capability data supplied by the South African Agricultural Geo-referenced Information System (AGIS) indicates that the catchment is unsuitable for farming activities (AGIS, 2010). This assertion is supported by Laker (2000) who classifies the land as unsuitable for rain-fed agriculture.

The generalized soil map of the upper Tina River Catchment (see Figure 2.8) shows that low altitude areas in Makhoaseng consist of red-yellow well drained soils (AGIS, 2010). The red colour of the soil in the AGIS (2010) identification can at a glance be attributed to two possible sources, namely: the reddish colour of mudstone of the Elliot Formation and the eroded iron rich Drakensberg basalt. The map also shows that soils in Khamopele River catchment fall into two classes, those that have limited pedological development and those that are weakly structured.

Bredenkamp *et al*. (1996) showed that soils in the quaternary catchment were leached and erodible. The erodibility of soil in the catchment can be attributed to the red beds in the catchment and the underlying Molteno Formation, which has been shown to be highly erodible by Rowntree *et al*. (1991). In addition, the Department of Water Affairs (2008) found that the duplex and dispersive nature of the soils in Mzimvubu River primary catchment makes them easily erodible.

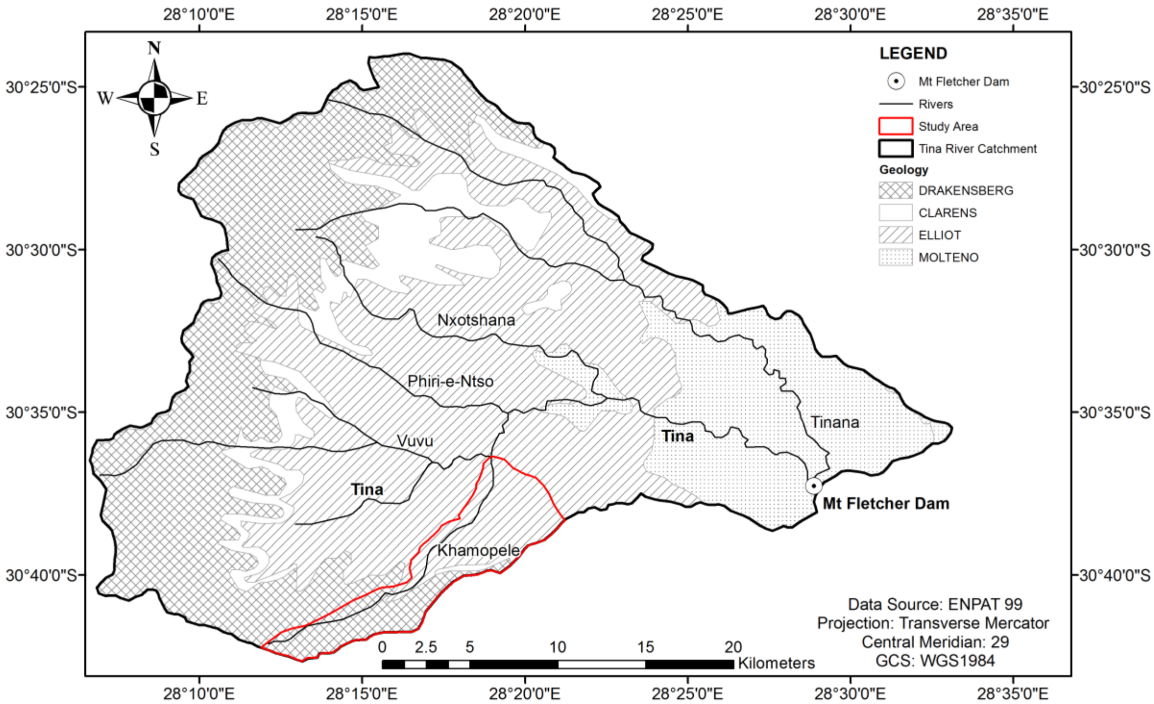


Figure 2.7: Geological map of quaternary catchment T43A (*Source*: ENPAT, 1999).

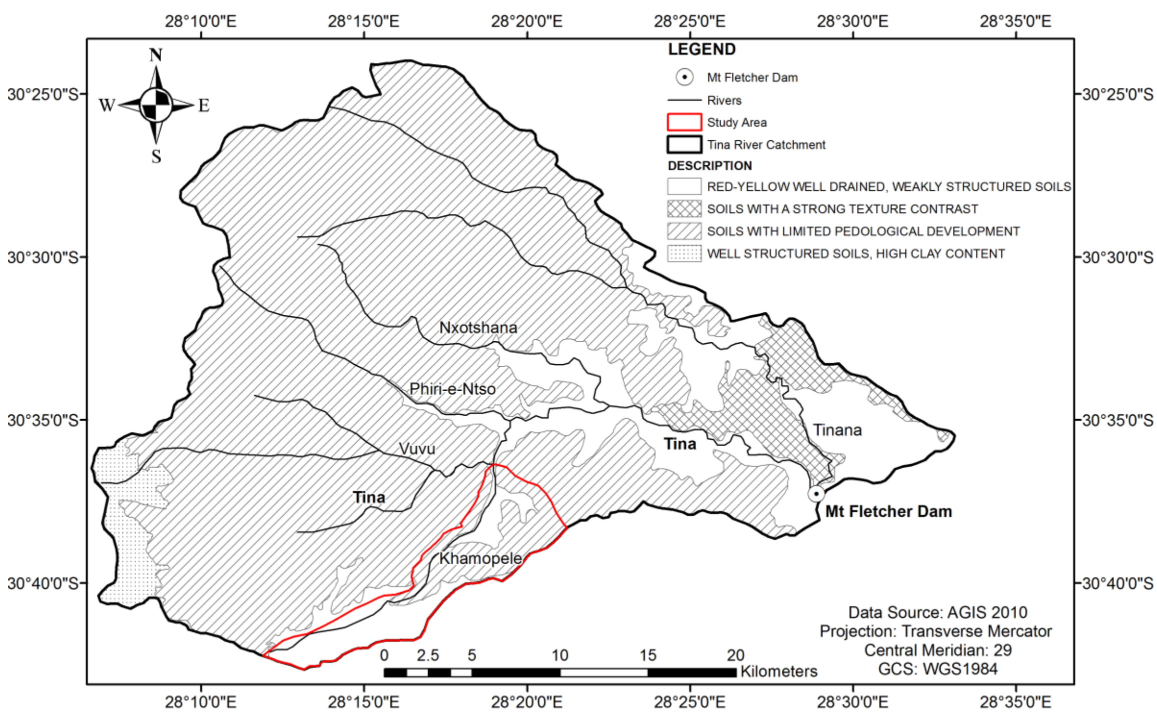


Figure 2.8: The generalised soil pattern in quaternary catchment T34A (*Source*: AGIS, 2010).

2.2.5. VEGETATION

According to Bredenkamp *et al.* (1996), the vegetation in the catchment is of the Moist Upland Grassland and often occurs adjacent to Afromontane Forest. Highveld sourveld is another name given to this vegetation in older texts (O'Connor, 2008). Common grass types in the catchment include *Themeda triandra* (Redgrass), *Hyparrhenia hirta (Thatchgrass)* and *Tristachya leucothrix* (Hairy Tridentgrass) (Bredenkamp *et al.*, 1996).

The vegetation classification map by Mucina *et al*. (2006) shows that Khamopele River catchment is home to three grassland types: Lesotho Highland Basalt Grassland (12 %), East Griqualand Grassland (36 %) and Southern Drakensberg Highland Grassland (52 %), respectively. The latter is often found in steep and mountainous areas of the southern Drakensberg, wherein the study area is located. All three grassland types correspond with the aforementioned geological units with *Themida Triandra* as a common grass species.

Fire is a very important component in this biome in regenerating grass species, particularly in areas dominated by *themida triandra* (Bond *et al.*, 2003). Frequent burning and overgrazing are as seen as a hazard in the Grassland Biome in South Africa because they promote the invasion of unpalatable grasses and weeds (Bredenkamp *et al*., 1996; Mucina *et al*., 2006; Elundini Local Municipality, 2011).

Acocks (1988) theorised that in the near future, lower lying areas in the Mount Fletcher region may undergo a vegetation transition to *Cymbopogon-Themeda* veld. In addition to the abovementioned species, Acocks (1988) found the general presence of *Elionurus muticus* (Wire grass), *Eragrostis racemosa* (Narrow heart love grass) and *Digitaria tricholaenoides* (Purple finger grass) is common in this area.

2.3. SOCIO-ECONOMIC BACKGROUND

The 2009 Elundini Municipal Situational Analysis indicated that degradation was pronounced in communal areas of the municipality such as Khamopele River catchment (Ukhahlamba District Municipality, 2009). Some authors link the severity of erosion in this municipality to its homeland roots because land degradation values seem to be higher in the communal areas of South Africa (Hoffman and Todd, 2000). This is not to say that this is the sole reason for the observed degradation as soil degradation cannot be attributed to a single factor. There are a number of factors, simple and complex, that act in unison to promote soil degradation. This section aims to address objective *a* by focusing on anthropogenic factors that promote soil degradation in Khamopele River catchment.

2.3.1. CONTEXT

Makhoaseng village lies in a densely settled rural area of the Eastern Cape. The village population is largely seSotho with a small Xhosa minority. Culturally, the seSotho speaking population is Southern Sotho and have their roots in Lesotho, which is about 20 km away in a straight line distance from the village. The Nguni culture is represented by the Xhosa minority and their ancestry can be traced back to the East African migrations south. Most villagers are bilingual. The dialects are both part of the Bantu languages, but they differ in that the latter has a number of clicks and the latter hardly any (Republic of South Africa, 1986).

Makhoaseng village lies in the former Transkei homeland. The word *Transkei* refers to the former Xhosa homeland stretching from the Kei to the Umtamvuna River in the Eastern Cape Province (see Fig 2.9). Homelands were residential areas for natives of the Republic of South Africa during the Apartheid years. Some homelands have been integrated into post-apartheid planning but most remain rural communal lands/areas.

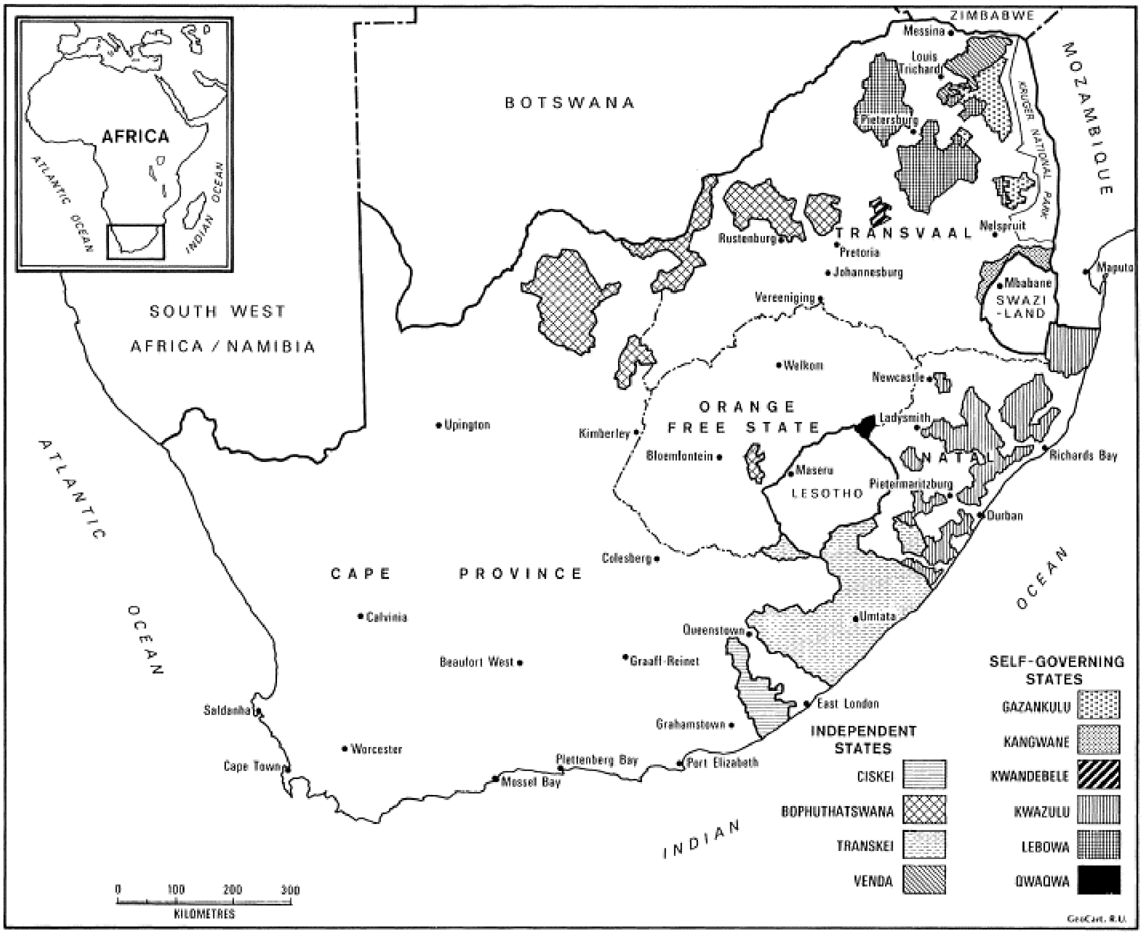


Figure 2.9: The former homelands of South Africa (*Source*: Nel and Binns, 2000).

The problem of soil erosion is markedly pronounced in the former homelands of South Africa (Hoffman and Todd, 2000). Part of the reason that former homelands experience pronounced degradation is due to conservation policies that often failed the homeland resident. One such policy, betterment planning, is discussed briefly.

2.3.2. BETTERMENT PLANNING

Betterment Planning was an effort by the pre-democracy government of South Africa to fight erosion and rehabilitate degraded land in homeland areas (de Wet 1989, Mc Allister, 1989). The aim of Betterment is well surmised by Mc Allister (1989) who states that Betterment sought: “to transform the pattern of land use in reserves by dividing rural locations in to residential, arable and grazing units, fencing off grazing camps and fields and grouping homesteads into villages” (Mc Allister, 1989: 347). To achieve this goal, land was divided and set aside for specific uses i.e. arable, grazing and residential units were clearly demarcated and separate from one another (de Wet, 1989). This is in contrast to pre-betterment land uses where settlements were scattered and customary tenure was in place (Eastern Cape Provincial Government and UN-HABITAT, 2010).

The early history of Betterment Planning or Betterment Schemes started in 1936 with the Native Trust and Land Act (Mc Allister, 1989) but by 1939 it was called the Control and Improvement of Livestock in Native Areas Proclamation (Khan, 1997). The policy was further revised and in 1963 the government initiated Betterment Planning after the findings of the Tomlinson Report (Goqwana *et al*., 2007). The underlying goal was to make homelands agricultural areas with minimal urbanization (de Wet, 1989).

The implementation of the plan was met with resistance due to the unfair demands it made on people, particularly on their religious and cultural beliefs and social connections (Mc Allister, 1989; Khan, 1994). For example, stock culling (de Wet, 1989; Khan, 1997; Goqwana *et al*., 2007) was seen as a means to reduce the demand on grazing land, but for the Bantu people cattle is closely tied to wealth, status and religious and cultural beliefs. Further opposition was related to relocation factors because it often meant that people had to move to smaller plots i.e. the formation of villages (de Wet, 1989; Mc Allister, 1989), endure limitations on arable and grazing land (Khan, 1997) and contend with increased stock, population and natural resource pressure (de Wet, 1989). Goqwana *et al* (2007) estimate that in the Transkei homeland the population density was eighty people per square kilometre, compared to twenty five people per square kilometre outside the homeland area. This unequal distribution meant that the carrying capacity of the land was weakened. Unfortunately for some areas this was enough to induce soil erosion (de Wet, 1989).

Laker (2000) notes that land that was set aside for farming by the plan is now severely degraded land. Overall, the intentions for Betterment Planning were good but it was the practical application that saw the demise of the plan. The lesson here is that political, anthropogenic and physical factors, if left unchecked, can cause increased levels of degradation in communal areas such as Khamopele River catchment.

2.3.3. LOCATION

The Khamopele River catchment lies in the Grassland Biome which makes up 39 % of the Eastern Cape Province area (Berliner and Desmet, 2007). The Grassland Biome is home to the majority of the population in South Africa (National Grasslands Programme, 2011) and supports a great number of agricultural and commercial activities. The National Grasslands Programme has identified the area in which Khamopele River catchment lies as a conservation priority (National Grasslands Programme, 2011).

In 2011 the Government Communication and Information System (GCIS) estimated that 30 % of the Grassland Biome has been degraded. This finding has spurred aims to ensure diverse biodiversity and ecosystem services in this region (SANBI, 2010). These efforts are in line with South Africa's National Protected Areas Expansion Strategy (Cadman *et al.*, 2010). More recently, the Grasslands Declaration, which stipulates government's commitment to conserve the biome, has been signed by the Minister of Water Affairs (SANBI, 2010).

Administratively, the study area is located in Joe Gqabi District Municipality and is locally managed by Elundini Local Municipality (ELM). Service nodes in close proximity to the study area are Mount Fletcher and Matatiele. The estimated density for the ELM is 24 people per square kilometre (Department of Health, n.d). The 2001 Census data shows that the population density in Khamopele River catchment was 138 people per square kilometre (Statistics South Africa, 2001). By 2004, the population had increased to 206 people per square kilometre (Statistics South Africa, 2004).

2.3.4. ECONOMIC ACTIVITIES

People in the catchment engage in primary activities with public works providing some income for women through the Expanded Public Works Programme (EPWP). The communal forest area (forest plantation) provides the sole commercial scale activity. Subsistence farming generally occurs within the homestead garden plots with few residents actively involved in cultivation elsewhere. Stock farming (cows and sheep) is important in this catchment. Sheep shearing provides additional income to sheep owners.

Factors such as high stocking rates and subsistence farming have been cited as contributing factors to soil erosion in the former Transkei (WSP, 2010). This is particularly true in Khamopele River catchment. Aerial photography (see Figure 2.10) shows evidence of the change in scale and type of activity in the catchment from 1956 to 2004.

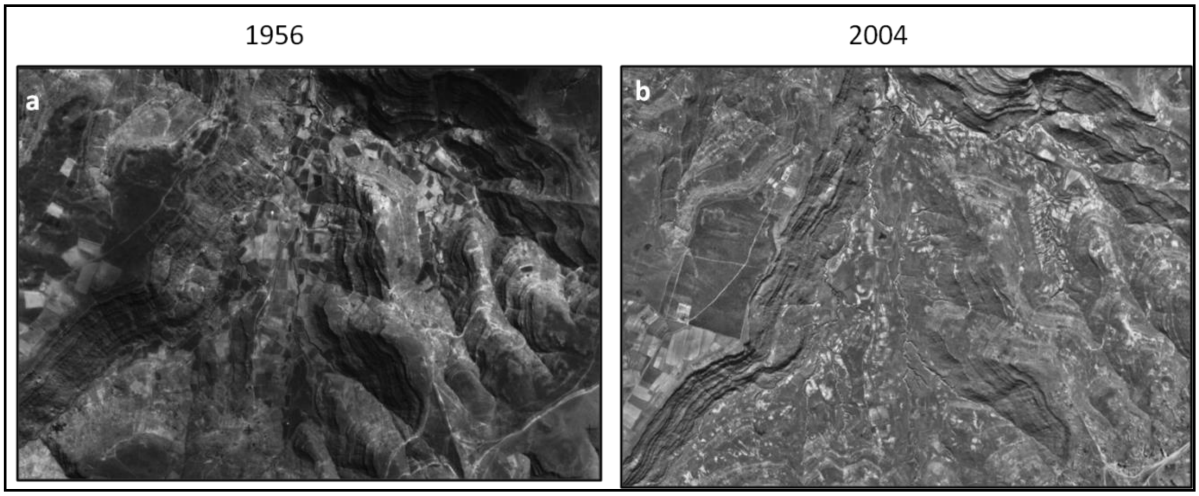


Figure 2.10: Land use changes in the valley bottom areas of Khamopele River catchment (*Source*: Chief Surveyor General Mapping, 2010).

The 1:50 000 topographical maps of 1980 and 1984 show that the study site was under cultivation, but today it stands devoid of any widespread agricultural activity. Aerial photographs of the catchment show widespread farming from as early as 1952. However, by 2004 there is hardly any evidence of farming and sheet erosion can be detected. This may indicate a shift in the activities that people engage in in the catchment.

2.4. SURVEY FINDINGS: LAND USER PERSESPECTIVES ON SOIL DEGRADATION IN KHAMOPELE RIVER CATCHMENT

2.4.1. INTRODUCTION

Questionnaires were administered in Makhoaseng village to understand the nature and cause of degradation in the catchment. The gaps in knowledge regarding the inception and expansion of erosion features in the Makhoaseng catchment pre- and post-1956 can be provided by oral history and memory of residents. The advantage of this method is that unsolicited information arises during the interview process (Hofstee, 2006), which enables the researcher to make linkages that were otherwise not apparent in biophysical field surveys. Furthermore, Fraser *et al.* (2006) have shown that top-down approaches in land management do not foster an attitude of stewardship as communities feel that they have not participated in the process and nor been able to suggest solutions to problems in their backyard. By using a bottom up approach, in this case in the form of questionnaires in the village, there is a coordinated effort in identifying and mitigating degradation issues. Another contributing factor to the use of questionnaires was that the headwoman was enthusiastic about the research project and suggested incorporating community views on the soil degradation problem in the village as residents have first-hand knowledge on the changes taking place in their environment.

In Phase 1 (P1), twenty five semi-structured questionnaires were distributed (see Appendix E for questionnaire) on the 22nd and 23rd July 2011. The questions, fifteen in total, were divided into three sections to fit in the broad themes of: land use, conservation awareness and historical information. Phase 2 (P2) of questionnaire survey was opportunistic as a community meeting occurred while the researcher was in the study area on the 4th and 5th March 2011. The semi-structured format was selected as the respondents could use their own words to explain their experience, ideas and suggestions.

2.4.2. RESULTS

Land use

Survey results from P1 and P2 showed that land in Makhoaseng village was largely used for growing crops at the subsistence level. In P1 grazing was selected as the second most popular activity, whereas in P2 the majority of respondents indicated that brick-making or building was the second dominant activity in the catchment. The results indicated that residents engaged in primary activities, with a growing secondary sector that produced bricks for houses/building. None of the respondents used the land exclusively for residency or mining.

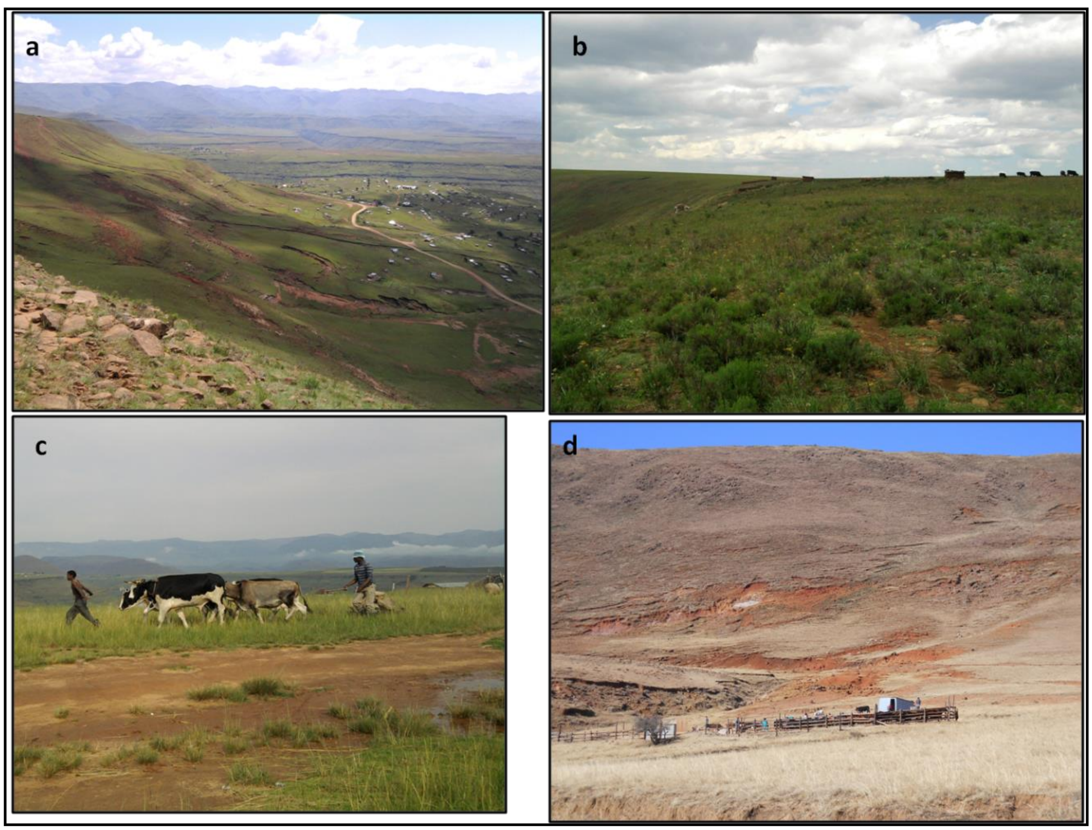


Figure 2.11: Grazing areas and factors promoting degradation in Makhoaseng village. **a**- eroded patches leading to the drainage divide; **b**- grazing area: flat topography at the drainage divide; **c**- cow-sled and evident erosion near settlements; **d**- cattle dip in foreground with bare patches around it.

Residents of Khamopele River catchment employed a rotational grazing system in two areas of the catchment. During the winter months (May, June and July) cows, goats and sheep were allowed to graze in the former valley bottom wetland area. Thereafter, the area was burned ahead of the spring season. For the rest of the year the stock enjoys pastures on the drainage divide behind the village as shown in Figure 2.11b.

Soil degradation in the village was exacerbated by cattle as they have a steep climb to the drainage divide for pasture (see Figure 2.11a). The frequent movement of cattle not kept overnight in kraals at the drainage divide increases the connectivity of bare soil patches along paths leading to pasture upslope and the village downslope. In addition frequent use of cattle tracks to visit the village cattle dip (Fig 2.11d), which lies at the lower slope, increased the connectivity of up slope and down slope bare patches.

Conservation awareness

In P1 respondents were asked about the suitability of the land in Khamopele River catchment for farming. Most respondents answered that the catchment was good for farming and that they would continue to farm. Fertile soils were listed as an enabling factor to continued farming, especially in the valley bottom area of the catchment.

Two respondents stated that the catchment was not a good place to farm because of the soil type and slope. Generally, residents have small farming plots in close proximity to their houses, either directly in front or behind the houses. Others have their plots in an easy walking distance from their houses such as the community garden.

When asked whether their activities contributed to soil degradation in the catchment, 92 % of the respondents felt that soil erosion was a problem in the catchment and that the factors listed in Figure 2.12 contributed to its increase.

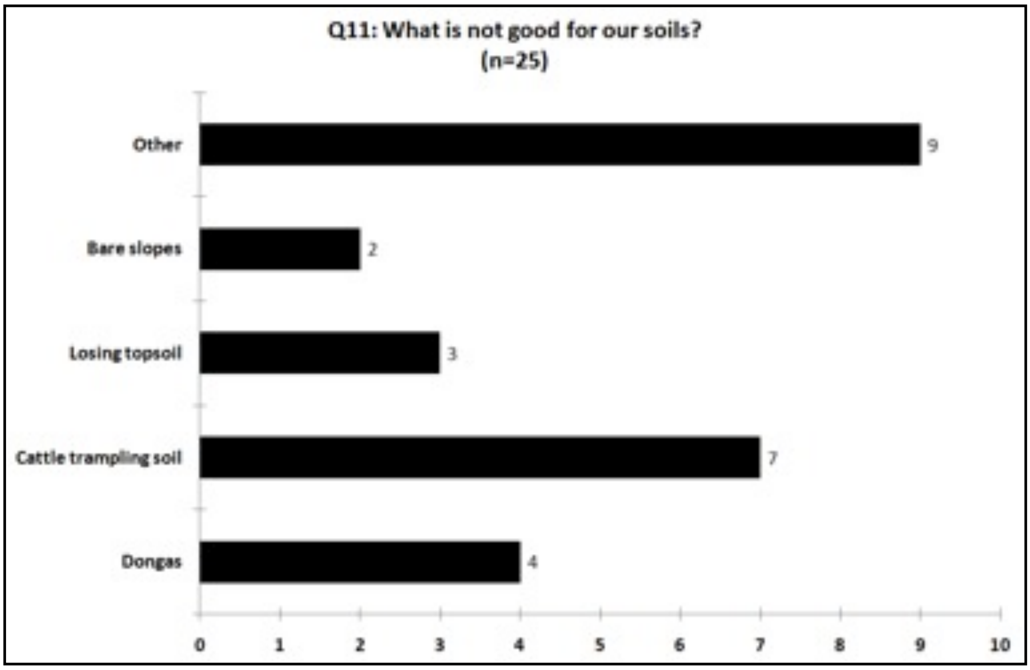


Figure 2.12: Bar chart showing responses to factors that adversely affect soil in Makhoaseng village in P1.

The responses showed that there was a good mix of anthropogenic and physical factors that have promoted erosion in the catchment area. In the "Other" section respondents indicated that slash and burn practices, heavy rains, wind and hail also contributed to soil loss in the catchment. Responses to the same question from P2 are summarized in Table 2.1.

Table 2.1: Summary of practices that promote soil degradation in Makhoaseng village.

Veld fires	Overgrazing
Storms	Brick-making: leaves a pit in the ground that seldom gets refilled.
Tracks: cattle, human and sledges.	Leaving the land fallow
Furrows in cultivated areas	Overcrowding (population)
Scattered cattle holding areas	

Respondents talked about factors that promoted gully expansion in the catchment such as heavy rainfall events. Some respondents were unhappy about the amount of surface water lost during these events as gullies allowed the water to move quickly into the Tina River. A number of respondents in P1 had highlighted the water scarcity issue in the catchment and their desire for water harvesting systems that would increase water supply. The need for water schemes arose as there was no running water in houses in the catchment. Communal taps were available but they were few and most villagers relied on natural springs.

A small proportion (14 %) of the respondents in P1 indicated that gullies had a negative effect on farming. They stated that gullies made it difficult to farm in the village because they cannot plough the land in some areas. Others mentioned that fertile soil was lost with the inception and expansion of gullies, thereby decreasing the amount of land that can be farmed in the catchment.

More than half (52 %) the respondents in P1 felt that gullies were dangerous. Gullies were deemed dangerous to both humans and livestock. One respondent stated that the dongas were dangerous or unsafe because children would be walking or collecting cow dung and land would give way as they were walking. The danger was that children could break a limb. The number of incidents where cows had fallen in dongas had increased in the past five years. This was a problem for villagers as stock was a commodity.

Most respondents wanted gullies to be stopped or rehabilitated. Specific interventions suggested by respondents include the reclamation of indigenous trees and to possibly reclaim *themida trianda*. Respondents wanted to address the gully problem by stopping gully expansion by vegetating bare patches and others suggested fencing off stock areas. Vegetation cover e.g. grass, trees or other species, was selected as the best response to rehabilitating the landscape by 16% of the sample group in P1.

Historical information

Respondents in P2 indicated that in the past most of the farming plots were located at the valley bottom (see Figure 2.10) and that their grand and great grandparents farmed at a larger scale than they did. At the time of the study, only a handful of villagers used the plots in the valley bottom area for farming. Socio-political factors, locality and migration into bigger cities, were in part responsible for the change in the scale and location of agricultural activities in Khamopele River catchment.

Respondent B and Respondent X explained that in 1976 Kaizer Matanzima's (former Prime Minister of the Transkei) government gave orders for the villagers to move from their settlement in the valley bottom wetland area to their present day village site. Reasons for the movement were linked to the formation of Trust Villages in the former Transkei and accessibility to medical services for the elderly, sick and pregnant. By 1993 most of the villagers had moved from the valley bottom wetland site to the current Makhoaseng village site. This movement was completed shortly before the first democratic elections of 1994 and voter registration. Administratively this move was advantageous as it increased accessibility for Independent Electoral Commission (IEC) workers and decreased the distance to polling stations for village residents. This meant that the vast majority of residents abandoned their plots and were no longer able to tend to their plots in the valley bottom. The abandonment of agricultural land has been linked to the initiation of gullies in communal areas of the Eastern Cape e.g. Ngqushwa (Kakembo *et al*., 2009).

Regarding observed changes at the 5 to 10 year scale, 19 % of respondents in P1 stated that nothing had changed whereas others (15 %) felt that the gullies in the catchment had increased laterally and vertically. Results indicated that villagers had observed a decrease in wild vegetables, trees, grass cover, water availability and large scale farming activities. Another important change that had occurred in the catchment was the change in grassland vegetation. Respondent

(P) wanted to find a solution to reclaim the more palatable *Themida triandra* as it is no longer as abundant as before. Respondent (Z) echoed the vegetation change issue in the catchment as he had noted a gradual invasion of thorny trees and shrubs. The vegetation change has had negative implications for stock farmers as their cattle did not get satisfied and pastures were diminished. Some respondents noted an increasing frequency of landslides, particularly after heavy rains.

Anthropogenic activities had also changed in this period. One respondent had observed that farming activities in the catchment had decreased and that this change was responsible for gullies dissecting the village landscape because nobody is taking care of the land.

2.5. CONCLUSION

Makhoaseng catchment presents a number of factors that contribute to the observed soil degradation. The interview process has shown that residents are well aware of the natural and anthropogenic factors that adversely affect their natural environment. Uncontrolled grazing, veld fires, heavy storms, tracks and furrows are the top reasons for the observed degradation. Additional drivers of soil erosion in the catchment include erodible soils, diminished vegetation cover and land use activities on marginal land. Participants have provided the historical and contemporary information necessary to interpret the processes that promote gully formation in the catchment. Rehabilitation efforts therefore need to take into consideration the socio-economic conditions in the catchment and the physical factors governing erosion processes in the catchment.

CHAPTER 3

PHYSICAL FACTORS

INFLUENCING SOIL DEGRADATION IN KHAMOPELE RIVER CATCHMENT

3.1. INTRODUCTION

Soil erosion is a problem that plagues many land use types worldwide. The FAO (nd) estimates that 5 to 7 billion hectares of soil is lost through erosion annually. The effects of soil erosion are well known and include loss of vegetation cover, reduced soil productivity and declined water holding capacities in soils. The deterioration in quality and quantity of natural resources such as soil can negatively affect economies, particularly those in developing countries, as the degradation of natural resources can lead to decreased food production, leading to increased vulnerability and declining food security.

GLASOD define soil degradation as "*a process that lowers either the current or future capacity of soils to produce goods and services or both"* (Scherr and Yadav, 1996: 5). The definition shows that soil erosion can be an inherited problem i.e. a present day reality arising from historical decisions necessitating its prevention today and in the future. This makes soil erosion a unique and enduring problem that is present throughout time and at varying degrees. It requires constant effort to mitigate its adverse effects as societies and economies grow.

South African researchers such as Dardis *et al*. (1988) have long called for processes of soil erosion to be quantified in depth to inform control strategies. This approach ensures that the root causes are dealt with as soil degradation is a symptom of an overall degraded catchment (Stocking and Murnaghan, 2000). This chapter takes its lead from their approach presenting the physical factors controlling erosion in Makhoaseng catchment.

3. 2. LITERATURE REVIEW

While this research is situated in the broad domain of land degradation, the focus is specifically on soil degradation and its manifestation in Khamopele River catchment. In Chapter Two, questionnaire results indicated that residents in Makhoaseng village were concerned about the expansion of "*dongas*" (South African term for gullies) in the catchment. A review of gully literature is provided in this section.

3.2.1. INTRODUCTION TO GULLIES

Gullies are trench-like features that are the result of surface and sub-surface erosion processes. They form by concentrating water into channels or pipes and tunnels thus allowing for the removal of soil (Poesen *et al.*, 2003). Their width and depth are their distinguishing characteristics with authors such as Brice (1966), Hauge (1977), Imeson and Kwaad (1980) and Poesen *et al.* (2003) approximating their minimum width as 0.3 m, approximate minimum depth of 0.6 m and a cross sectional area of 929 cm^2. Features that have a cross section less than 929 cm^2 are classified as rills.

Gullies often develop in the drylands of the world and approximately half of the world's surface falls into this land classification (Meadows and Hoffman, 2003; Poesen *et al.*, 2003). Gullies generally occur where topsoil has been lost and where the upper layers of soil have been encrusted (Stocking and Murnaghan, 2000; Poesen *et al.*, 2003). Factors contributing to gully initiation in grassland areas include low vegetation cover, slope steepness and soil type (Meadows and Hoffman, 2003; Poesen *et al.*, 2003). Areas under irrigation are especially susceptible to soil erosion and the formation of gullies (Poesen *et al.*, 2003). These areas have high salt contents, infrastructure that require ditches and saturated soils; factors that promote gully erosion. Wetland loss has also been linked to gully development due to a lowered water table (Whitford *et al*., 2010) and sedimentation in reservoirs (Le Roux *et al*., 2008).

3.2.2. SURFACE FLOW PROCESSES IN GULLY FORMATION

Gullies develop over time and when controlled by surface processes such as overland flow, their formation is generally preceded by sheet erosion and rilling. Sheet erosion is defined as the removal of easily transported material from the soil surface by runoff on a homogenous surface (Hogg, 1982). Rills are small linear erosion features formed by concentrated surface flow (Bowyer-Bower and Bryan, 1986).

There are five stages of gully formation as described by Leopold *et al.* (1964) and Morgan (2005: 31). The description of the stages of gully formation is further complemented by input from Stocking and Murnaghan (2000: 32 - 34). The first stage of gully formation is the interruption of vegetation cover due to soil removal by overland flow. This is followed by a stage of incision to form a ditch. The third stage is characterized by the development of the gully headwall. In stage four, the base of the headwall is worn away so that the headcut is no longer supported and it collapses. Lastly, the collapse of the headwall allows the gully to retreat further upslope thereby increasing in size.

3.2.3. SUB-SURFACE FLOW PROCESSES IN GULLY EROSION

While gullies can be surface water controlled, they may also be sub-surface controlled or in some cases a combination of the two. In the previous section the focus was on surface erosion but as Dardis *et al.* (1988)'s classification shows there is provision for sub-surface erosion in gully literature and natural systems.

In this section subsurface erosion in the form of piping and tunnelling is discussed. Piping and tunnel erosion has been found to co-exist with gully erosion in South African research, particularly in KwaZulu-Natal and the Eastern Cape provinces (former Ciskei and Transkei). The works of Dardis *et al*. (1988), Beckhedahl and Dardis, 1988, Beckhedahl (1996), Sonneveld *et al*. (2005) and Grellier *et al.* (2012) show the extent of piping in selected study areas in South Africa.

In the engineering field, where piping is often destructive and the cause of loss of revenue, there has been much attention paid to its early prediction and modelling. The standard definition of piping most often cited in engineering literature is provided by Gattinoni and Francani (2009) which describes piping as "a process that occurs due to the seepage of water through permeable material to produce a drag force sufficient to dislodge material at the outlet through Coulomb failure and (or) liquefaction" (Gattinoni and Francani, 2009:471).

Goldsmith and Smith (1985), Bonelli *et al*. (2007) and Gattinoni and Francani (2009) established that groundwater plays a significant role in the formation of pipes which lead to tunnelling. Goldsmith and Smith (1985) suggest that where shallow groundwater levels exist one is likely to find piping. General consensus in the literature is that erosion by tunnelling and/or piping is indicative of either a dispersive or sodic soil (Beckedahl *et al*., 1998; Sumner and Meiklejohn, 2000; Paige-Green, 2001). Beckedahl *et al.* (1998) showed that mineralogy and chemistry were significant factors in piping systems at Inxu Drift. Conditions necessary for the initiation of piping are compared in Table 3.1.

Table 3.1: Summary of piping conditions (based on Jones (1981) and Goldsmith (1985)).

Jones (1981)	**Goldsmith and Smith (1985)**
Concentration of water	Source of water (ground or surficial)
A discriminant zone of subsurface water movement	Surface infiltration to be greater than the permeability of the lower layers
Hydraulic head	A dispersive layer, generally above an impermeable layer
Outlet	A hydraulic gradient and an outlet

Jones (1981) and Goldsmith and Smith (1985) show that there are similarities in piping conditions, particularly in step two where there are distinct differences in permeability down the soil profile. The latter authors provide the link between dispersive soils and piping as shown in Beckedahl *et al.* (1998).

The mechanism that promotes piping involves the clay fraction of the soil that is removed by water in a process of dispersion or deflocculation (Beckedahl, 1993). The clay mineral montmorillonite controls dispersion and soils that contain montmorillonite also have high plasticity, shrinkage and cracking properties thus making them susceptible to tunnelling (Sherard *et al*., 1972).

The initial piping and tunnelling stage is marked by a vertical morphology because base level is the gully floor (Bryan and Yair, 1982; Goldsmith and Smith, 1985). However, if base level is not achieved and an impermeable layer exists, flow will be sub-horizontal along the impermeable layer to the outlet (Bryan and Yair, 1982). This creates a hydraulic gradient, via a tunnel in the soil profile, which exacerbates gully erosion (Bonelli *et al*., 2007).

At the catchment level piping is controlled by topography, geology, soils and hydrology (Goldsmith and Smith, 1985). Other factors to consider include land use, infiltration rates, intensity and frequency of rainfall, burrowing and root depth and soil erosivity (Beckehdahl, 1996). Beckedahl (1996) and García-Ruiz (1997) found that the C - horizon is the soil horizon most susceptible to piping. Piping can lead to slope failure and the destabilization of gully sidewalls (Gattinoni and Francani, 2009).

Sub-surface erosion once initiated is a difficult process to stop (Beckhedahl *et al.*, 1998). This means that soil mitigation strategies need to be in place before the onset of such sub-systems as they decrease agricultural production capacity and have the potential to destroy costly infrastructure.

3.2.4. GULLY CLASSIFICATION

There have been a number of attempts to classify of gully forms. Stocking and Murnaghan (2000) categorize gullies into two classes: continuous and discontinuous gullies. Ndomba *et al*. (2009) recognise the same classes as classic and ephemeral gullies. Stocking and Murnaghan (2000) and Ndomba *et al*. (2009) use Heede's (1970) classification which is based on development stages (Soufi, 2004), whereas Poesen *et al*. (2003) employ a morphometric approach i.e. the width, depth and shape is used to classify gullies.

Poesen *et al.* (2003) groups gullies into three types namely, bank, ephemeral and permanent gullies. Bank gullies are permanent erosion features controlled by failure processes such as slumping and piping (Poesen *et al*., 1996; Boardman and Favis-Mortlock, 1998). They develop where there is a height drop as a result of a river bank or terrace (Poesen and Hooke, 1997). Ephemeral gullies are the most easily recognised type of gully; they are concentrated water erosion features that may be erased by ploughing (Poesen *et al*., 1996) i.e. rills. Gong *et al*. (2011) indicates that ephemeral gullies relate to a relatively new type of erosion form classification adopted from American nomenclature and that this class is separate from rills. Ephemeral gullies as defined by the Soil Science Society of America (2001) are “small channels eroded by concentrated land flow that can be filled by normal tillage, only to reform again in the same location by runoff events” (Poesen *et al.*, 2003: 94). Permanent gullies, in contrast, cannot be mitigated by fill or ploughing due to their width and/or depth (Bradford and Piest, 1980; Poesen *et al.*, 2003; Ndomba *et al.*, 2009).

Imeson and Kwaad (1980) classified gullies into two groups, V and U shaped gullies. This system is simple and applicable to this day. However, as research grew there was a need to further classify gullies and their dominant processes.

Three additional gully classifications are discussed in this chapter. The first regards location in the catchment, the second gully head morphology and the third gully sidewalls.

Location

Gullies can be classified by their location in the catchment as either valley-bottom; valley-side or valley head gullies (Poesen *et al.*, 1996). This system is self-explanatory and employs the use of the terrain unit classification to gully location.

Gully head morphology

Ireland *et al.* (1939) proposed that six types of gully heads exist in the landscape: linear, dendritic, bulbous, trellis, parallel and compound. The classification made strong linkages between the catchment drainage pattern and gully head morphology. This is a process based classification system that can be used in conjunction with other classification systems to better quantify gully erosion (Rosewell *et al.,* 2007).

Ireland *et al.* (1939) further found that there were four types of process based gully heads: inclined, vertical, caved and vegetated. Poesen *et al.* (2002) supported the observation of the four types of gully heads; however, their nomenclature differs. Poesen *et al.* (2002) offer the following names: gradual, transitional, rilled-abrupt and abrupt gully heads. Gradual gully heads evolve from rills and the gully head is smooth and near horizontal. The transitional or inclined head type is characterised by a sloping headwall and a V-shaped morphology (Rosewell *et al.*, 2007). The rill-abrupt (caved) and abrupt (vegetated) gully head types have a vertical morphology; the former is marked by rilling preceding the gully head and a plunge pool at the base of the vertical head (Poesen *et al.*, 2002). The latter does not have rilling; the soil surface which may be vegetated is abruptly disturbed by the vertical head that lies at a right angle (Poesen *et al.*, 2002).

Gully sidewalls

The gully sidewall classification system by Crouch and Blong (1989) considers three sidewall factors, namely: morphology, activity and processes. Figure 3.1 below indicates the aspect of morphology in their classification scheme.

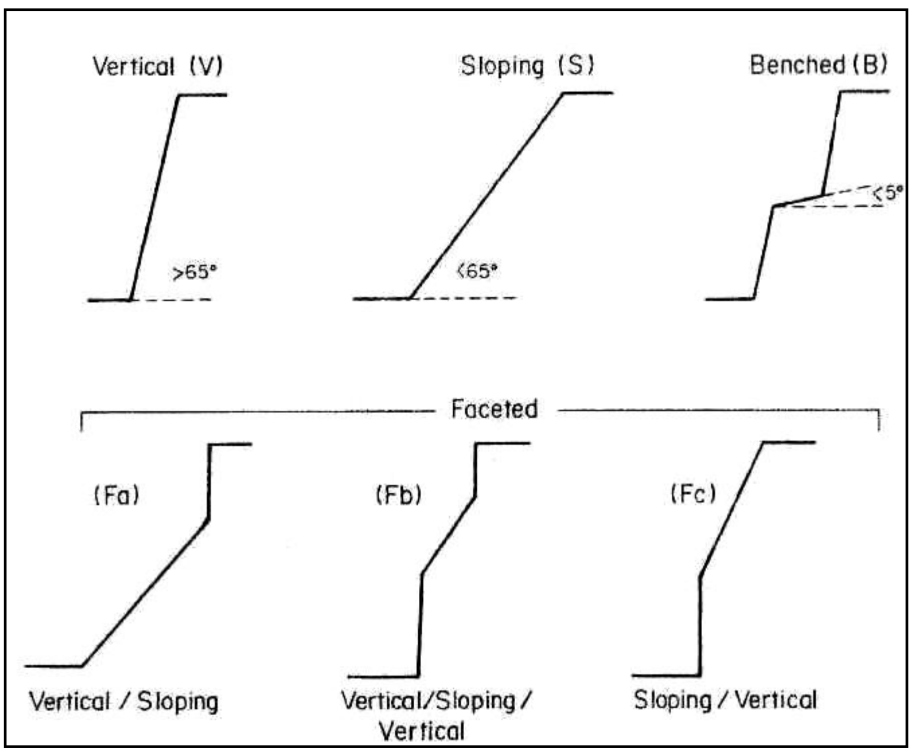


Figure 3.1: Types of gully sidewall profiles (Crouch and Blong, 1989: 294).

The premise of the classification scheme is that if the dominance of subsurface erosion is negligible, it can be assumed that the gully head and gully sidewalls provide eroded sediment in a catchment (Crouch and Blong, 1989: 291). The classification uses inclination to classify sidewalls. Some sidewall forms are simplistic, but the classification also makes provision for other process controlled sidewall morphology as faceted and benched sidewalls are included in the classification.

Application of gully classification systems

Gully assessments depend on a three pronged approach, investigating the morphology, processes and activity of the sidewalls/gully to provide information about the evolution and function of gullies. In southern Africa there have been two classification schemes that have been brought forward to describe soil erosion and associated gully features.

The Southern African Regional Commission for the Conservation and Utilization of the Soil (SARCCUS) classification system came out in 1981 and became popular in land degradation studies in the region at the time. SARCCUS (1981) made a distinct classification between water and wind erosion, the former received most of the attention as it the predominant type of erosion in this region. An ordinal scale was used to classify the intensity of erosion and a symbol is given to each erosion class as shown in Table 3.2 (Dardis and Moon, 1988).

Table 3.2: SARRCUS classification of gully erosion (*Source*: SARCCUS, 1981).

Class of erosion	Symbol	Description
None Apparent	G1	As for sheet erosion
Slight	G2	Clearly observed on air-photos and usually up to 1m deep. Cannot be crossed by farm machinery.
Moderate	G3	Intricate pattern of deep gullies (mainly 1 to 3 m) exposing entire soil profile in places. Many “islands” of topsoil remain.
Severe	G4	Landscape dissected and truncated by large (3 to 5 m) gullies. 25% - 50% of area unproductive.
Very Severe	G5	Large and deep (often >5 m) gullies have totally denuded over 50% of the area.

Geomorphologists from the then University of Transkei (UNITRA) Geography Department played an active role in producing volumes of work related to gully morphology in the Transkei. The result of years of research was the development of a morphogenetic classification system by Dardis *et al.* (1988) specifically applicable in southern African context. The classification system, shown in Figure 3.2, identifies nine types of erosion which are grouped by flow path, flow regime, geometry, host material and dominant process (Dardis *et al.*, 1988). The advantages of this system to this day are its applicability in the field due to its detail and photographic guide of erosion features. The classification system by Dardis *et al.* (1988) was used for this research.

Table 3.3: Southern Africa Soil Erosion Type Classification (Source: Dardis *et al.*, 1988:192).

Type	Flow Path *	Flow Regime+	Geometry	Host Material‡	Dominant Process
1	A	A	Sheet; horizontal or gently inclined planar surface; weak anastomosing or braided channelling	A	Overland flow, sheetwash, sheet flooding
2	A	B	Sheet; horizontal or inclined planar, undulating or sinusoidal surface; no channelling	A/B	Aeolian; saltation; deflation
3	B	A	Linear channels (rills)	A/B/C	Overland flow, sheetwash
4	B	A	Sub-surface cavity; vein; crack; isolated cavity; non-linear	C	Sub-surface flow; solution, deflocculation
5	B	A	Conduit; linear; meandering; bed-rock cut; V-shaped	A/C	Sub-surface flow; piping, roof and sidewall collapse
6	B/C	A	Linear closed-open conduit; single channel or channel network	C	Overland flow and subsurface flow; roof and sidewall collapse; headcut erosion;
7	C	A	Linear open conduit; single channel or channel network; U-shaped; flat bottomed	C	Overland flow; piping; sidewall collapse; headcut erosion; sidewall rilling
8	C	A	Open conduit; single channel or weakly developed channel network; v-shaped	A/B	Overland flow; sidewall rilling; headcut erosion; general absence of piping
9	A/C	A/B	Planar surface; degraded	A	Overland flow; sheetwash; rill erosion; aeolian activity

* A: unconfined
B: confined (closed conduit)
C: confined (open conduit)

+ A : Hydrodynamic
B: Aerodynamic

‡ A: *Resistant* - Colluvium or bedrock layer
B: *Homogenous* - Colluvium or sand
C: *Heterogeneous* - Colluvium or sand with beds of variable resistance

The grouping classes that Dardis *et al*. (1988) use are similar to Crouch and Blong's (1989) core groupings in that both classification systems ultimately investigate morphology, process and activity, the former for gullies and the latter for gully sidewalls.

3.2.5. GULLIES IN THE LANDSCAPE

Hooke's (2003) channel conceptual framework can be used to understand the three ways in which gullies may exist in the landscape: connected, unconnected and partially connected systems. *Connected systems* are by definition those where sediment moves with ease from slope to channel. *Unconnected systems* function in isolation i.e. sediment production, transfer and deposition happen at the same general locality. *Partially connected* systems require an extreme rainfall event or anthropogenic intervention for sediment to be transported between two unconnected systems. Although not widely applied in gulley literature, this is a nuanced and perhaps more comprehensive way to understand gullies in addition to the ephemeral and permanent gully literature that Poesen *et al.* (2003) provide because their classification is locale specific.

Rosewell *et al.* (2007) use the terminology continuous and discontinuous gullies to describe the severity of gully erosion. The former denotes moderate erosion and the latter low levels of erosion. An additional class of branching gullies is associated with severe erosion. The terminology of Rosewell *et al.* (2007) has been used in this research to interpret the severity of gully erosion in Khamopele River catchment.

Landscape connectivity

The Landscape Connectivity Framework has been used successfully in biodiversity and habitat conservation studies, channel morphology maintenance and in alien invasive vegetation eradication (Pither and Taylor, 1998; Vlok and Engelbrecht, 2000; Bunn and Arthington, 2002; Belisle, 2005; Brierley *et al*., 2005). In this research the Landscape Connectivity Framework is used somewhat differently to its resource patch and biodiversity conservation roots. The main principles of the framework are applicable to an extent in geomorphic studies because they can provide alternate means to explain the spatial relationships that exist at the catchment and sub-catchment levels, which is important when attempting to understand the evolution and function of a system over time (Hooke, 2003; Brierley *et al*, 2006).

Landscape connectivity is defined as “the degree to which the landscape facilitates or impedes movement along resource patches” (Belisle 2005:1988). There are essentially two broad classes of connectivity: functional and structural connectivity (Taylor *et al*, 1993). Structural connectivity is concerned with the physical linkages between elements in the landscape, for example, distances and absence or presence of corridors (Meiklejohn *et al*., nd; Taylor *et al*., 1993). Functional connectivity is the definition of landscape connectivity, that is, “the degree to which the landscape facilitates or impedes movement along resource patches” (Taylor *et al.,* 1993:571). The latter is the focus of this review and research.

Three types of functional connectivity exist, namely lateral, longitudinal and vertical connectivity (Brierly *et al*, 2006). Lateral connectivity is the focus of this research and primarily deals with supply interactions in the system (Brierly *et al*., 2006). These interactions involve the relationship from slope to channel and from the channel to the floodplain. Longitudinal connectivity is concerned with flow considerations and can be surmised as the interactions between upstream and downstream processes (Brierly *et al*., 2006). Vertical connectivity describes the surface and subsurface interactions that occur in riverine system (Brierly *et al.*, 2006). An example of this type of connectivity is the sediment and nutrient relationship (eutrophication) in stagnant waters.

Lateral, vertical and longitudinal connectivity can and are often impeded by natural and artificial structures. The structures in the literature are termed blankets, buffers and barriers (Brierley *et al.,* 2006; Fryirs *et al.,* 2007a; Fryirs *et al.*, 2007b). Lateral connectivity is impeded by buffers because they prevent deposits from reaching the river channel e.g. river terraces (Fryirs *et al.*, 2007b). Structures that disrupt vertical connectivity, such as bedrock steps and floodplains, are termed blankets as they protect landforms from scouring and modification by fluvial, wind and glacial processes (Brierley *et al.*, 2006). Barriers affect longitudinal connectivity and may be artificial (as in the case of dams) or natural (Brierley *et al.*, 2006).

An area in the landscape where connectivity is unimpeded is termed a *coupled system* whereas disconnected areas are termed *decoupled systems* (Brierley *et al.*, 2006). Evidence of coupling and decoupling can be found in the landscape and begins to reveal the evolutionary history of a catchment. It is also important to note that the (de) coupling of systems is often controlled by the seasonality and intensity of extreme events, particularly in semi-arid environments (Faulkner, 2008).

Hooke (2003) promotes the visualization of systems in the greater context of the catchment, in this case gullies. This is a holistic approach because gullies can be understood as part of a whole, and can be scaled down to a particular context (Hooke, 2003; Stocking and Murnaghan, 2000). In order to understand geomorphic processes at the catchment level, there is a need to describe in detail the interactions that occur between and/or across different compartments. This practice provides a strong basis for research and understanding the conveyance of sediment across the landscape. The next section deals with this component which is largely based on Schumm's (1977) model.

3.2.6. GULLIES AS SOURCES, PATHWAYS AND SINKS

Soil erosion, transport and deposition processes are influenced by underlying geomorphological and hydrological processes (Owens and Collins, 2006). Therefore, the location of sources, pathways and sinks will be constrained by these processes in a catchment. The movement of sediment from and/or between these compartments is influenced by rainfall events that provide the energy necessary for transport (Yair and Lavee, 1981).

Yair and Lavee (1981) and O'Connor *et al*. (2003) describe the location of sediment sources as mountains, the beginning of channels and hillslopes. These areas tend to have shallow soils underlain by rocks or derived from outcrops and are termed sediment production areas (O'Connor *et al*., 2003). There are two types of sources, natural and artificial. Examples of sediment source types in the landscape include erosion features such as gullies, rills, pedestals and mass movement features (Walling, 2005). Artificial sources include drains and roadway embankments (Charman and Murphy, 2007).

A widely accepted practice is the desktop assessment of source types based on their locality. The difficulty arises in pinpointing seasonal source areas (Dickson and Wall, 1977). This is because physical and geochemical properties of sediment are controlled by source area conditions (Owens *et al*., 1999; Walling, 2005). Recently, the use of distinguishing tracers such as pollen, radionuclides and isotopic signatures has proved more useful in distinguishing source areas (Walling, 2005). These techniques are described further in Chapter 4.

Sediment pathways are transfer zones that connect source zones to sink zones (Morgan, 2006). Their scale is variable, ranging from rivers, gully floors, furrows to footpaths (Morgan, 2006). Sediment that is found in pathways has been detached by agents of transport such as wind and water (Morgan, 2005). The formation of pathways is largely a result of overland flow (Yair and Lavee, 1981). The size of material in pathways is differentiated and this implies that pathways are distinguished by the processes and/or the velocity of the transporting agent.

Features such as gullies generally act as conveyance and production areas, but in some instances they pose no threat in washing away sediment as they have stabilized e.g. relict gullies (Le Roux *et al*., 2008).

In terrestrial systems material is transported through transfer zones by rolling, saltation and creep mechanisms (Biedenharn *et al.,* 2006). Material can also be transported in suspension by either intermittent or continuous suspension (Boggs, 2001). Material that has been deposited as a result of suspension is generally found in sink zones due to velocity changes relative to particle size as outlined by Hjulstrom (1935).

Sinks, also known as deposition zones, serve as sediment stores in the landscape (Boggs, 2001; Hooke, 2003). They are the receiving end of the processes from the source and transfer zones. Sink zones are characterised by the accumulation of sediment in their localities. Sink zones may be natural (lakes) or can be artificial (reservoirs) (Boggs, 2001). They can be permanent or temporary; the latter is exemplified by fans, bars, islands and estuaries. Depending on the distance travelled, there is a general sorting of particles such that finer sediment is found in sink zones.

The identification of sources, pathways and sinks can go a long way in revealing the root causes of problems in the catchment. By understanding the processes that occur in each of these zones, research begins to feed into catchment scale observations and processes.

3.2.7. GULLY EROSION IN THE KHAMOPELE RIVER CATCHMENT

Soil erosion in South Africa is most noticeably observed in the eastern parts of the country. The Great Escarpment is in part responsible for the observed degradation. Its locality in the centre of the country and sharp decrease in altitude to the sea provides the necessary gradient for sediment transport. Other factors involve the land use, population density and climatological factors.

In 2007, Le Roux *et al*. (2007b) provided a national map depicting potential water erosion risk South Africa. The map, shown in Figure 3.2, made the linkage between earth observation and physical environmental factors driving erosion in the country. The Khamopele River catchment lies in the moderate soil loss class of their (Le Roux *et al*., 2007b) classification.

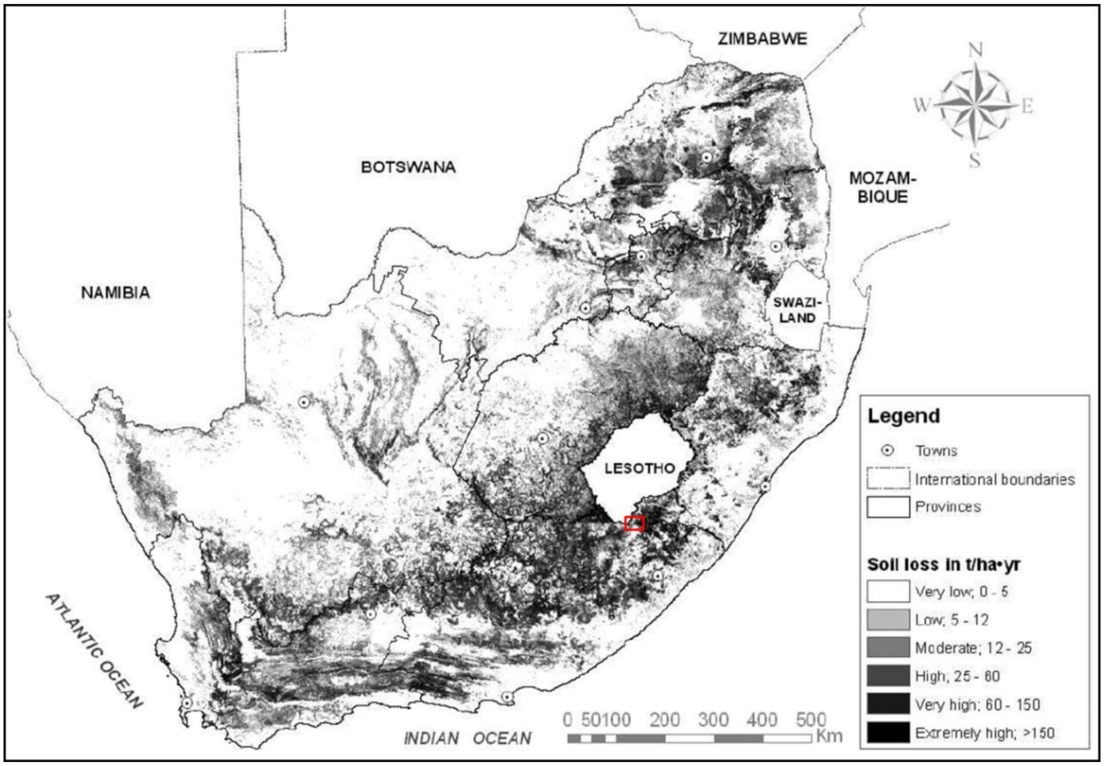


Figure 3.2: Map depicting the actual soil erosion risk in South Africa (*Source*: Le Roux *et al*. (2007b: 310)). The small square indicates the location of the study area.

The Khamopele River catchment in tertiary T34 finds similarities with Le Roux and Sumner's (2010) appraisal of gullies in the adjacent Tsitsa River catchment (T35), where gullies and sheet wash erosion developed on gentle slopes along drainage pathways. These findings hold true for the Khamopele River catchment where erodible soils from clastic rocks, diminished vegetation cover and land use activities on marginal land have caused a serious degradation problem in this catchment. Therefore, understanding the processes that drive degradation in the catchment is an important goal if rehabilitation works seek to restore natural capital. Quantitative descriptors of the catchment hold the key to ascertaining the factors promoting erosion in the Khamopele River catchment.

3.3. METHODS

An inductive approach to research was used to feed into an empirical model that can explain the processes and relationships present in the catchment. The objective of this section is to assess the physical factors promoting soil erosion (soil, gully morphology, connectivity, geomorphic controls) in the Khamopele River catchment. The structure of the section follows a three step process i.e. desktop mapping, field methods and laboratory methods to address this objective.

3.3.1. DESKTOP MAPPING

Secondary reconnaissance work in the form of desktop mapping was used to locate and map erosion areas to inform the field sampling strategy. Aerial photographs, Google Earth® images, GIS data, topographic and orthophoto maps were used to assess the catchment and scale of the problem.

Black and white aerial photographs were digitally available for the years 1954, 1956, 1966, 1975, 1995, 1999, 2000 and 2004 from the Chief Surveyor General. Aerial photographs depicting the study area were printed on matte paper at the Rhodes University Printing Unit and examined under a mirror stereoscope. The scale of the photographs ranged from 1: 30 000 to 1: 50 000. To interpret the features on the photographs Vink's (1964) guide of aerial photograph interpretation was used. Sheet erosion was visible as white bare patches in the landscape. Gullies in the catchment were associated with drainage features and appeared as black features on the lower slopes and valley bottom areas in the catchment. Buringh's (1960) identification of analytical elements in the landscape was used to interpret aerial photographs. Erosion features were discerned by terrain unit, colour tone, shape/texture and contrast using the stereograph (Vink, 1964).

To establish the relief, vegetation abundance and degradation in the catchment, Google Earth ® imagery was used. The satellite imagery used was date stamped 2012 and sourced from AfriGIS. The elevation profile function was used to draw a number of cross sections/profiles in the catchment to become familiar with the terrain. Additionally, geological cross sections were drawn using the Google Earth® elevation profile to provide an understanding of the underlying lithology.

GIS datasets were sourced from national government departments as most of the data was spatially relevant and freely available online. Other datasets, such as the soil classes and land type data, were sourced from the relevant institutions and their use is acknowledged accordingly in text and print where utilised.

Elevation vector data was sourced from the Rhodes University Geography Department's Database Tools. Contour lines (polyline features) from the 1: 50 000 topographical map sheet were projected and used to create a 20 m resolution Digital Elevation Model (DEM). Using ArcGIS® software, the Topo to Raster Tool in Spatial Analyst was used to create a DEM. The Spatial Analyst toolbox was further used to derive a slope raster and classified to provide slope classes for the Khamopele River catchment. Satellite imagery, SPOT 2008, was used to derive the Normalised Difference Vegetation (NDVI) for the catchment. The NDVI equation used is outlined below (CIESIN, nd):

$$NDVI = [(NIR - R) / (NIR + R)] \quad \ldots \text{ (Eq 1)}$$

where, NIR is the near infrared band and R the red band. The Spatial Analyst toolbox was used to calculate the NDVI in ArcMap®. Equation 1 was inserted into the Raster Calculator, which is in the Map Algebra toolset, to derive the NDVI. The Khamopele River catchment NDVI was extracted using the Extract by Mask function in ArcMap®. The NDVI raster was reclassified to show values between 0.2 and 0.3, a range which represents poorly vegetated patches (Shao, 2008). The reclassified raster was converted to polygons and the area of the polygons calculated. The poorly vegetated patches represent likely zones of erosion and possible source areas for mobilised sediment in the Khamopele River catchment.

The 1:50 000 topographic map of 3028 CB Setabataba was used as it covers the study area. Four 1: 10 000 Orthophoto maps dated 2003 were used to fully cover the catchment area, they were sheets 3028CB_11 TSOELIKE, 3028CB_12 ZANYENI, 3028CB_16 THABAKHUBELU and 3028CB_17 TOKWANA. The topographical map was produced in 1980 and the orthophoto maps in 2003. Due to the larger scale of the orthophoto map, gullies were traced onto a transparent sheet to map the erosion features in the Taung and Mhlakeng sample areas. The orthophoto map 3028CB_12 ZANYENI was georeferenced and digitized to represent gully erosion on a GIS platform. Erosion was classified into two types: connected and disconnected systems (Stocking and Murnaghan, 2000).

The advantage of using the methods stated above was that they were simple, fast and gave a good indication of the physical factors controlling degradation in the catchment before the field visit was undertaken.

3.3.2. FIELD MEASUREMENTS

The method used for gully surveys in this study is that of Stocking and Murnaghan (2000) as the pilot study showed that gullies in the Khamopele River catchment were not exclusively V or U shaped. Channel cross-section profiles were undertaken by measuring the depth to the thalweg, channel width and bank to bank distance using a 5 m survey staff and 50 m measuring tape. In total, 49 cross sections were surveyed to characterise the Mhlakeng River from the mouth to the base of the village.

For the gully cross section profiles, a minimum of three transects were taken for each gully at the following locations in the gullies: gully head, mid-section and gully toe. A 5 m survey staff and 50 m tape measure were used to measure the aforementioned gully dimensions (see Figure 3.3). A GPS reading was taken at the gully head or toe to ensure consistency of observations when mapping features digitally. Gullies were present on either side of the river in Taung sample area, therefore the prefixes “TL” (Taung Left) and “TR” (Taung Right) were used to denote the location of the gullies when facing downstream i.e. facing NNE.

The clinometer was used to provide the slope angle of the surface on which the gully was entrenched and the gully floor angle. These findings were verified with the slope DEM. No inclination readings were taken in the Lower Khamopele sample area as the sampling effort in the catchment was limited.

Figure 3.3: Gully surveying in the Taung sample area (Photo: KM. Rowntree).

The number of gully cross sections per sample area was as follows: Taung (19), Mhlakeng (3) and the Lower Khamopele (5). The disproportionate survey effort in the three sample areas was a result of the concentration of gully features in the Taung sample area. A lack of gullies in Mhlakeng sample area and time limitations in sampling the Lower Khamopele catchment also gave rise to the disproportionate assessments in these sample areas.

The following processes were considered to be indicative of current gully activity: sidewall collapse, piping, fluting, undercutting and rill and sheet erosion feeder zones to the gully (Vandekerchove *et al.*, 2000). These forms of active erosion informed the gully classification according to southern African soil erosion type classification scheme by Dardis *et al*. (1988) (Table 3.2).

Gully Profile Description

Sampling of soil horizons took place in all three sample areas. At the gully sites, the thickness of the soil profile (depth) was measured. The texture, dry colour and any other features such as concretions, mottling etc. were noted. A sketch of the gully profile was drawn to represent the soil horizons and associated characteristics. Thereafter, a soil sample was collected using a non-metallic trowel and inserted in to a plastic bag for further soil analysis in the laboratory.

The field sketches of gully surveys were transferred into an Excel spreadsheet. This data was used to estimate volume loss in the sample areas. The method of gully volume loss approximation applied by Stocking and Murnaghan (2000) was used. The cross sectional area of the gully was determined using Equation 2:

$$\textit{Cross Sectional Area } (m^2) = 0.5\ (Av\ W_1 + Av\ W_2) \times Depth \text{ ... (Eq 2)}$$

Where W_1 is the lip distance of the sidewalls and W_2 the width of the gully floor. The cross sectional area was used to determine the volume loss using Equation 3.

$$\textit{Volume lost } (m^3) = \textit{Cross sectional area} \times \textit{Length of gully} \text{ ... (Eq 3).}$$

Soil Sampling & Preparation

Soil samples were taken from three types of locality in the catchment: topsoil intergully area, gully sidewalls, pathways. A non-metallic trowel was used to collect bulk soil samples in the catchment. This was done to avoid contamination of the sample for magnetic analyses. A plastic spatula was also used to collect topsoil samples in the catchment. Bulk sample weights ranged between 125 g and 1.5 kg. In each sample locality a representative sample of soil was sought. For example in gullies, the soil horizon was followed downstream and sampled at three localities to give an indication of the soil properties of that horizon.

Erosion Pins

The direct method was implemented utilizing erosion pins which were inserted into the ground, on the surface of gullies and pathways on the 28th of August 2010 at the localities shown in Figure 3.4. The erosion pin type used in this research was a welding rod that had a diameter of 3 mm and a length of 300 mm. Erosion pins were arranged such that a meter grid (1 meter by 1 meter) was formed with nine rods (3 x 3) in the grid. Labelling of the grids is shown in Figure 3.4a.

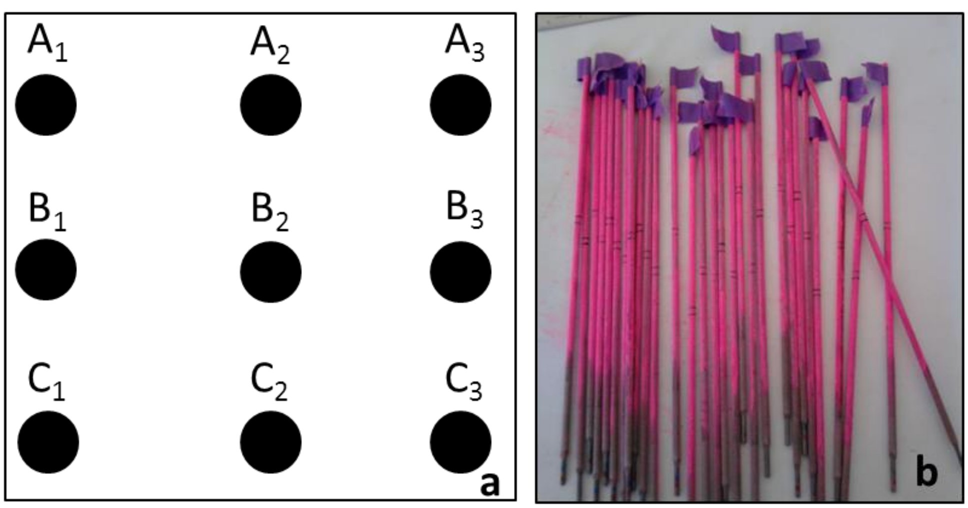


Figure 3.4: Erosion pin placement method used in the study; a) the 1 m x 1 m plot labelling scheme and b) erosion pins used in the study.

Five 1 m x 1 m grids were placed in the Taung (2) and the Lower Khamopele (3) sample areas. In the Taung sample area the erosion plots were placed in the interfluve area. In the Lower Khamopele, erosion pin plots were placed at similar localities, two plots in gully floors and one plot in an interfluve area. The meter grid concept was used by van der Waal (2009), who realised that with the frequency of erosion pin theft and disturbance by stock and wild animals, the removal/ disturbance of one or two pins would not decrease comparisons significantly. Furthermore, it was easier to spot a grid of pins compared to a single pin on the ground in for recurring monitoring purposes.

The pins were pre-marked to 15 cm (see Fig 3.4b) so that half the pin would be in the ground and the other half exposed. In some instances the soil was compacted, therefore the pin was hammered as far as possible and the remaining height recorded. The GPS location of the grid was subsequently recorded and the pins were left for six months. This period ensured that the changes resulting from early rains and the rainy season were captured. Erosion pin data was transferred into a sketch, where the overall grid area was classified as an area of net degradation or aggradation.

Measuring the movement of soil during rainfall events provides an understanding of the sediment yield in a catchment. This can be done by applying direct and indirect methods of measuring changes in sediment patterns i.e. aggradation or degradation (Morgan, 2005). Whitford *et al*. (2010) and Keay-Bright and Boardman (2009) show that although a useful tool, there are apparent disadvantages of using erosion pins. These include the spatial variability that exists in soil, slope and depth in a given area and that these short periods of measurement and monitoring are not representative of processes in the whole area. Lastly, seasonality plays a strong role in the results obtained.

3.3.3. LABORATORY METHODS

All laboratory experiments were carried out at the Rhodes University Geography Department's Soil Laboratory. Prior to drying, soil colour was determined using the Munsell Colour Chart. Soil samples were sprayed with water to determine the moist colour of soil. All colours presented in the chapter represent moist colours unless otherwise stated.

After transportation to the laboratory, soil samples were dried in an oven at 39 ºC until the weight was constant over a 24 hour period. The temperature was set low to allow for the magnetic properties of soil to be maintained (see Chapter 4). The weight after drying was recorded and the following tests were carried out: pH, organic matter content, aggregate stability, carbonate content and particle size distribution.

Particle Size Distribution

This method was used to establish the relative proportions of sand, silt and clay in the soil sample. There are two techniques that can be used to ascertain this, namely: mechanical and sedimentation analyses (Faniran and Areola, 1978). Mechanical techniques utilize sieving as a means to separate soil fractions, whereas sedimentation analyses involve the use of pipettes, hydrometers and sedigraphs to separate fine fractions i.e. silt and clay (Rowell, 1994). Sieving methods are dependent on gravitational forces and agitation, whereas sedimentation methods are largely based on Stokes Law. Both methods were used in this study to determine the distribution of sand, silt and clay fractions (Faniran and Areola, 1978).

After oven drying, soils were disaggregated to get rid of clods, so that the soil could be sieved. The soil sample was put into a soil stack (*phi* size sieves) with the following sizes: 2 mm, 1 mm, 500 µm, 250 µm, 125 µm and 63 µm. The stack was placed in a sieve vibrator shaker for 15 minutes; thereafter the weight of remaining soil from each sieve was recorded. The 125 μm and less than 63 μm size fractions were stored for later analysis in a sedigraph and use in tracer analysis. The Udden-Wentworth scale was used in this research and it differs from other scales in that the clay fraction consists of particles that are less than 0.0039 mm.

The MICROMETRICS® X-Ray Sedigraph was used to determine the percentage of the silt and clay fraction in the soil samples. Soil was not subjected to pre-treatment by hydrogen peroxide. Instead, Pritchard's (1974) method of soil analysis was used. Pritchard (1974) suggests the removal of organic matter by loss on ignition at high temperatures (400 °C). Thereafter, samples are inserted into an ultrasonic bath to fully disaggregate them. Calgon (5 %) was used as a dispersant to ensure that particles were well homogenised in the mixture. Steps outlined in Appendix A were used to process samples using the sedigraph.

Soil pH

Soil pH is a good indicator of soil fertility, nutrient and mineral abundance (Peverill *et al*., 1999). Soils with a measurement of less than 7 indicate acidic soils whereas a measurement that exceeds 7 indicates alkaline soils.

To obtain the best comparative results from the pH measurements, all measurements were done in a salt solution of 0.1M KCl (Rowell, 1994). Measuring pH in water is an acceptable practice but problems arise as some samples contain more soil water than others and may be readily exchanged, thus influencing the pH reading. Although $CaCl_2$ is usually used for this measurement (Watson and Brown, 2010), KCl was readily available in the laboratory and was used as alternative. By homogenising the solution with KCl, the cation exchange of Ca^{2+} and Al^{3+} is reduced. However, the resulting pH is 0.5 units less than the pH in distilled water (Rowell, 1994).

Equipment that was used to measure the pH was the ORION Research Model 201 Digital pH Meter®. Five grams of soil was weighed out and diluted with 15 ml 0.1M KCl. The solution was shaken in a glass bottle where it was left to stand for 20 minutes, with gentle swirling every 10 minutes. Before a measurement was taken, the suspension was stirred again and the electrode was inserted until a stable (30 seconds) reading was obtained. This process was repeated twice for each sample and the values recorded. Due to the malfunction of measuring equipment, the Hannah HI98130 pH/EC/TDS/T° Tester was used to measure soil pH at later stages.

Aggregate Stability

Soil aggregate stability can be defined as *"the ability of aggregates to resist degradation"* (USDSA, 2001:1). This measure is used as an indicator for soil erodibility.

The greater than 2 mm soil fraction (5 - 10 g) was gently inserted into a 50 ml glass cylinder and the volume occupied was recorded. Water was added with care into the cylinder so as not to disintegrate the soil particles (Briggs, 1977). Soil samples were left to stand for a 30 minute interval (Briggs, 1977). The volume change was recorded at the end of the second 30 minute period. The soil aggregate stability was calculated using Equation 4.

$$\text{Aggregate stability } (S\ \%) = [1 - ((V_1 - V_2)/ V_1))]\ X\ 100 \quad \dots \text{(Eq 4)}$$

High percentages indicate that aggregates are stable and lower values indicate easily disintegrated soils (Clapp *et al.*, 1986).

Organic Matter Content

Loss on ignition tests are the most commonly used tests to measure the amount of organic matter in a soil sample. At high temperatures (between 105 ºC and 550 ºC) organic matter will be burnt off (Briggs, 1977), thus providing a means to calculate its abundance in a sample. The weight before ignition (W_0) and after ignition (W_1) was measured. The percentage loss was taken as the amount of organic matter lost given by Equation 5.

$$\% \text{ Organic Matter} = (W_1 / W_0) \text{ X } 100 \ldots \text{(Eq 5)}$$

Conductivity

The Soluble Salts by the Soil Water Extract method was used to determine the electrical conductivity (EC) of the soil samples (Dahnke and Whitney, 1988). The method was modified due to equipment constraints for the soil paste method within the laboratory. A 1:1 (20 mL to 20 g) ratio of soil and de-ionized water was used to create a suspension and left to stand for an hour. After the allocated time period the solution was stirred and inserted into the Heraeus Christ® Centrifuge for 15 minutes. The centrifuge was set to attain 4200 rpm. Once the solution had separated from the soil, 10 mL was extracted into a 50 mL beaker using a pipette, to measure electrical conductivity.

The Hannah HI 98130 pH/EC/TDS/Tº Tester® was used to measure electrical conductivity. The temperature was also recorded because electrical conductivity is affected by temperature changes (Whitney, 2010). The meter was calibrated with a standard solution of 1.4113 µS and 12.88 milli-Siemens (mS). The latter calibration standard was discontinued due to depletion. The calibration was checked every ten samples. To obtain a reading the probe was inserted into the shaken extract until the meter stabilized and the reading in µS or mS and the temperature was recorded.

Conversions for Electrical conductivity (EC) to the singular dS/m unit required the use of the following metric conversions.

$$1 \text{ dS/m} = 1000 \ \mu\text{S/cm} \ ... \ (\text{Eq } 6)$$

$$1000 \ \mu\text{S/cm} = 1 \text{ mS/cm} \ ... \ (\text{Eq } 7)$$

$$\text{Total Cation/Anion Concentration (meq/L)} = 10 \times \text{EC (dS/m)} \ ... \ (\text{Eq } 8)$$

Carbonate Test

The amount of calcium carbonate ($CaCO_3$) available in soils affects soil-relationships (Bashour and Sayegh, 2007). The presence of high levels of calcium carbonate is associated with soil erodibility (Morgan, 2005).

The gravimetric method was used to determine the carbonate content of soils in the Khamopele River catchment. Gravimetric soil techniques use weight ratios to ascertain the content of a particular substance (Black, 1965). This was done by weighing 5 - 10g of soil and adding it to 20ml 2M HCl. The weight of the soil in the crucible was recorded as W_1, the weight of the crucible and 20ml 2M HCl was recorded as W_2 and the weight after the cessation of the reaction was recorded as W_3. Equation 9 was used to determine the amount of $CaCO_3$ present in the sample.

$$\% \ CaCO_3 = W_3 - (W_2 \ X \ (227.2 / W_1)) \ \ldots \ (\text{Eq } 9)$$

This method provides an accurate means to determine the carbonate content. In this test carbon dioxide is given off which is correlated to the quantity of $CaCO_3$ present in the sample.

3.4. RESULTS

In terms of areal extent, the Lower Khamopele sample area was the largest in area but had the lowest percentage of gullied area within its boundaries (see Figure 3.6). The sample area was largely used as a grazing area (see Table 3.4).

Table 3.4: Attributes of the three sub-catchments in Makhoaseng catchment.

	Taung	Mhlakeng	Lower Khamopele
Area (km^2)	2.05	6.33	7.43
Mean Elevation (m.a.s.l)	1575	1553	1612
Rivers	Non-Perennial	Perennial	Perennial
Land Use	Abandoned cultivation	Sparse farming plots and grazing	Grazing
Volume Lost (m^3)	211872	45563	-
Soil Loss (t/ha)	1178	107	-
Gullied Area (%)	3.53	2.26	2.01

The Mhlakeng sample area was of similar areal extent as the Lower Khamopele sample area; however, Mhlakeng sample area had anthropogenic influence as the area was used for grazing, farming, thatch grass collection and fuel (cow dung). The Taung sample area, which had the smallest catchment area, had the highest percentage of gullied area. Land use in the Taung sample area was restricted to occasional browsing by sheep.

Gullies in Makhoaseng catchment were digitized from orthophoto maps and matched to records where the researcher noted the presence of gullies in the field. Figure 3.6 shows that the majority of gullies had their mid and lower sections located in valley bottom areas. In most cases gullies were branched and well defined.

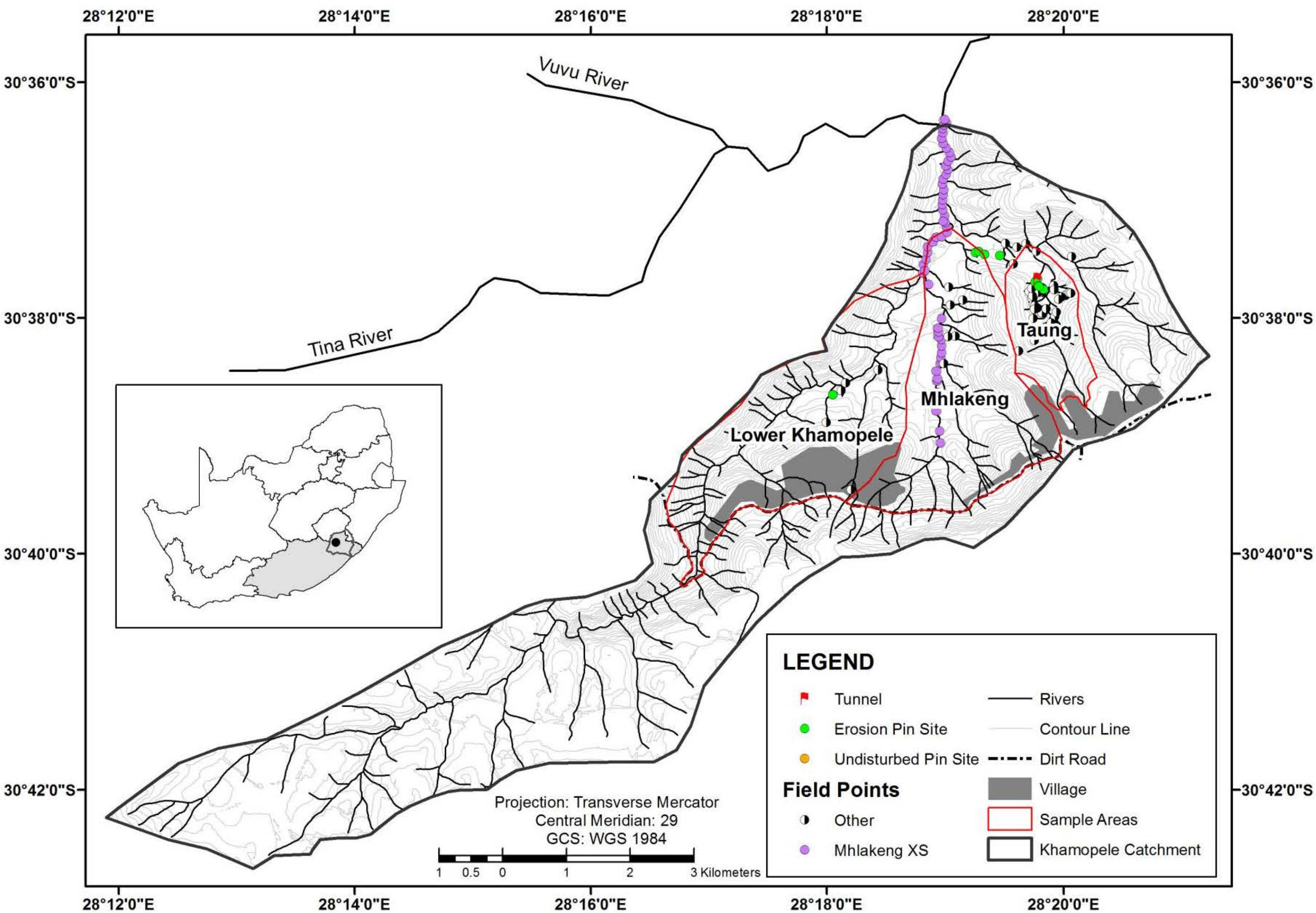


Figure 3.5: Field points in Khamopele River catchment.

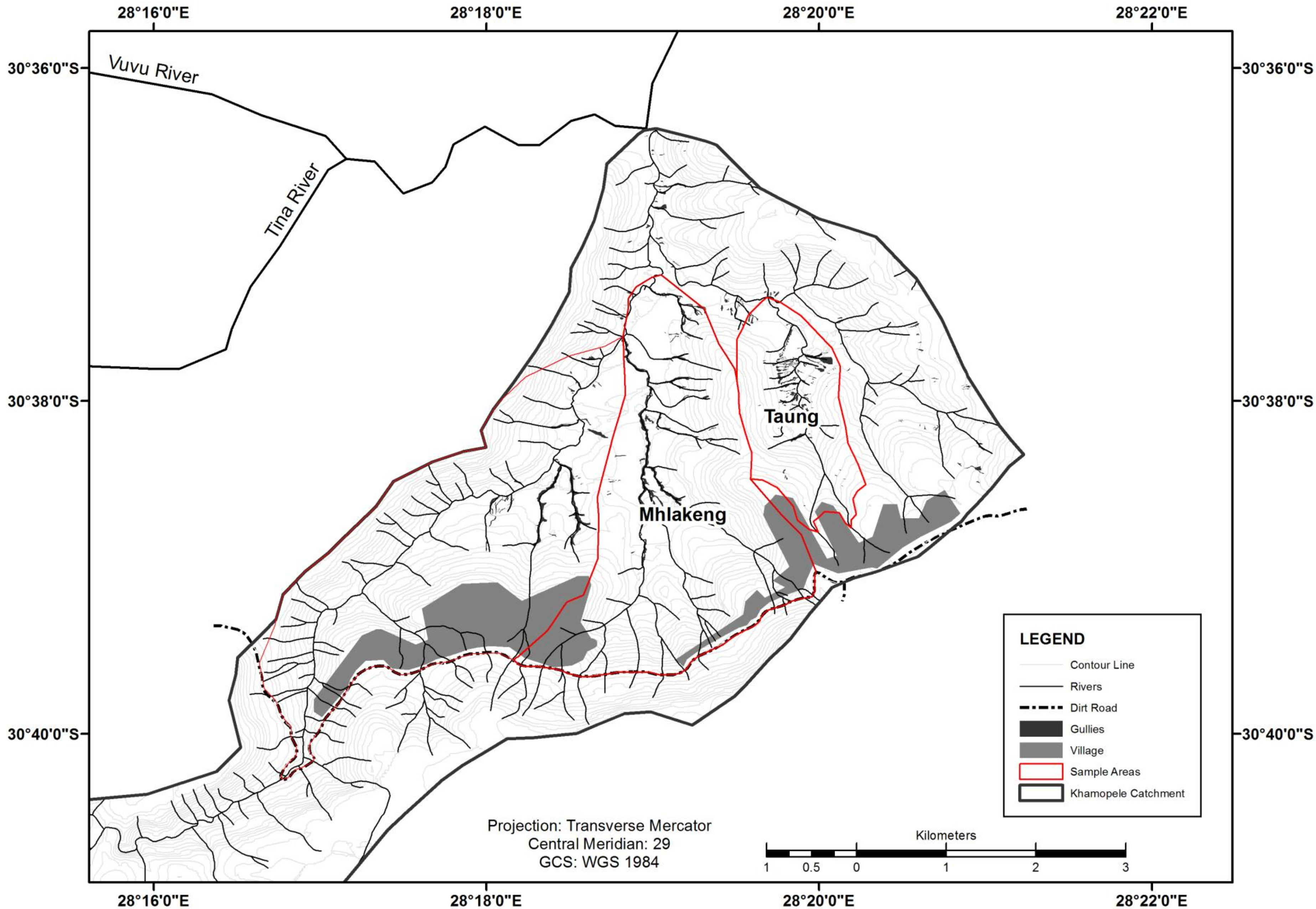


Figure 3.6: Gullies in Khamopele River catchment.

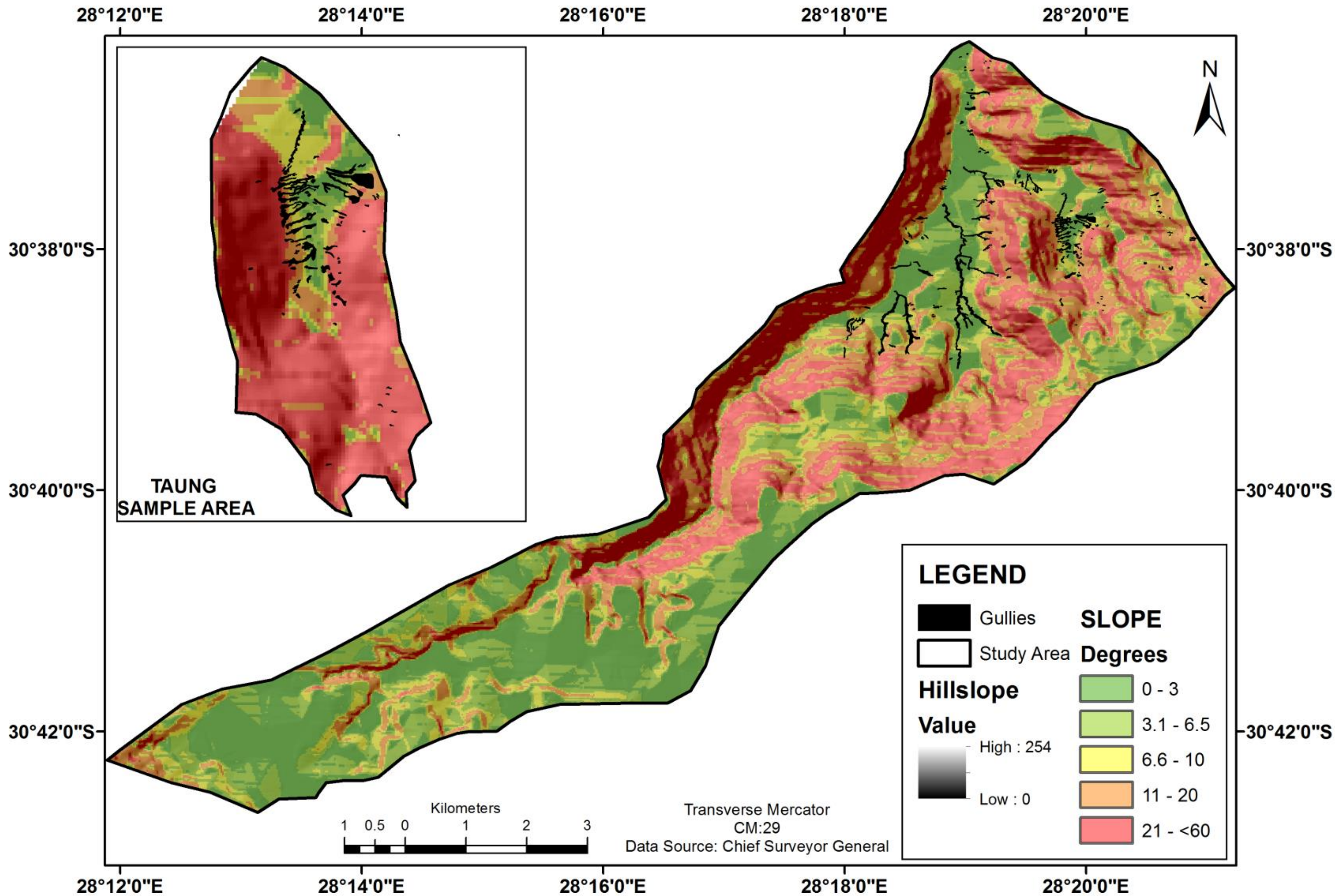


Figure 3.7: Slope classes in the study area**.**

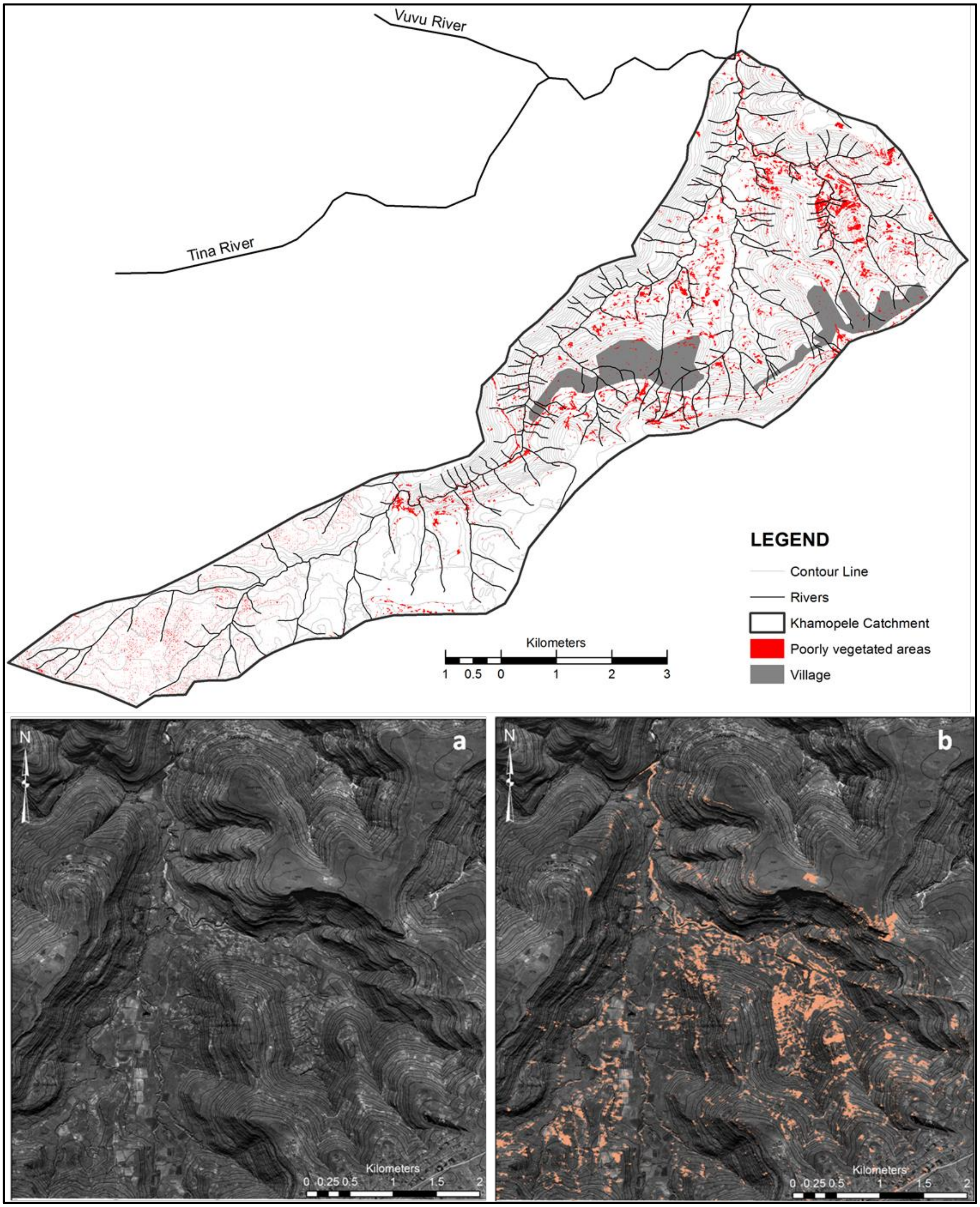


Figure 3.8: Results of the reclassification of the Normalised Difference Vegetation Index for the Khamopele River catchment (**3.8a** shows the original orthophoto (dated 2003) and **3.8b** the poorly vegetated overlain on the orthopoto map)

Young gullies were found on steep slopes and were linear in nature, generally unconnected to the main gullies. The majority of gullies in Makhoaseng sample area were valley side gullies that had vertical gully heads. Where gullies had been entrenched for a longer period, evidence of branching was found.

Results from the NDVI assessment show that the poorly vegetated patches in the catchment were concentrated in the Taung sample area. These sparsely vegetated areas make up 4.8% of the Khamopele River catchment. The percentage of sparse vegetation patches per sample area was: the Lower Khamopele (18%), Mhlakeng (16%) and Taung (15%). The combined percentage of the poorly vegetated areas in the aforementioned sample areas is 49%. Other localities that showed a high concentration of sparse vegetation were the slopes behind the villages and the villages themselves, especially areas of heavy foot traffic.

3.4.1. GULLY INCLINATION

Slope angle results (see Table 3.5) showed that gullies in the Makhoaseng catchment lie in the 5º to 6º range. Gully floors were found to lie at shallower inclinations except TR2 and TR3 where the gully floor readings were 14º. The geometric mean for gully surfaces was 5.6° and the gully floors 3.4°.

Table 3.5: Slope angle results for surveyed gullies in the Makhoaseng catchment.

Gully	**Surface (°)**	**Floor (°)**	**Gully**	**Surface (°)**	**Floor (°)**
TL1	7.5	4.0	TL6	5.5	2.0
TL2	3.0	4.5	TL7	8.0	2.5
TL3	7.0	1.5	TL10	7.0	2.0
TL4	7.0	-	TL11	7.5	2.5
TR1	7.0	3.5	TL15	-	2.0
TR2	6.0	14.0	MG1	5.0	3.0
TR3	7.0	14.0	MG2	4.5	-
TR4	1.0	5.0	**AVERAGE**	6.0	5.8
TR5	6.0	3.5	**STD DEV**	2.3	4.8
TL5	8.5	2.0	**MEAN**	5.3	4.4

The surface inclination results were comparable to the slope classes derived from the DEM (see Figure 3.7). Gullies in the Taung sample area had their toes in the 0° – 3° range, the mid-gully section was in the greater than 6.6° - 10° class and gully heads formed on slopes exceeding 11°. In the Mhlakeng sample area the surface inclination results were also consistent with the derived slope classes as most of the gully length was in the 0 - 6.5° range. Gully heads in the Mhlakeng sample area were also found on slopes greater than 11°. Majority of the gullies in the Lower Khamopele sample area were in the 0° – 6.5° class. Gully heads in the area were generally in the 11° - 20° class. None of the gully heads were found in the 21° to less than 61° class and this may be a result of the steep slopes and outcrop exposure in the Lower Khamopele sample area.

An observed feature of gullies in Makhoaseng catchment was that in older gullies, the mid-slope sections of the gullies were generally linear in nature. Furthermore, gullies in the catchment were closely linked to drainage lines. The gullies were linked to first and second order streams in the Khamopele River catchment.

3.4.2. EROSION TYPES AND CONNECTIVITY

The dominant type of erosion in Makhoaseng catchment was Type 8 gully forms (refer to Table 3.2 for gully types). These were young linear gullies on hillslopes and river banks. Type 8 gullies located in valley bottom areas were connected to the rivers as shown in Figure 3.9a. Type 7 features (Figure 3.9c) were the second dominant erosion features in all three sample areas. Type 7 features were similar to Type 6 erosion features (Figure 3.9d) but lacked the strong sub-surface flow interactions present in Type 6 forms (Dardis *et al.*, 1988). Type 6 gullies were typified by a smaller and less extensive gully floor.

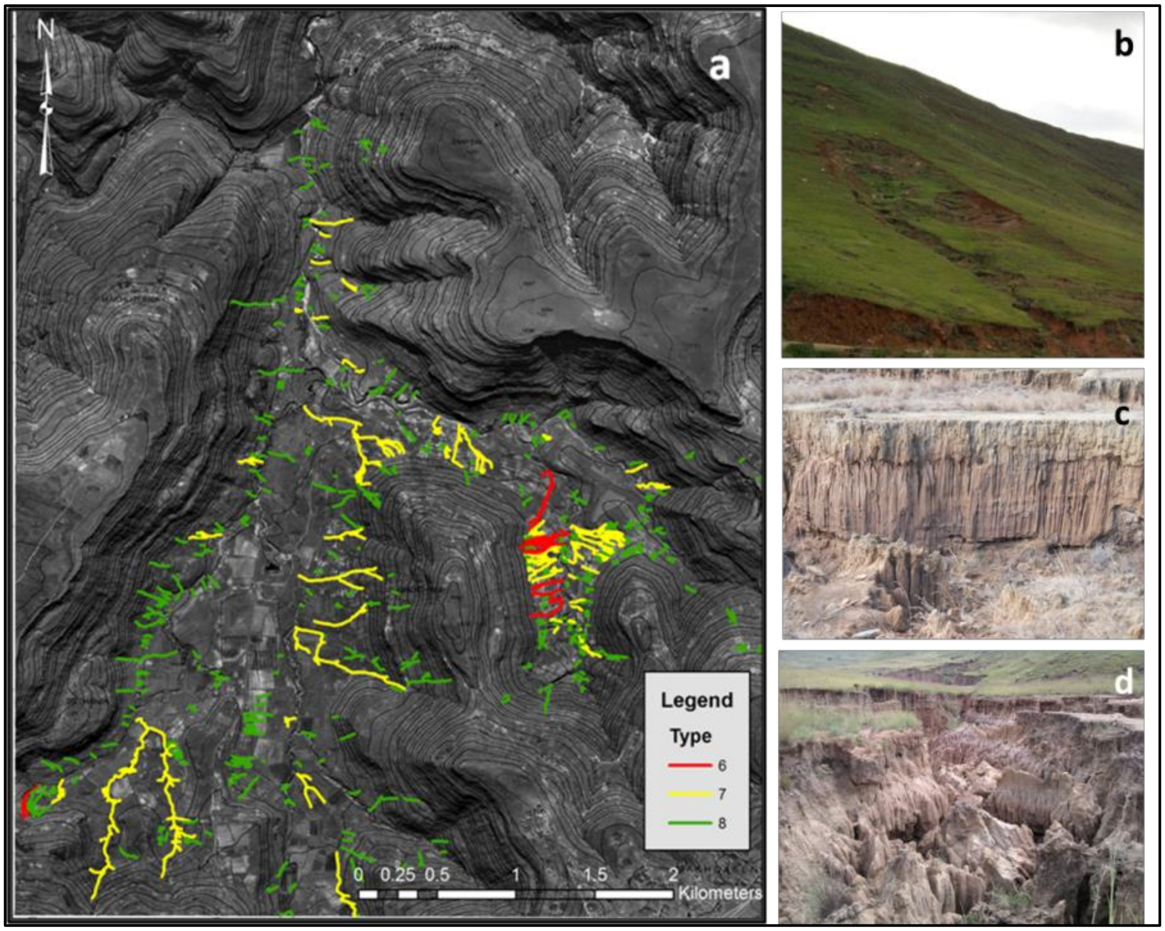


Figure 3.9: (a) Erosion types in Makhaoseng catchment, (b) Type 8 erosion features, (c) Type 7 erosion features and (c) Type 6 erosion features.

The length of Type 6 and 7 gully forms surpassed that of Type 8 erosion forms. This may be a result of the differences in the inception of the gullies. Another distinguishing feature amongst the gully forms was that most Type 6 and Type 7 erosion features were immediately connected to rivers in Makhoaseng catchment. Type 8 features were occasionally connected to the main rivers (see Figure 3.10). The partially connected gullies at steeper slopes fed into Type 7 and Type 6 gully forms.

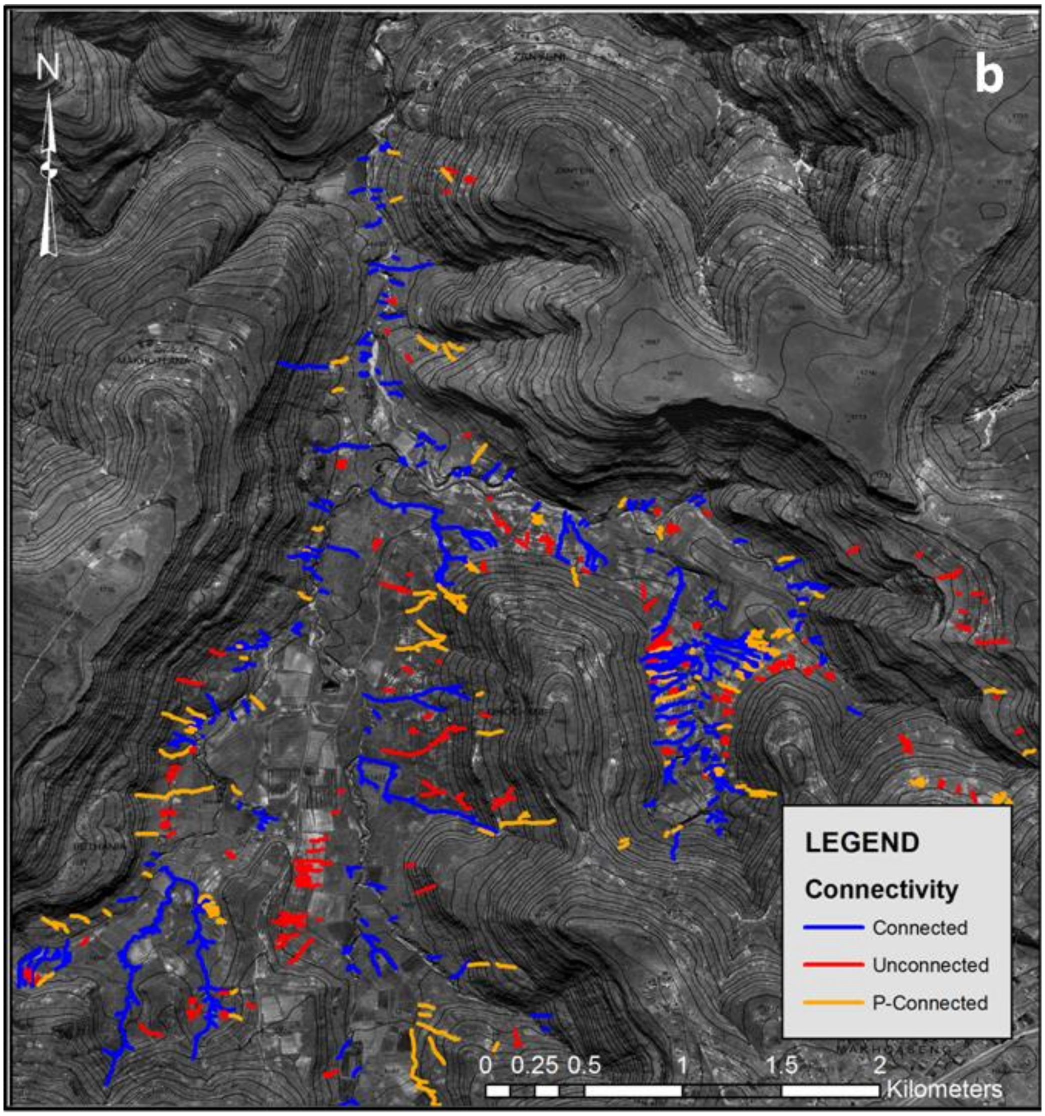


Figure 3.10: Connectivity types in Makhoaseng catchment.

Unconnected gullies in Mhlakeng sample area were longer that those found in the Lower Khamopele and Taung sample areas. The sample area also had the highest number of unconnected gullies.

3.4.3. GULLY MORPHOLOGY

Sample area divisions were used to group gullies and their observed morphology. Three in-depth soil profiles from the Taung sub-catchment are used as examples to give a visual representation of the gully forms in the catchment.

Taung Sample Area

Gullies in the Taung sample area were found in colluvium in the footslope unit. A number of collapsed pipes were found in the lower mid-slope region. The collapsed pipes were less than 70 cm in width and seldom exceeded 30 cm in depth. Evidence of subsurface feeder areas was found in the lower mid-slope regions. Gully heads extended to the lower mid-slope region and were transitional if not fed by seepage. Older and seepage-fed gullies had vertical headwalls. Figure 3.6 below shows an example of a sub-surface feeder area into a gully at the footslope unit.

Figure 3.11: Sub-surface feeder zone for a gully at the footslope unit.

Overland and subsurface flows were thought to be the main agents of erosion in this dendritic drainage network. Sub-surface controlled erosion forms were exclusively found on the left (TL) side of Taung sample area.

The collapsed walls and lack of vegetation on the gully floors provided evidence of some gully activity in the catchment. Bedrock (greyish purple mudstone and sandstone) was exposed at the toe of most gullies, especially in gully TL15 where instances of bedrock steps were noted twice in areas well before the gully toe. The exposure of bedrock at the toe of most gullies created a significant hydraulic head as this was the terminus of the gully and sediment collects after free fall at the base to be carried by channel flow. Gully floors were generally flat in nature as shown by clinometer readings.

Soils in the catchment showed evidence of crusting and pedestals were found in the areas before and around the gully heads. Piping, fluting and dispersive soils were observed in soil horizons. Sidewalls generally had a vertical morphology; those with sloped sidewalls were fairly young and short. The majority of deeply entrenched gullies in this catchment presented Type 6 and 7 erosion types.

CASE 1

Gully system TL3 was an example of a Type 7 erosion feature (Figure 3.12). This gully system had evidence of collapsing sidewalls, cavities and fluting. The average depth of the gully was 3.4 m and an average wall to wall width of 5 m. Profile TL3 consisted of five distinct soil horizons as shown in Figure 3.12. The upper layer was the E-horizon as determined by its Munsell Colour and its texture was loamy sand. The dark grey colour of the top horizon can be attributed to reduction from this layer and saturation during the wet season (Soil Classification Working Group, 1991). The A horizon was absent in the soil profile.

Sub-rounded sandstone clasts were found in the thin, structureless and laterally persistent second horizon. The presence of rock fragments in this horizon indicates that the layer may be the lithocutanic B horizon (Soil Classification Working Group, 1991). Texturally the soil in the horizon was classified as loamy sand. Colour classification indicated that the third and fourth horizons were yellow-brown apedal B-horizons. The third horizon had a loamy sand texture and cavities were found in this horizon. The honeycomb structure shown in Figure 3.13b below is an example of the process of cavity formation in the soil horizon.

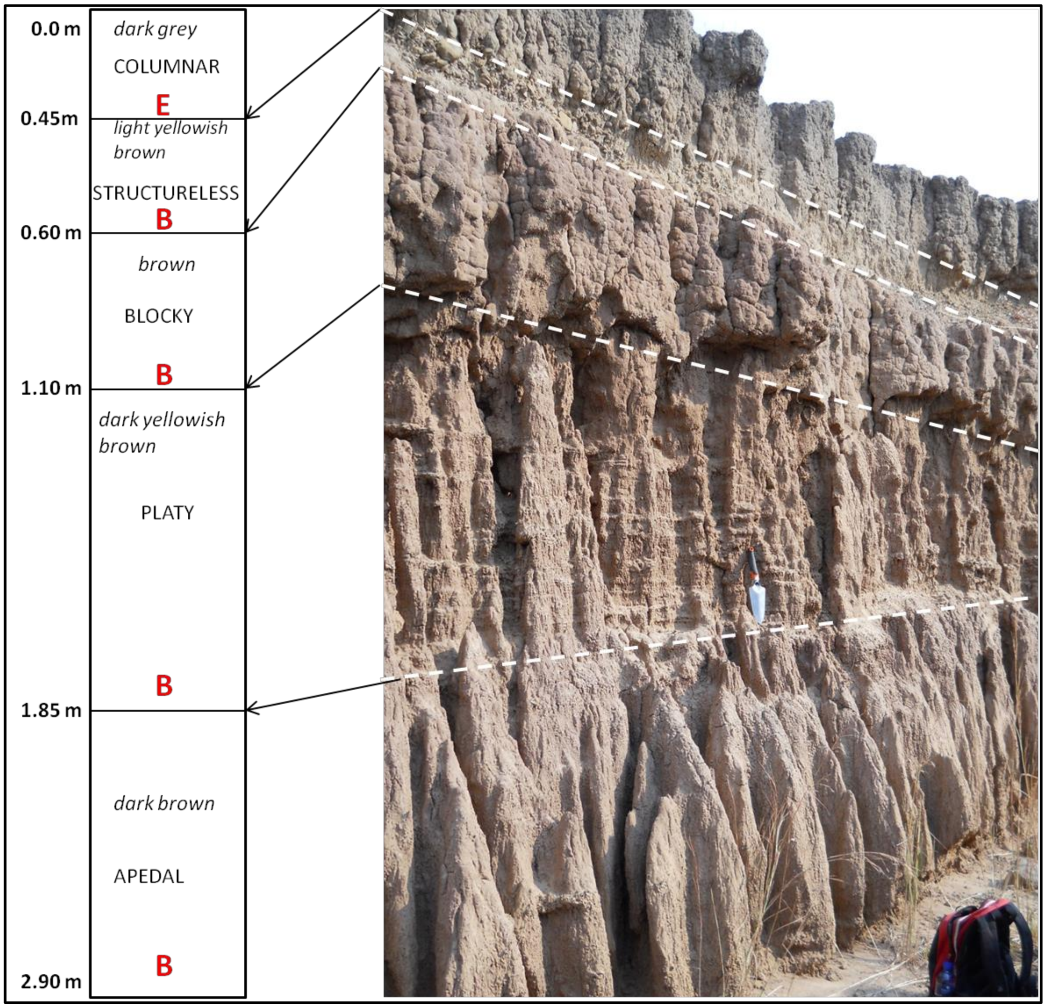


Figure 3.12: Typical soil profile in gully system TL3 (duplex soils).

The fourth horizon consisted of fine sand with visible horizontal layering and a friable texture (platy). Rilling was observed and noted as result of water concentration in the steep profile. The last horizon had a dark reddish grey colour in the dry state and was fluted. The dry colour allows this horizon to be classified as the soft plinthic B horizon (Soil Classification Working Group, 1991).

Texturally, the horizon consists of coarse sand and evidence of mottling was found, as shown in Figure 3.13c below. The black colours in the mottles in Figure 3.13c represent manganese oxides (Soil Classification Working Group, 1991; FAO, 2006) and the outer red the presence of iron oxides in the horizon.

Figure 3.13: Associated erosion features in Taung sub-catchment (a: sidewall collapse b: cavities c: mottling).

Using the FAO Soil Description Sheet (FAO, 2006) the following attributes were observed for the mottles (see Table 3.6).

Table 3.6: Mottle attributes.

Abundance: 1%	*Contrast*: Prominent
Size: Medium (6 - 20 mm)	*Boundary*: Sharp

The yellow-brown apedal nature of the soils and mottling in this gully system allows it to be classified as either the Avalon or Clovelly Form (Soil Classification Working Group, 1991). However, the second horizon with the clasts of sandstone makes the existence of the Cartref Form plausible in this gully system.

CASE 2

Gully system TL7 and TL3 showed similarities in that horizon one, three and five were preserved, as Figure 3.14 shows. Furthermore, both systems had Type 6 erosion. The average wall to wall width was 8.9 m and the average depth was 3.3 m.

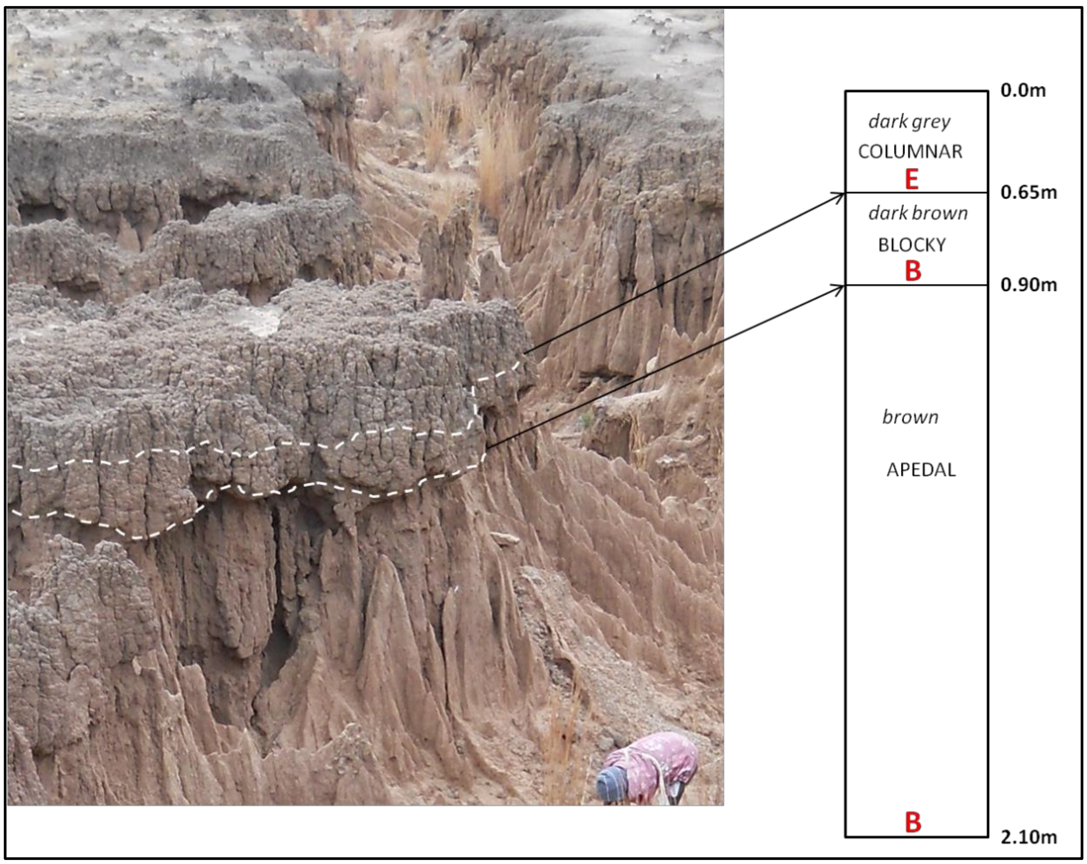


Figure 3.14: Characteristic soil profile for gully system TL7.

The absence of the A-horizon was continued in the profile of this gully system. The uppermost horizon had pedestals and was loamy sand in texture. This horizon was identified as an E horizon using the South African Soil Classification System (Soil Classification Working Group, 1991). The second horizon was also loamy sand and showed evidence of dispersion at its base. The lowermost horizon was a yellow-brown apedal B horizon that was fluted. Texturally, coarse sand was dominant in this horizon. The presence of a discernible E horizon overlying a yellow-brown apedal B horizon indicated that the soil profile TL7 belongs to the Constantia Form which is oxidic in nature (Soil Classification Working Group, 1991; Fey, 2010).

CASE 3

The last example of soil profiles in the Taung sub-catchment shows soils that undergo periodic saturation. Soil profile TR3 consists of four discernible soil horizons as shown in Figure 3.15 below. The accompanying schematic soil profile shows five horizons, the last two horizons are treated as one as they both are friable and show similar colours in the C horizon.

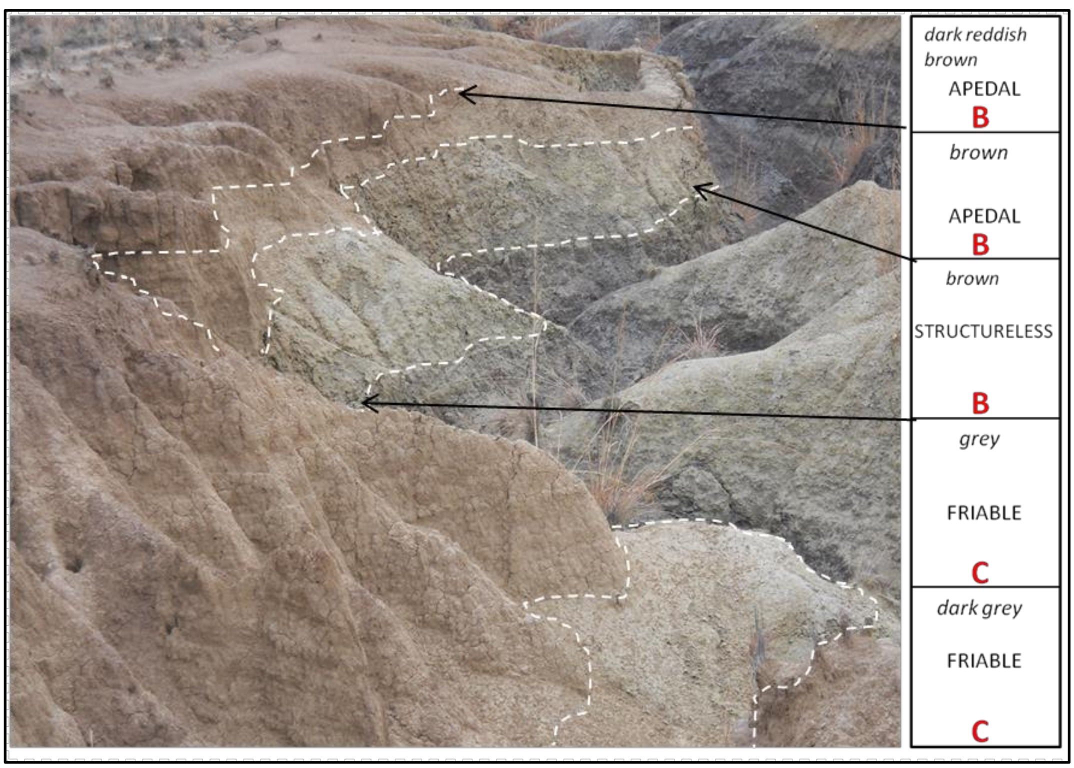


Figure.3.15: Gully system TR3 indicating typical Type 7 erosion in the Taung sample area.

The upper three soil horizons in TR3 represented the B horizon, classified using Munsell colours (Soil Classification Working Group, 1991). The uppermost loamy sand horizon was a red apedal B horizon that belonged to the Hutton Form. The second horizon was a structureless yellow-brown apedal B horizon that had fine loamy sand texture. The last horizon graded into bedrock closer to the toe of the gully. The profile did not match the requirements of the Mispah Form as the organic matter content of the horizon overlying bedrock was very low. This classified the profile as either the Hutton or Clovelly Form.

Soil profiles for other gully systems in the Taung sample area are presented in schematic form as shown in Figure 3.16.

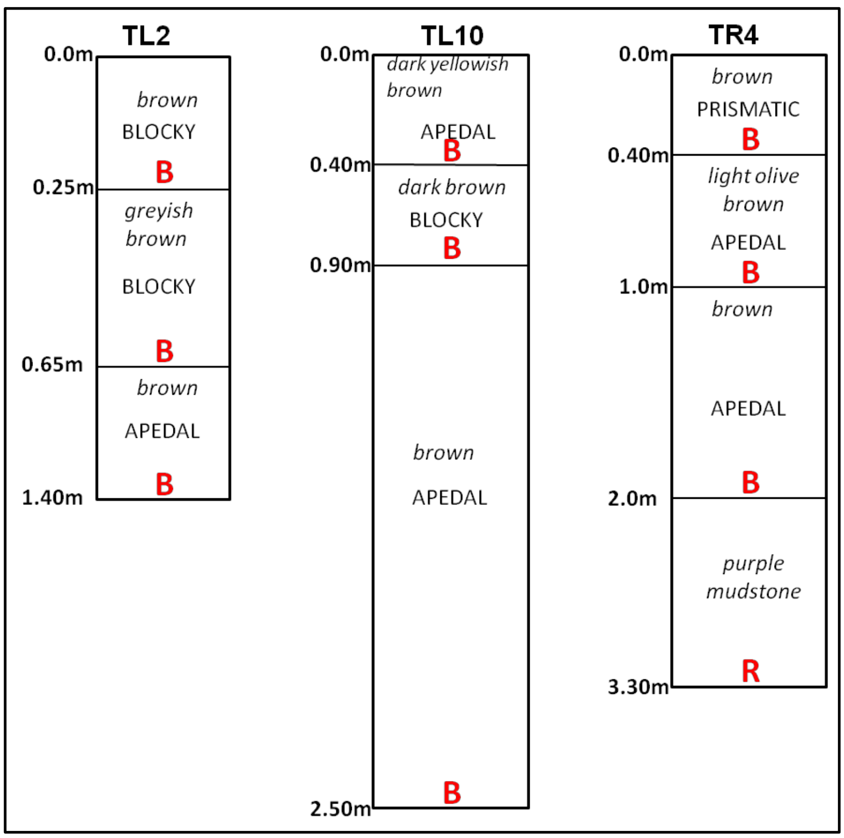


Figure 3.16: Summary of the master horizons and texture of soil profiles in the Taung sample area.

Results show that the yellow-brown apedal B horizon was the dominant and most distinguishable soil horizon. The O and A horizons were absent from the soil profiles. Evidence of fluting was found on all three lower B horizons. Evidence of mottling was found in the second horizon of TR4.*Mhlakeng Sample Area*

Gully heads in the Mhlakeng sample area were found at the mid-slope region. Gully trunks generally occurred at the footslope unit. Gully systems in this area (see Figure 3.17) graded into the valley bottom and joined the main Mhlakeng River channel. Bedrock exposure was largely limited to the main Mhlakeng River channel. Unlike the Taung sample area, bedrock exposure in this sample area was limited to the gully head area. For example, M3 had a sandstone outcrop at the gully head. Gully M2 had a spring in the gully head area. The spring is also indicative of the mudstone and sandstone interface at this locality.

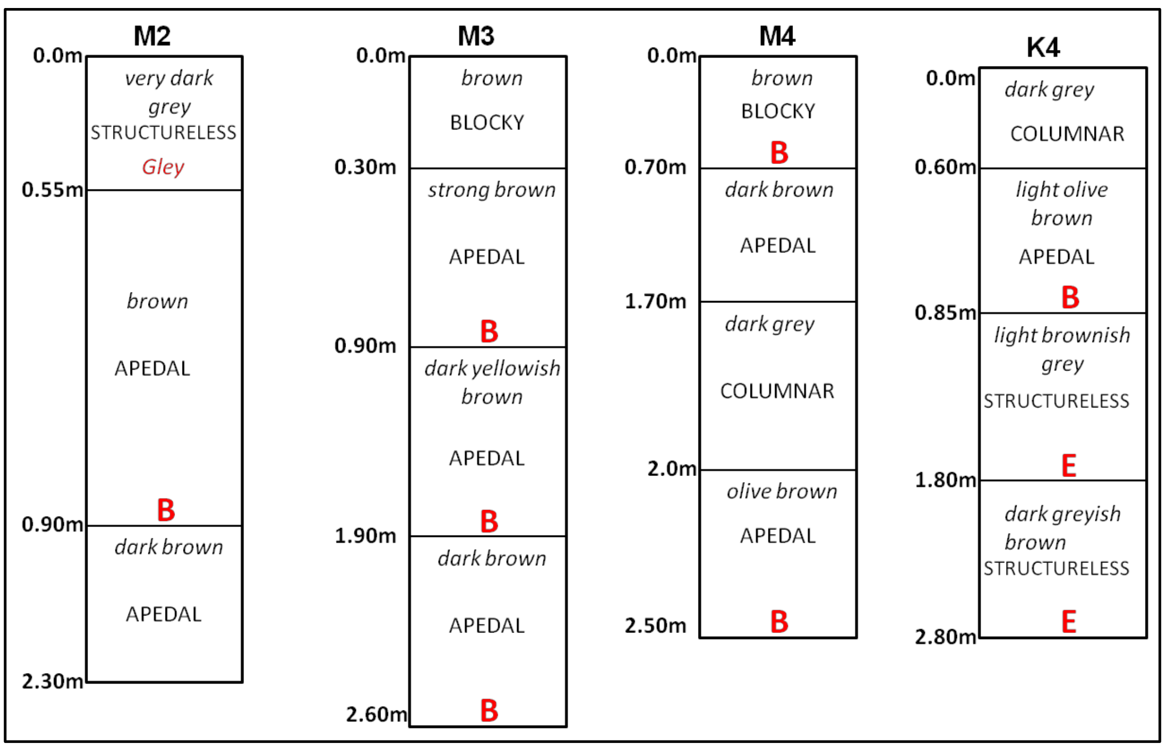


Figure 3.17: Master horizons of soil profiles in the Mhlakeng and the Khamopele sample areas.

No evidence of mottling was found in the vertical soil profiles at the footslope. Survey results showed that these gullies were active because there was evidence of sidewall collapse. Soils in the valley bottom had a characteristic very dark grey horizon indicative of the old wetland soils. Fey (2010) states that soils with such a characteristic grey colour indicate gleying and can be described as soils of the Kroonstad Form. Profile M2 is an example of such a profile. The other two Mhlakeng profiles were taken at the footslope and had brown coloured upper horizons.

Rounded calcareous nodules were exclusively found in the topsoil in the sample area. The yellow-brown apedal B horizon was most preserved as shown by the soil profiles. Gullies in this sample area indicated similarities to Taung sample area gullies in that both sample areas exhibited Type 6 and 7 erosion forms of deeply entrenched gullies.

Lower Khamopele Sample Area

The Lower Khamopele sample area differs from the other two sample areas in that gullies were linear and ravine-like in morphology i.e. Type 8 erosion forms. Gullies in this catchment were shallow and concentrated along drainage lines. Rounded calcareous nodules were found in the topsoil and none of the horizons showed evidence of mottling or piping. The gullies were V-shaped i.e. sloping sidewalls. The shorter gullies in this catchment showed signs of stability; some even had grass growing on the gully floor. There were two systems of well-connected gullies in the catchment, the rest of the smaller gully systems were unconnected systems.

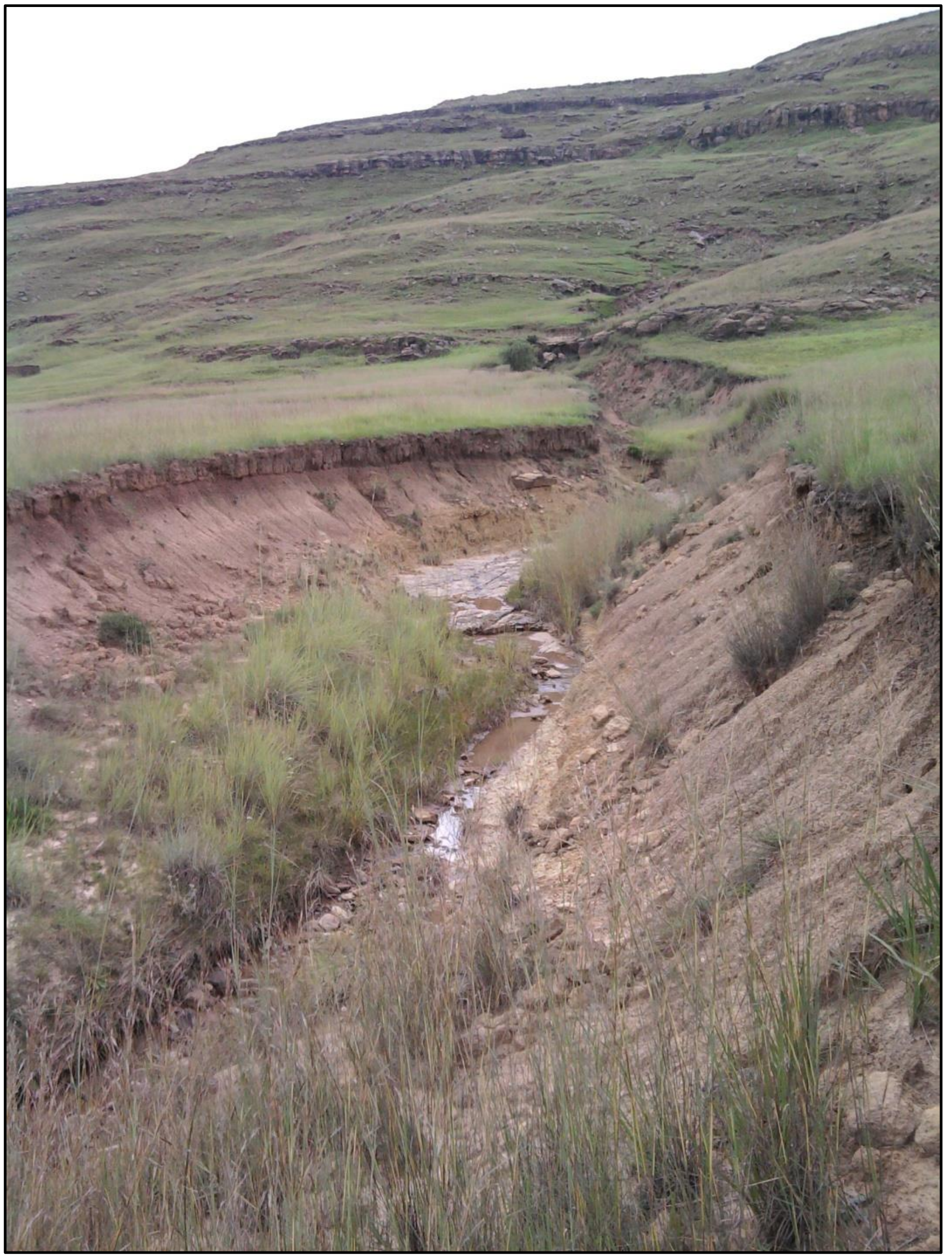


Figure 3.18: An example of a gully in the Lower Khamopele sample area**.**

The soil profile taken from gully system K4 shows that the E horizon lies under the B horizon. This is discordant with the sequence of master horizons, suggesting that inversion of soil horizons may have occurred.

3.4.4. SOIL TEXTURE RESULTS

Sixteen soil samples were processed through the sedigraph to determine the soil texture. The samples used were: TL2a, TL2b, TL2c, TL7a, TL7b, TL7c, TL7d, TL10a, TL10b, TL10c, TL10d, TL10e, TR3a, TR3b, TR3c and TR3d (see Appendix B for result sheets). Results indicated that the soil from the gullies was largely sandy in nature (see Figure 3.19).

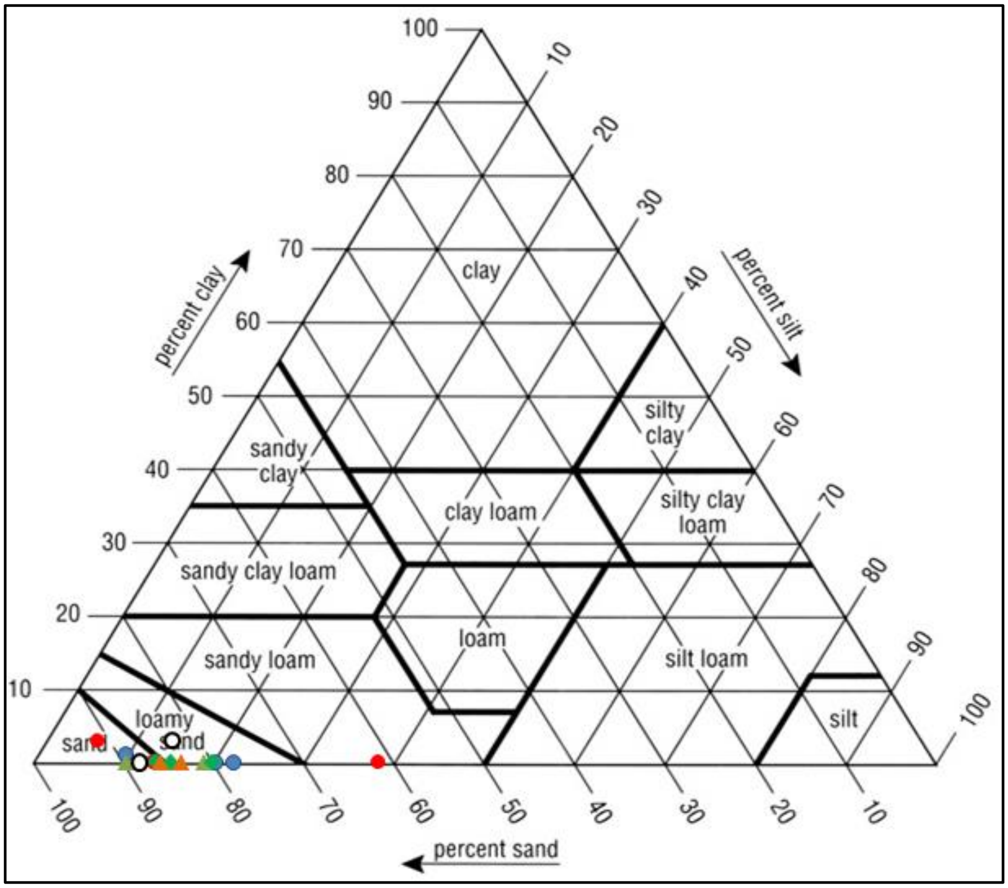


Figure 3.19: USDA soil texture diagram for Makhoaseng catchment derived soils.

The results were compared to the soils forms in the catchment from the national Land Type survey (Land Type Survey Staff, 1972 – 2006). The South African Sugar Association Experiment Station (1999) classification of soil was used to determine the dominant texture of soil for the soil forms in the catchment. The textures of the forms found in the catchment are as follows:

Table 3.7: Associated texture classes of soil forms in Makhoaseng catchment**.**

Form (Land Type Survey Staff, 1972 - 2006)	**Texture** (South African Sugar Association Experiment station, 1999)
Hutton	Sandy Loam
Katspruit	Loamy sand to sandy loam
Mispah	Sandy clay loam
Cartref	Loamy sand
Clovelly	Sandy clay loam
Kroonstad	Sandy loam
Avalon	Sandy loam
Constantia	Loamy sand to sandy clay loam

The limited number of samples prevented a discussion on the soil texture, but what is evident is that the gully morphology results pointed to the forms that show the textures in Table 3.7 i.e. Avalon, Kroonstad, Constantia, Cartref, Katspruit and Hutton soil forms are represented in the catchment.

3.4.4. GULLY SURVEYS

Gully dimensions were transferred into Excel® spreadsheets where the average width and depth were calculated. The gully length was also entered into the spreadsheet. Equation 3 was used to calculate the cross sectional area of the gully. Equation 4 was used to calculate the volume lost from the total gully length. The volume lost was expressed as a meter loss over the sample area. This was done by multiplying the volume lost by the catchment area in m^2. To determine soil loss in tonnes per hectare Equation 10 was used (Stocking and Murnaghan, 2000:34):

$$\textit{Soil Loss (t/ha)} = \textit{Soil Loss } (m^3/m^2) \times \textit{Bulk Density} \times 10000 \ldots \text{(Eq 10)}.$$

The abovementioned process yielded the results shown in Table 3.6, Table 3.7 and Table 3.8. Results show that the soil loss in Taung sample area was 1484.92 t/ha and 454. 86 t/ha for Mhlakeng sample area. The soil loss in the Taung sample area is approximately three times greater than that of Mhlakeng sample area. The volume lost in Mhlakeng sample area was 214870.40 m^3 and in Taung sample area 211871.80 m^3. These results indicate that the volume lost in the two sample areas was very similar. However, due to the area differences the soil loss in Taung sample area was three times greater than that of Mhlakeng sample area. This result may also represent the concentration of gullies and rate of erosion in Taung sample area when compared to Mhlakeng sample area.

Table 3.8: Summary of Taung sample area gully dimensions (Tables represent the LHS and RHS, respectively).

	W_1 (m)	W_2 (m)	d (m)	Gully Length (m)		Cross Sec Area (m^2)	Volume lost (m^3)	Soil Loss	Soil Loss (t/ha)
TL1	7.2	5.6	2.8	248.8		17.72	4409.83	0.0022	28.83
TL2	9.0	6.5	7.5	289.5		57.80	16732.96	0.0082	109.38
TL3	11.0	3.0	3.4	419.0		23.74	9945.33	0.0049	65.01
TL4	10.3	4.6	3.0	105.6		22.22	2346.38	0.0011	15.34
TL5	12.3	5.1	4.2	347.5		36.14	12560.28	0.0061	82.10
TL6	9.2	2.4	3.3	163.9		18.83	3086.07	0.0015	20.17
TL7	9.8	4.5	4.0	257.8		28.73	7407.12	0.0036	48.42
TL8	6.8	4.1	2.0	179.0		10.98	1965.58	0.0010	12.85
TL9	17.7	2.6	4.1	214.0		41.31	8840.45	0.0043	57.79
TL10	13.7	3.2	5.0	229.3		42.64	9776.99	0.0048	63.91
TL11	14.2	4.1	5.4	169.8		49.12	8340.47	0.0041	54.52
TL12	11.7	2.9	4.6	139.0		33.16	4608.98	0.0022	30.13
TL13	16.2	2.5	5.8	82.0		54.32	4454.09	0.0022	29.11
TL14	15.0	2.2	7.7	285.0		65.62	18702.06	0.0091	122.25
TL15	22.8	3.5	6.6	405.1		86.46	35027.99	0.0171	228.96
Average	12.4	3.8	4.6	3535.3	**SUM**	588.79	**148204.56**	0.0723	**968.75**

	W_1 (m)	W_2 (m)	d (m)	Gully Length (m)		Cross Sec Area (m^2)	Volume lost (m^3)	Soil Loss (m^3/m^2)	Soil Loss (t/ha)
TR1-L	27.4	9.5	6.7	246.3		123.62	30446.37	0.0149	199.02
TR1-R	8.9	2.7	6.0	107.3		34.80	3734.04	0.0018	24.41
TR2	9.3	2.5	6.3	211.7		37.17	7868.89	0.0038	51.44
TR3-L	15.9	1.8	5.0	373.1		44.25	16509.68	0.0081	107.92
TR3-R	13.5	1.0	5.2	37.4		37.70	1409.98	0.0007	9.22
TR4	8.5	1.8	3.2	89.7		16.48	1478.26	0.0007	9.66
TR5	6.1	4.8	0.4	76.6		2.23	171.16	0.0001	1.12
TR6	5.9	2.0	3.9	133.0		15.41	2048.87	0.0010	13.39
Average	11.9375	3.2625	4.58875	159.3875	**SUM**	311.65	**63667.24**	0.0311	**416.17**

Table 3.9: Summary of Mhlakeng sample area gully dimensions.

	W_1 (m)	W_2 (m)	d (m)	Gully Length (m)		Cross Sec Area (m^2)	Volume lost (m^3)	Soil Loss (m^3/m^2)	Soil Loss (t/ha)
M1	17.9	2.3	6.2	223.2		62.80	14017.15	0.0022	29.67
M2	15.9	2.6	4.0	376.1		36.49	13723.91	0.0022	29.05
M3	11.7	2.9	4.2	586.5		30.39	17822.31	0.0028	37.73
	45.5	7.7	14.4	1185.8	**SUM**	129.68	**45563.37**	0.0072	**96.45**

Table 3.10: Summary of Mhlakeng channel dimensions.

	W_1 (m)	W_2 (m)	d (m)	Gully Length (m)		Cross Sec Area (m^2)	Volume lost (m^3)	Soil Loss (m^3/m^2)	Soil Loss (t/ha)
MC1	18.7	3.0	4.2	194.2		45.57	8849.69	0.0014	18.73
MC2	19.8	2.0	4.2	563.8		45.34	25564.95	0.0040	54.12
MC3	22.0	1.9	4.8	154.6		57.12	8830.91	0.0014	18.69
MC4	29.0	4.7	6.3	59.4		106.16	6305.61	0.0010	13.35
MC5	28.5	3.0	6.4	77.2		100.80	7781.76	0.0012	16.47
MC6	28.6	5.1	6.8	55.9		114.58	6405.02	0.0010	13.56
MC7	30.0	6.1	6.8	100.1		122.74	12286.27	0.0019	26.01
MC8	27.4	7.2	8.5	108.7		147.05	15984.34	0.0025	33.84
MC9	15.6	5.5	3.8	74.5		40.09	2986.71	0.0005	6.32
MC10	26.3	5.9	9.3	77.6		149.73	11619.05	0.0018	24.60
MC11	22.4	2.5	4.2	144.6		52.29	7561.13	0.0012	16.01
MC12	30.0	2.0	6.3	121.3		100.80	12227.04	0.0019	25.88
MC13	31.0	3.2	5.3	36.3		90.63	3289.87	0.0005	6.96
MC14	40.0	5.3	5.8	177.5		131.37	23318.18	0.0037	49.36
MC15	15.4	5.1	5.1	110.2		52.28	5760.71	0.0009	12.19
MC16	16.3	4.0	5.3	80.2		53.80	4314.36	0.0007	9.13
MC17	20.2	2.0	5.0	112.1		55.50	6221.55	0.0010	13.17
Average	24.8	4.0	5.8	2248.2	**SUM**	1465.84	**169307.13**	0.0267	**358.41**

3.4.5. EROSION PINS

Only two of the original eight erosion pin sites were found to be well preserved after a seven month period. Erosion pins that were found bent and those missing suggested anthropogenic and stock interference and were classified as null. The first preserved pin site was in the Lower Khamopele sample area (Site A) and the second between the Mhlakeng and Taung sample areas (Site B). Site A was located in a relatively flat interfluve area and Site B was a pathway feeding into a gully. Table 3.11 shows that Site A experienced net degradation whilst Site B experienced net gain.

Table 3.11: Erosion pin data from undisturbed sites in the Taung sample area.

	Period	Site A (cm)	Site B (cm)
A1	28/10/2010-03/03/2011	+1.4	+0.4
A2	28/10/2010-03/03/2011	+0.1	-0.6
A3	28/10/2010-03/03/2011	-3.1	+0.2
B1	28/10/2010-03/03/2011	-2.0	+1.0
B2	28/10/2010-03/03/2011	-0.8	-0.5
B3	28/10/2010-03/03/2011	-0.6	+0.1
C1	28/10/2010-03/03/2011	+0.4	+0.3
C2	28/10/2010-03/03/2011	+2.6	+1.0
C3	28/10/2010-03/03/2011	+0.74	-0.2
Total Gain		4.84	3.0
Total Loss		-6.50	-1.3
Net Loss or Gain		-1.66	1.7

The results of the erosion pins show the dynamism of erosion process. Site A, which is exposed to precipitation and wind experienced net loss. This may be a result of sediment being transported from the interfluve area downslope or into a gully. Site B represents a transport zone. The net gain experienced at the site indicates that the site has received sediment to feed into the gully recently.

3.4.6. PHYSICAL PROPERTIES

Soil pH

Figure 3.20 shows a summary of the physical properties of gullies examined in Makhoaseng catchment. Soil pH results indicated that the majority of soils were acidic in nature. A further 18.6 % of samples were neutral as defined by Hazelton and Murphy (2007:61) i.e. they range between 6.6 and 7.4. According to the Sugar Association Experimental Station (1999) the near neutral values are plausible for the Katspruit, Mispah, Clovelly and Kroonstad soil forms as their bounding pH values are 7.0. The Avalon and Hutton soil forms have their upper bounds at 6.0 and 6.5 respectively. In most gullies, the most acidic samples were found in the uppermost soil horizons. Samples that had a neutral pH were almost exclusively found in samples representing the lowermost soil horizons. The USDA (1999) chart shows that the pH of these soils is indicative of Sub-humid grassland soils.

Calcium carbonate

$CaCO_3$ results ranged between 6.4 % and 9.1 %, indicating a 2.7 % difference. The highest $CaCO_3$ values were found in the Mhlakeng sample area and the lowest in Taung sample area. This may indicate subsurface influence in the latter area.

Organic matter content

Loss on ignition results indicated that the majority of samples did not exceed 5 % in organic matter content. Soils with a 5 % organic matter content or above are deemed fertile soils (Tan, 2005). Seven samples, representing 16.3 % of soil samples examined, exceeded this threshold. Of the seven samples that had organic matter content greater than 5 %, five of the samples were in Mhlakeng sample area. This may be an indicator of the former wetland soils.

Aggregate stability

Organic matter content and aggregate stability (S %) showed a proportional relationship in samples collected in the Taung sample area. Stable aggregate percentages vary within the soil profile and showed no discernible horizon trends. Soil samples showing the greatest aggregate stability were from the Mhlakeng sample area.

Electrical conductivity

Electrical conductivity results showed that soils in all sample areas were non-saline as their values were between 0 and 0.98 for USDA (1999) standards, and below 2 for the standards presented by Hazelton and Murphy (2007). The limited salinity may indicate leaching or proof of well drained soils in this catchment

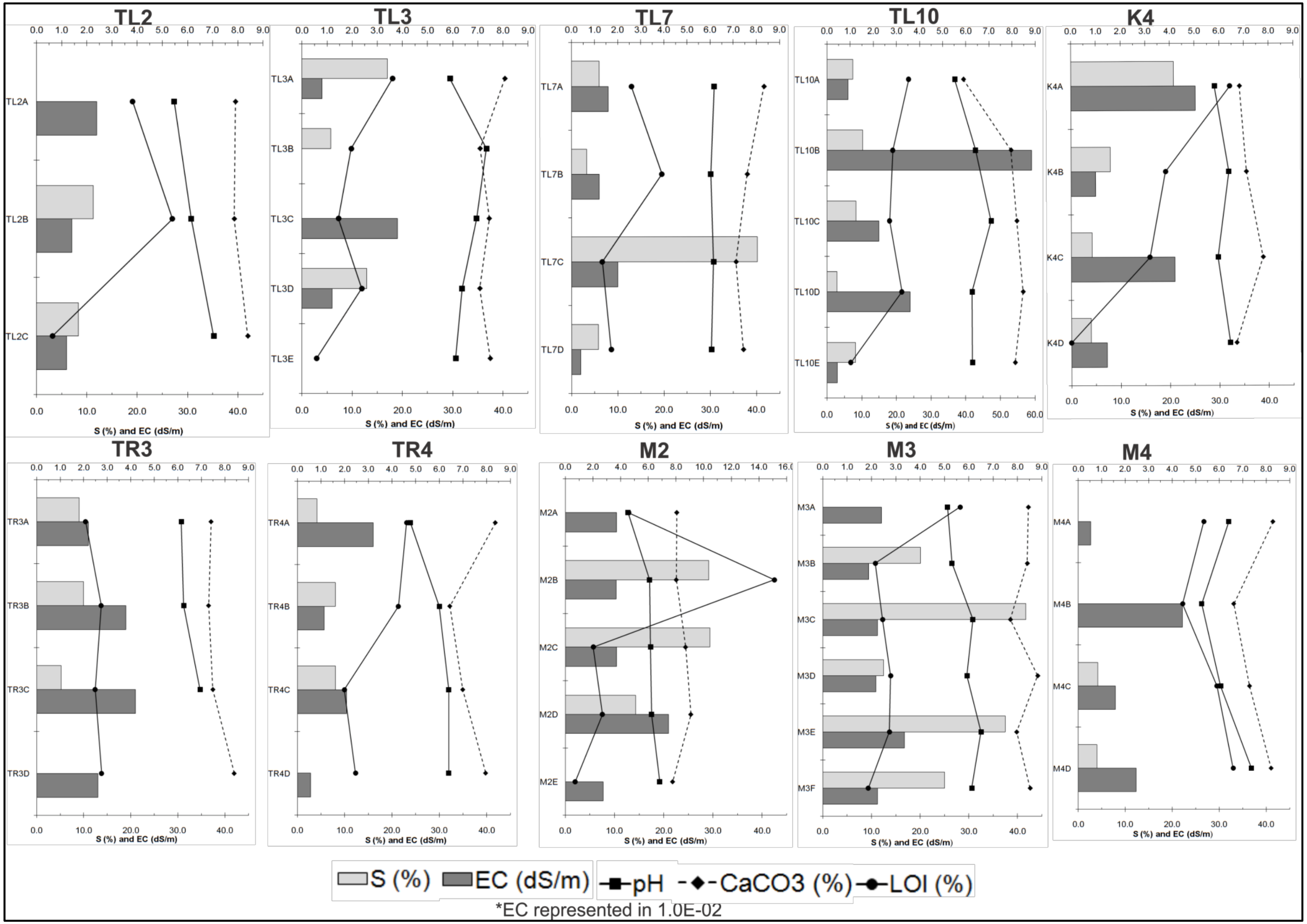


Figure 3.20: Summary of the physical properties of gullies in Makhoaseng catchment.

3.4.7. STRUCTURAL CONTROL

A tunnel was found at the head area of TL3 on the 5th of March 2011. The tunnel could fit three grown adults and was 8 paces in length (1 pace ≈ 70 cm), ending at the site of a collapsed pipe (see multimedia in Appendix C). The presence of a tunnel indicated that there was good subsurface connectivity in this gully system and dispersive soils (Goldsmith and Smith, 1985). The discovery of the tunnel spurred the sketching of a geological transect across gully TL3 to ascertain the influence of geology. The cross section through TL3 is presented in Figure 3.21 (dashed line in Figure 2.6).

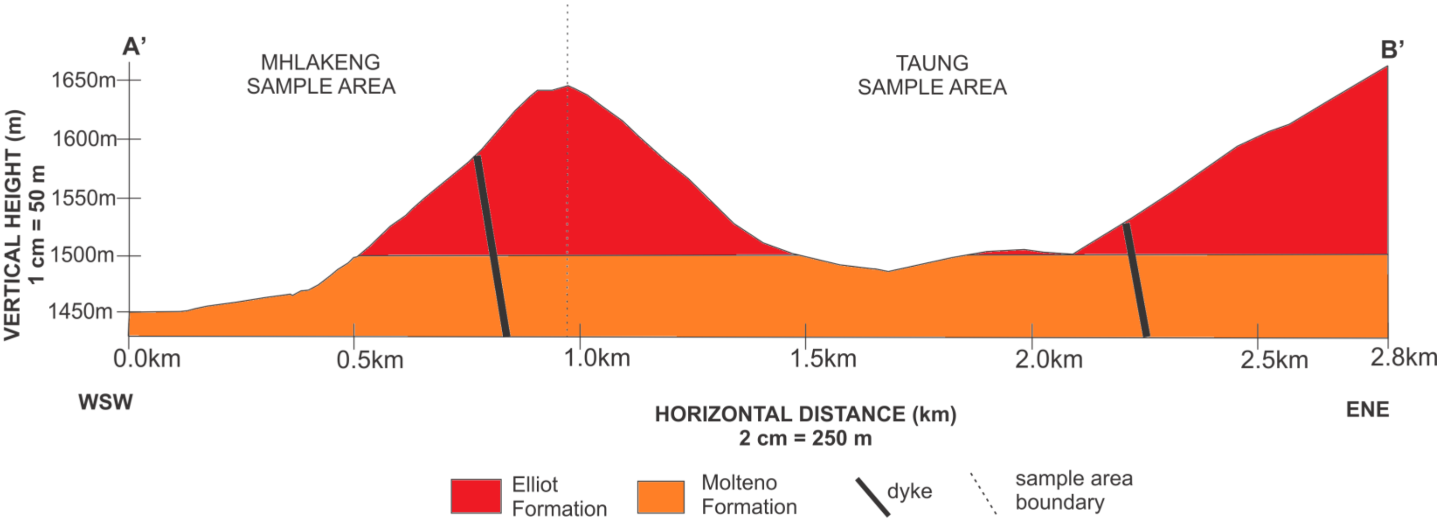


Figure 3.21: Cross section A' - B' of the structural considerations in the Mhlakeng and Taung sample areas.

The geological cross section profile shows that the Molteno Formation is exposed at the valley bottom and footslope zones of both the Taung and Mhlakeng sample areas.

The cross section profile above indicates that there were two dolerite dykes that influenced the local surface water and groundwater interactions in the Taung sample area. The two dykes form a hydraulic trap environment in the Taung sample area i.e. they compartmentalise the sample areas. Showers (2005) observed that the impermeability of dolerite dykes in the Lesotho lowlands causes underground water to move slowly. This has implications for hydrology and soil mineralogy (Showers, 2005).

3.5. DISCUSSION

Results from Makhoaseng catchment indicated that gullying was largely concentrated in the Taung sample area. Soil loss results show that this sample area had lost the most sediment. This finding was further supported by the percentage area of the catchment that was gullied which was greater than the other two sample areas. This was not surprising as Chorley *et al.* (1985) observed that smaller catchments have higher sediment yields when compared with larger ones. The density of gullies and concentration of poorly vegetated areas in this sample area may be a result of good lateral and longitudinal connectivity as smaller catchments have fewer buffers, barriers and blankets. Furthermore, the intensity and scale of agricultural activities historically in this sample area may be a contributing factor to the observed severity of gully erosion. Bedrock steps were evidence of blankets in the gully systems in the Taung sample area. However, contrary to normal blanket function, the exposed bedrock at the gully toe worked to create a local base level, thus encouraging headward erosion and piping.

Connected systems in Makhoaseng catchment were exemplified by gullies that were connected to the drainage lines or river channels. Unconnected systems include gully systems that were in mid-slope or footslope positions but had not connected to the main channel or tributary. Partially connected gullies were represented by gully fan areas that when wet were susceptible to rilling, thereby transporting sediment to the main channel during rainfall events or in the wet season. Gullies in the Taung sample area formed a coupled system evidenced by continuous gullies and seepage feeder zones at the lower mid-slope region.

Gully types dominant in the sample areas were Types 6, 7 and 8. The first two types were indicative of the surface-subsurface water interactions in gully formation. Type 8 gullies lacked the subsurface component, which may be a result of soil mineralogy and drainage. The above mentioned gully types represented the scope of young to well established gullies in the catchment. The age of gullies was further supported by the South African Sugar Association Experiment Station (1999) which states that red apedal B and yellow-brown apedal B soils (e.g. Hutton and Clovelly Forms) represent old and mature freely drained soils. The maturity of the soils, particularly in the Taung sample area, may be a result of the colluvial host material in which the gullies were entrenched. Dardis *et al*. (1998: 204) observed that Type 6 and Type 7 gullies were largely found in stratified colluvium.

Soil profiles in Makhoaseng catchment were devoid of an A and O horizon. This was be interpreted in two ways, either they have been stripped by erosion or cultivation has led to their disappearance. Profile K4 in the Lower Khamopele sample area had an inverted E horizon. This profile was indicative of either the Kroonstad Form or mixing via farming practices. The Kroonstad Form is highly erodible and farming is discouraged in this form as it is a poorly drained soil (South African Sugar Association Experimental Station, 1999).

Most soil profiles indicated the dominance of the B-horizon, particularly the yellow-apedal B horizon as classified by the Munsell Colours. Soil forms that were characteristically yellow were the Clovelly (well drained), Avalon (poorly drained) and Constantia Forms (poorly drained). The B horizon is by definition a zone of illuviation (Soil Classification Working Group, 1991). Therefore, there was cause to believe that this horizon would be enriched in soluble material. However, EC results indicated that majority of gullies had low concentrations of salts due to piping and leaching, thus decreasing salinity.

Soil Classification Group (1991) describes yellow-brown apedal B horizon soils as forming where there is an oscillating or seasonal water table. Although there was periodic wetting and drying of the soil in the catchment, these soils were not gleyed. According to the Soil Classification Working Group (1991) the grey colour in soils points to gleying within the horizon. Gleying is associated with reduction; grey colours are associated with soils devoid of iron bearing minerals and those with greenish tints indicate enrichment in iron minerals (Soil Classification Working Group, 1991; Hazelton and Murphy, 2007) e.g. soil profile M4. Soils collected from the former wetland soil were grey in colour, indicating saturation and poorly drained soils. The evidence provided by colour and water saturation marks indicates that soils in Makhoaseng catchment were hydromorphic.

Soils that exhibit the red apedal B horizon of the Hutton Form are mostly found in dry and warm areas (Fey, 2010; Soil Classification Working Group, 1991). The red colour is associated with haematite. However, if acidic moist and cool conditions prevail the soils are more likely to have a yellow-brown colour due to the presence of goethite (Fey, 2010). This suggests that soil in the Taung sample area had more goethite than the Mhlakeng and the Lower Khamopele sample areas.

Regarding soil forms, soils in the catchment were largely oxidic (Clovelly, Hutton and Constantia Forms) although lithic (Mispah, Cartref) soils were present. Fey (2010) found that oxidic soils indicated freely drained soils and that apedal soils were associated with high rainfall areas such as the Khamopele River catchment. The Cartref and Constantia Forms are highly erodible and the Mispah Form lacks the capacity to retain soil moisture (South African Sugar Association Experimental Station, 1999). These factors create the conditions necessary for soil erosion to find widespread dominance in the catchment.

Soil pH results indicated that soils in the catchment were acidic, making them unproductive (Fey, 2010; Hazelton and Murphy, 2007). Mandiringana *et al.* (2005) found soils in the adjacent quaternary T34D to be acidic too. Charman (2007) points out that acidic soil is indicative of leaching, particularly in sandy soils. Leaching is associated with wet conditions, in line with the humid zone that this catchment lies in. The soil pH results indicate that soils in the Makhoaseng catchment range from mesotrophic to dystrophic.

Acidic soils are often associated with low EC values. High rainfall areas also have low ECs, low EC shows structural problems in soils (Sandor and Estrada, 2008). All these factors point to the lack of plant nutrients in catchment soils (Semple and Johnston, 2007).

There was a direct relationship between aggregate stability and organic matter content. Logically, vegetation stabilises soils making them resistant to erosion. High aggregate stabilities show less erodible soils, whilst low aggregate stabilities indicate erodible soils. Gullies in Mhlakeng sample area had high aggregate stability and organic matter content when compared to Taung sample area gullies. This further showed that soils in Taung sample area were more erodible when compared to Mhlakeng sample area soils.

Low calcium carbonate results further confirmed that the soils were unstable as calcium carbonate is responsible for the formation of stable aggregates by replacing the Na^+ cation in soils (Bashour and Sayegh, 2007; Charman, 2007). Again the

Taung sample area had low $CaCO_3$ indicating subsurface influence in soils and erodibility. In addition to the structural weakness of the soils in the catchment, the presence of piping, duplex soils and prismatic and columnar B horizons suggested that soils in the catchment were sodic (Beckedahl *et al.*, 1998; Summer and Meiklejohn, 2000; Paige-Green, 2001; Charman and Murphy, 2007).

The geological cross section of the catchment showed that the Molteno Formation was exposed in valley bottom areas. This formation largely consists of shales and mudstone towards the contact with the Elliot Formation (Johnson, 1976). Rowntree *et al*. (1991) found that the Molteno Formation was highly erodible. The fining upward sequence of the Elliot formation creates steep slopes as shown on the DEM as there are layers of variable resistance with a thin cover of soil.

In oil and gas studies, shales and mudstones are termed cap rocks as they are impermeable (Bjorlykke, 2010). In this catchment the rocks of the Molteno Formation form an aquitard, indicating the presence of a perched water table. Evidence of a perched water table was provided by the presence of springs, seepage zones, mottling and piping in the sample areas.

Another factor promoting water concentration in the Taung sample area was the dolerite dykes. They formed a barrier between groundwater flows, thereby increasing saturation in lower soil horizons as water will saturate those layers the longest. This may also explain the low EC values in the lower soil horizons. Gattinoni and Smith (1985) state that shallow groundwater levels promote tunnelling and (or) piping. This may be pronounced during the wet season where the soil becomes thoroughly saturated by both surface and groundwater.

3.6. LIMITATIONS AND FURTHER RESEARCH

The mapping of gullies was limited by the available time, travel distance to site and terrain in the catchment. The sampling effort could have been extended in the Lower and Upper Khamopele areas to get more comparable results across the three sample areas.

Surveying could have included the use of geodetic survey equipment. The equipment utilized was lightweight and portable but not as precise as a dumpy level or total station. Furthermore, not every gully was measured. The most accessible gullies were measured.

Perhaps an approach for future work would be to determine the volume lost from gullies using a time series of photographs and earth observation imagery to estimate the volume loss and rate of erosion in the Khamopele River catchment. This can be compared against measured gully dimensions in the field to bring confidence in the volume and soil loss estimation results.

The dominant types of erosion in the Khamopele River catchment were Type 6, Type 7 and Type 8 erosion features. Type 3 and Type 5 erosion features were also present but were not discussed in depth. Type 1 features were also present. Future work could quantify all of the erosion types in a sample area and show how over time the erosion types have intensified or graded into other types and the factors promoting the change.

One of the lead indicators of an erodible soil is soil salinity. This research did not fully incorporate salinity and as such is lacking in the comprehensive description of the factors that promote soil erosion in Makhoaseng catchment. Future work could establish the salinity of soils in the catchment and its impact on the erodibility of soil.

Lastly, sediment production rates could not be calculated as erosion pins were not found at the last site visit (29 July 2011) which would have coincided with the year interval. Therefore, these results cannot be extrapolated for sediment yield calculations.

3.7. CONCLUSION

This chapter has described the physical properties of soil and topographic controls that influence and enhance soil erosion in the Khamopele River catchment. Results show that the Taung sample area, which was the smallest sample area, had the highest amount of volume loss and the area with the highest number of gullies by percentage area.

Soil erosion in Makhoaseng catchment is controlled by surface and subsurface flow. Most soils were loamy sands and acidic in nature. Grey soil horizons, mottling and low electrical conductivities indicated that the catchment experiences periodic saturation caused by structural and climatic controls. Gullies in Makhoaseng catchment indicate that sample area size and connectivity play and important role in sediment studies.

CHAPTER 4

TRACING SOURCE AREAS USING ENVIRONMENTAL MAGNETIC AND RADIONUCLIDE TECHNIQUES

4.1. INTRODUCTION

Sediment tracing is an overarching description of the use of specific properties of a component in the environment such as soil to differentiate source types in catchment studies (Motha *et al.*, 2004). Common tracer properties include soil colour, organic matter, particle size, plant pollen, mineral magnetic signatures and geochemical properties (Motha *et al.*, 2004; Walling, 2005). Recent tools in sediment fingerprinting studies such as environmental magnetism and radionuclide dating have enabled researchers to more accurately interpret the erosion-transport-deposition history of data poor catchments. The emergence of environmental magnetism and radionuclide dating techniques allows researchers to begin to better inform environmental management practitioners because the underlying principles of sediment connectivity and conveyance in the landscape are better understood.

This chapter presents the application of sediment tracing to the Khamopele River catchment. First, a review of mineral magnetic tracing and radionuclide dating literature is presented followed by the application of the techniques as used in the study catchment in the methods section. Results obtained from the Khamopele River catchment are presented followed by a discussion section and a brief summary of the chapter.

4.2. ENVIRONMENTAL MAGNETISM

Sediment tracing uses natural magnetic properties of materials and has gained much popularity since the late 1990s because magnetic properties can be used as proxies for environmental processes in catchment studies (Caitcheon, 1993; Dekkers, 1997). Magnetic minerals are introduced into the earth by volcanoes, rock forming processes, erosion-transport-deposition processes, pedogenesis, anthropogenic activities and magnetotactic bacteria (Evans and Heller, 2003). The widespread occurrence of such minerals has seen the application of environmental magnetism techniques being extended to the fields of hydrology, sedimentology, geomorphology, archaeology, soil science, oceanography and land use studies (Verosub and Roberts, 1995; Dekkers, 1997; Dearing, 1999). The popularity of the technique arises from four main factors: namely that the method is fast, cheap, non-destructive and simple (Caitcheon, 1993; Verosub and Roberts, 1995; Poręba, 2006). Dekkers (1997) finds that the ability of magnetic techniques to detect mineral grain sizes allows them to be used in tandem with geochemical techniques, thus making their application extensive. Caitcheon (1993) proposes that this technique is applicable to tracing sediment at any scale where there is a confluence from two catchments, thus lending environmental magnetism greater scope. Its use in the soil sciences as a tracer is perhaps the most widespread use of environmental magnetism (Evans and Heller, 2003).

In South Africa, mineral magnetic techniques have been used by Foster and Rowntree (2010) in correlating sink zones to source areas in small farm reservoirs in the Eastern Cape Karoo. Boardman and Foster (2008) have used the technique in badlands in the Karoo to establish a sediment transport history in the small catchment using magnetic signatures from cores to identify catchment sources of erosion. Caitcheon (1993) shows that in Australia, environmental magnetism has been successfully used to differentiate suspended load and bedload in source type ascription. The latter study shows that environmental magnetism techniques are also applicable in fluvial systems, as Walling (2005) also shows in a more recent study.

Magnetic susceptibility

Magnetic susceptibility can be defined as the "ratio of induced magnetization acquired by a sample in the presence of a magnetic field (Verosub and Roberts, 1995; 2176)." Minerals that receive the most attention in the field of environmental magnetism are the iron bearing minerals that occur naturally and abundantly in the lithosphere (Dearing, 1999; Evans and Heller, 2003). The iron oxides magnetite (Fe_30_4) and haematite (α-Fe_20_3) are the most acknowledged tracer minerals in magnetic studies as they indicate iron enrichment in terrestrial environments (Sager and Hall, 1990; Smith, 1999). Both haematite and magnetite are secondary minerals found as part of pedogenic processes (see Figure 4.1); the difference is that magnetite is generally associated with igneous rocks as part of the low temperature fractionation process whereas haematite is a naturally occurring mineral in sedimentary rocks (Oldfield, 1999; Evans and Heller, 2003; Liu *et al.*, 2007; Frank and Nowaczyk, 2008). Other important minerals in magnetic studies include maghaemite (γ-Fe_2O_3), goethite (α-Fe_2O_3), greigite (Fe_3S_4) and illmenite ($FeTiO_3$) (Oldfield, 1999).

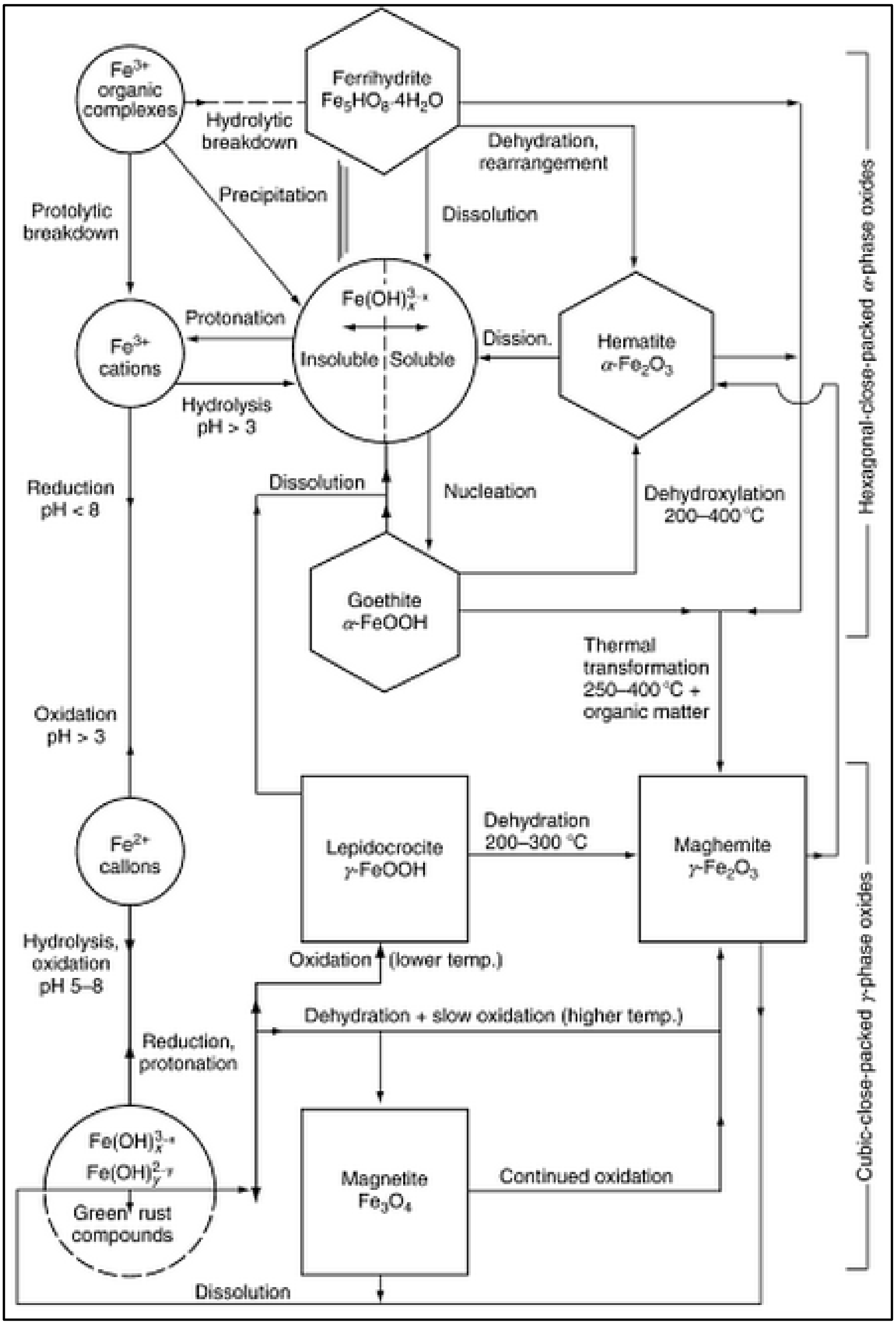


Figure 4.1: Iron oxide formation and transformation (Chesworth, 2008: 366).

The application of magnetic techniques is not limited to the above mentioned iron oxides, hydroxides and sulphides. Verosub and Roberts (1995) note that all substances on Earth have some form of magnetism, even if it is in trace amounts. All materials on Earth exhibit one of the following types of magnetism: ferrimagnetism, ferromagnetism, antiferromagnetism, paramagnetism and diamagnetism (Dearing, 1999; Evans and Heller, 2003). Each of these types of magnetism has a characteristic susceptibility, which begins to point researchers to the mineralogy and provenance of that particular sediment (Evans and Heller, 2003). A summary of the types of magnetism is presented next.

Diamagnetism

All materials have some form of diamagnetism when exposed to a magnetic field because electrons carry a charge and this interaction creates a small magnetic moment (Evans and Heller, 2003). This type of magnetism is characterised by the absence of unpaired electrons (Smith, 1999). In the presence of a magnetic field diamagnetic substances have a weak and a negative magnetic moment (Butler, 1992). Magnetization is removed when the external field is removed. Examples of diamagnetic materials include calcite, silicates, organic matter, calcium carbonate and water (Dearing, 1999; Evans and Heller, 2003).

Paramagnetism

This type of magnetisation arises from two magnetic spin moments because of the unpaired electron(s) (Evans and Heller, 2003). The electron therefore spins on its own axis around the nucleus (Evans and Heller, 2003). Minerals that exhibit paramagnetic properties have a small positive permanent magnetic moment. Magnetization is removed when the external field is removed (Evans and Heller, 2003). Examples of paramagnetic materials include biotite, olivine and ferrous sulphides.

Antiferromagnetism

This type of magnetism arises from equal strengths but opposite magnetic orientations in the crystal structure, it is also known as “canted” antiferromagnetism (Dearing, 1999; Evans and Heller, 2003). The magnetization is zero but due to grain defects, spin canting and vacancies, a weak magnetization can be detected (Solheid *et al*. 2003; Foster, 2010a). According to Dearing (1999) haematite is the most commonly occurring mineral in this group.

Ferrimagnetism

Found in most soils, this magnetism is characterised by strong magnetic forces in opposing directions (Butler, 1992; Dearing, 1999). Examples of ferromagnetic minerals include magnetite, pyrrhotite and greigite (Dekkers, 1997).

Ferromagnetism

Ferromagnetism occurs in natural elements and is greater, in susceptibility, than the aforementioned types of magnetism (Dearing, 1999; Evans and Heller, 2003). This type of magnetism is found in substances that have pure iron, nickel and cobalt (Dearing, 1999). The atoms are closely and regularly spaced and have magnetocrystalline anisotropy (Evans and Heller, 2003). The alignment of magnetic moments is uniform and is a result of overlapping orbitals which gives rise to strong magnetization (Foster, 2008). This type of magnetism arises due to unpaired electrons in the 3*d* subshell (Evans and Heller, 2003). In the absence of an external field there is spontaneous magnetization (Dearing, 1999).

Canted antiferromagnetic, ferrimagnetic and ferromagnetic substances are useful in tracer studies as they indicate sources, alteration and sediment changes in the catchment. Environmental magnetism can therefore be seen as a valuable tracing technique that can be used to study physical processes such as deposition-transport-erosion processes in palaeo and contemporary environments.

PROCEDURURAL STEPS IN MAGNETIC STUDIES

Literature indicates a six step process that has been widely adopted in mineral magnetic studies. These steps are shown in Figure 4.2 and they have been applied in this study. The first step is measurement; descriptive variables and remanence of soil samples are measured. Step two is a correction step as there is error in every measurement; however, correction of data provides a reliable baseline from which data can be interpreted. Each catchment has site specific lithologies, soils and rainfall patterns. Therefore, the researcher must select variables that best describe the action taking place in the catchment. This involves selecting useful and applicable indicators of source areas (Step 3). The interpretation (Step 4) of results is a pivotal step that begins to explain the erosion, depositional and transport history.

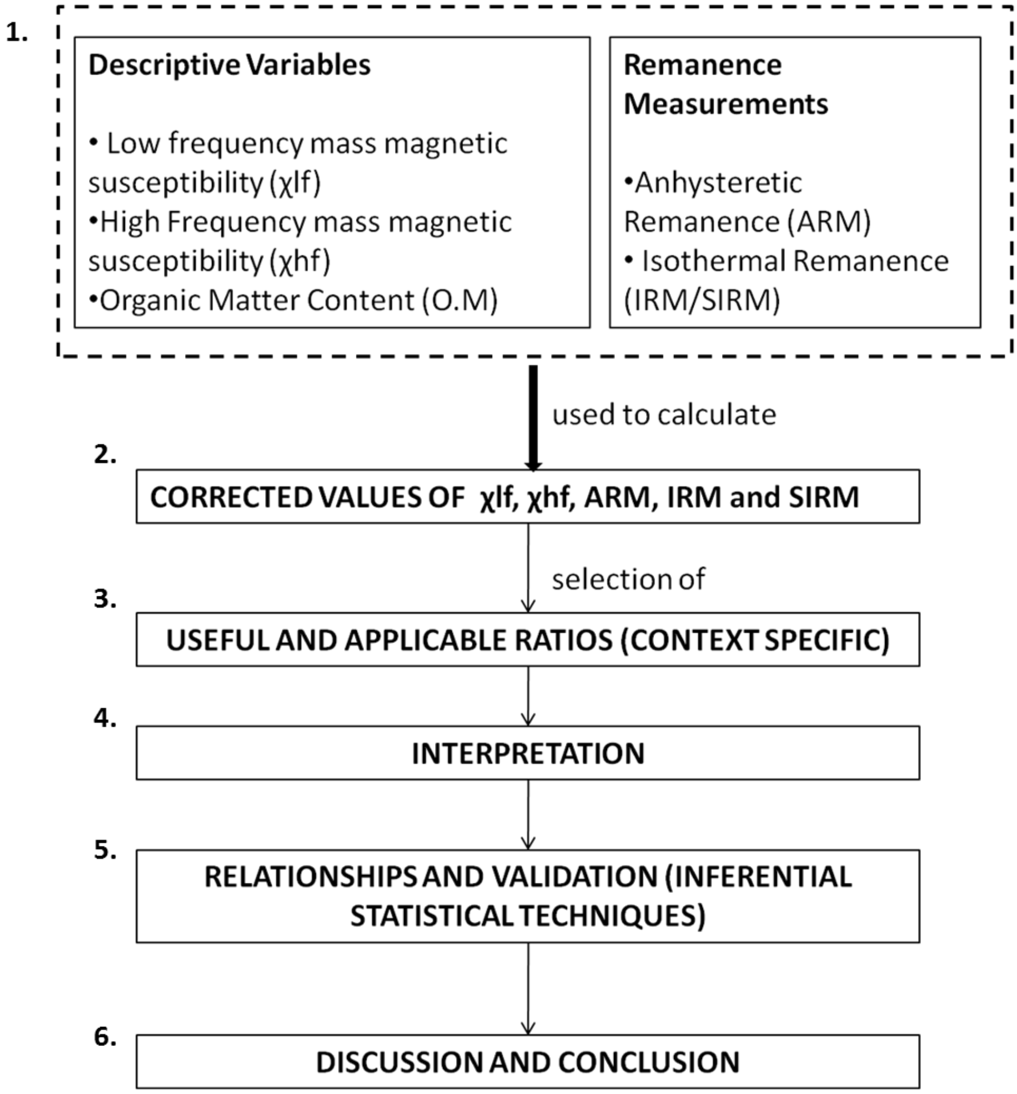


Figure 4.2: General mineral magnetic studies structure based on literature searches.

To test the validity of the observation, statistical methods are used to further explain and understand the findings (Step 5). Lastly, every report details the findings of the study indicating areas of divergence or convergence with literature and a conclusion of the study (Step 6).

4.3. RADIONUCLIDE DATING

In recent years, a number of studies in geomorphology have investigated the use of radionuclide fallout in interpreting catchment history. To achieve this, studies employ three methods to determine chronology: historical, absolute and relative dating (Foster, 2008; Church, 2010). Absolute dating is the focus of this study as radionuclide dating was piloted in the southern Drakensberg catchment to quantify the erosion rates in the Khamopele River catchment. In the scientific community, radionuclide dating has long been used to develop chronologies in sediments and geological units. Radionuclide dating is similar to environmental magnetism in that it also uses proxies, in the form of naturally occurring elements, to provide environmental information that indicates history and process (Foster, 2008).

4.3.1. CAESIUM-137

Radioactive material can be introduced in to the Earth's surface in three ways. The first is through materials that were present at the formation of Earth and have subsequently been reworked into the lithosphere (Noller, 2000). The second is cosmic ray bombardment in the upper atmosphere (Matisoff *et al.*, 2002). Lastly, radioactive material can be introduced into the environment by humans e.g. nuclear accidents and (or) weapons testing (Leslie and Hancock, 2008). This section presents ^{137}Cs, a radionuclide tracer that has become increasingly useful to the geomorphologist and the reasons it is employed in sediment tracing studies.

Caesium-137 is a by-product of fission in nuclear bombs and has a half-life of approximately 30.2 years (Ritchie and McHenry, 1990; Walling *et al.*, 2003). The Caesium-137 fallout record is useful in sediment erosion and depositional studies because its presence is a marker in the soil profile and as such can be used in chronology studies (Ritchie and Ritchie, 1995; Poręba, 2006). Its usefulness as a tracer stems from the availability of a calibration date as its presence was first detected in 1954, a result of weapons testing in the Northern Hemisphere (Foster, 2010). Most of the fallout has been concentrated in the Northern Hemisphere (Amos *et al.*, 2009).

The peak of weapons testing signifies maximum concentration of ^{137}Cs in the atmosphere and this is estimated to have occurred in 1963 (Porcelli and Baskaran, 2011). Walling *et al*. (1995) suggest that fallout stopped in the 1970s. The Chernobyl disaster in 1986 provided a second injection of ^{137}Cs into the atmosphere, thereby further strengthening the validity ^{137}Cs as a tracer in the Northern Hemisphere. Conversely, this injection of ^{137}Cs has not been detected in the Southern Hemisphere (Tabacova, 1995). Fallout evidence of the nuclear accident has been successfully used as a second calibration date in tracer studies (Golosov, 1999; Mabit *et al.*, 2008). Another advantage to using radionuclide fallout is that concentrations are independent of soil type and geology (Walling, 2005).

^{137} Cs has been used in estimating the rate of erosion/deposition in sediment source zones and accumulation sink areas by comparing the observed concentration to a reference inventory (Matisoff *et al*., 2002; Poręba, 2006). In the absence of a reference inventory, precipitation records are used and the fallout concentration modelled. Porto *et al.* (2001) observe that sources areas are generally depleted in ^{137}Cs accumulations whereas sink zones are marked by ^{137}Cs accumulations. Mabit *et al*. (2008) supports this observation as they observe that on convex slope the abundance of ^{137}Cs is less when compared to the amount found in valleys and footslopes.

With the exception of the Antarctic, tracer studies using ^{137}Cs have been successfully carried out by researchers in three southern hemisphere continents. For example in South America Schuller *et al.* (2002), Schuller *et al.* (2004) and Montes *et al*. (2012) have worked in Chile, Patagonia and Argentina using ^{137}Cs. In Australia Motha *et al.* (2004) and Amos *et al.* (2009) are some of the researchers that have used this technique in detail. Lastly, South African works from Manjoro *et al.* (2012), Rowntree and Foster (2012) and Boardman *et al.* (2010) show the growing interest and applicability of ^{137}Cs as a tracer in sediment studies in Africa.

The use of magnetic and radionuclide tracers has allowed geomorphologists to move away from methods that had a number of errors (Walling, 2005) and begin to embrace a suite of robust tracers to interpret sediment changes at the catchment scale. Their strength lies in the ability to more clearly pinpoint catchment sources of erosion, a pivotal step in catchment management. Dating techniques are not limited to the above mentioned technique and the reader is referred to Matisoff *et al.* (2002) and Shen *et al.* (2008) for further reading on Sulphur, Nitrogen and Potassium-Argon and Optically Stimulated Luminescence (OSL) dating. These are not reviewed here as they were not applied in this research. Other radionuclide tracers that have widespread use in geomorphic studies include ^{210}Pb and ^{7}Be.

4.3.2. CONVERSION MODELS

Conversion and mixing models are used in radionuclide studies to convert recorded counts to erosion rates and quantify the changes in radionuclide concentrations. This section presents common conversion and mixing models. A conversion model was used to estimate the soil erosion rate in the Khamopele River catchment. The model was used to gain quantitative insight to the extent of soil erosion in the catchment. Mixing models were not utilised in the study due to limitations in the study design and sampling.

Conversion models or equations are used to derive soil erosion rates using field radionuclide counts Walling and He (2002) recognise two types of conversion models; namely, empirical and theoretical. The latter is discussed here as the former model is limited in its use as it is catchment specific and requires an extensive soil erosion monitoring record.

Proportional Model: This model is used in establishing soil erosion rates in cultivated soils (Walling *et al*., 2006; Mabit *et al*., 2008). The proportional model requires three variables, namely: the year of first cultivation, bulk density and soil depth (Walling *et al*., 2006). The premise of the Proportional Model is uniform mixing within the cultivation layer (Ritchie and Ritchie, 1995). This model presents a simplistic means to derive soil erosion rates. However, it is riddled with inaccuracies regarding process and measurement (Mabit *et al*., 2008). Weigand *et al.* (1998) remark that enrichment ratios are ignored in this model, thus making its use limited.

Mass Balance Models (MBM): There are three mass balance models that exist; Mass Balance Model I, Mass Balance Model II and Mass Balance Model III (Mabit *et al*., 2008). These models are an improvement on the aforementioned Proportional Model and are largely applicable to cultivated soils (Mabit *et al*., 2008: 1800). Walling *et al*. (2006: 5) list measurements that are necessary for the models, they are: year of cultivation, bulk density, depth, proportional factor and annual fallout flux. The models differ from the Proportional Model in that they avoid the black box approach and aim to account for ^{137}Cs inputs and outputs (Walling *et al*., 2006). These models are generally applied in ^{137}Cs and ^{210}Pb conversions because of their validity (Parsons and Foster, 2011).

Profile Distribution Model (PDM): This model was initially used in ^{137}Cs and ^{7}Be uncultivated soil erosion estimation studies (Walling, 2002) but is now applicable in both cultivated and uncultivated ^{7}Be studies (Walling *et al*., 2011). The PDM model is simple and assumes an exponential decrease of ^{137}Cs in the soil profile because there are no mixing effects to consider (Zhang *et al*., 1990). Its weakness is comparable to that of the Proportional Model as it tends to overestimate erosion rates (Porto *et al*., 2001) and does not account for the migration of ^{137}Cs down the profile over time (Walling *et al*., 2011).

Diffusion and Migration Model: This model takes the Profile Distribution Model further by incorporating the temporal changes in the distribution of ^{137}Cs in the soil profile (Walling *et al*., 2006). The Diffusion and Migration model is used in uncultivated soil studies (Mabit *et al*., 2008). The addition of a migration rate and a diffusion coefficient give this model a greater accuracy compared to the former model (Walling *et al*., 2011).

Despite its limitations, The proportional model was the most applicable model in the study area as determinants such as the fallout flux and other variables necessary in the models were limited or unavailable.

4.3.3. MIXING MODELS

Mixing models are used because the movement of sediment from the catchment to the reservoir incorporates a number of complex processes during transport. Mixing occurs within a catchment, during transport and with sediment derived from other catchments and tributaries. This decreases the probability of a unique signature downstream, thus making mixing models necessary in radionuclide and environmental magnetic tracer studies as they provide a way to distinguish these sources (Stott, 1986).

The Monte Carlo Mixing Model is used in sediment fingerprinting studies and as Motha *et al*. (2004) point out, it is a scaled up model of that proposed by Bazemore *et al*. (1994) and Rowan *et al.* (2000). It is rooted in Bayesian Statistics and aims to account for uncertainty arising from mixing in sink zones (Walling, 2005). Very few authors outline the model in depth in sediment studies but Collins *et* al. (1997), Krause *et al*. (2003), Motha *et al*. (2004) and Walling (2005) describe corrections that need to be made before the model can be used. These include particle size and organic matter. Further statistical tests are recommended to ensure the validity of selected source types before input into the model.

4.3.4. CONTEXT OF PROPOSED RESEARCH

The research to be conducted finds its purpose in the work conducted by Meade (1982), who called for better quantification of source and storage zones in dealing with high sediment loads in rivers. Other similar work was that of Caitcheon (1993) who studied where sediment was derived in the Murrumbidgee and Ord Rivers in Australia. Literature clearly points to a need to investigate sediment dynamics at the catchment scale and then put this information in the context of the regional scale. In light of the above, this study aimed to identify and determine the location of the major sediment sources in the Makhoaseng catchment using selected environmental magnetic tracers and the radionuclide ^{137}Cs. A conversion model was used to interpret the results of radionuclide data collected in the catchment.

Further support for using magnetic signatures in the Khamopele River catchment was found in Wang *et al.* (2011) who used mineral magnetic signatures to discriminate between sediment production areas in two catchments in China by looking at reservoir sediments. Foster *et al.* (2008) were able to use mineral magnetic signatures taken from a core to deduce that sediment sources have shifted over time in an Egyptian lake. Similarly, Rowntree and Foster (2012) have used a combination of mineral magnetic and radionuclide dating techniques to establish dates and correlation of palaeo-sediment sources in a Karoo catchment. Grenfell *et al*. (2012) have been able to show that radionuclide dating can bring a new perspective on theories regarding erosion-depositional cycles in the contemporary environments.

In conclusion, environmental magnetic tracing techniques allow researchers to use iron oxides in naturally occurring substances, such as soil, to characterise and make inferences on source area mineralogy. Radionuclides such as ^{137}Cs and ^{210}Pb have allowed Earth scientists to better understand the timing of events in catchments and quantify significant events in catchment history.

4.4. METHODS

A quantitative research design approach was adopted to address objective c i.e. to employ environmental magnetism and gamma spectroscopy techniques to identify sediment source areas matched to data from sink zones. Environmental magnetism and radionuclide tracer techniques were used to identify sediment source areas in the catchment and compare to temporary and permanent sink zones in the upper Tina River catchment. Mineral magnetic signatures were used to determine whether gullies continued to be point sources of erosion in Makhoaseng catchment.

The environmental magnetism technique makes it possible to not only determine erosion sources in Makhoaseng catchment, but to determine whether sediments were similar to sediment found in sink zones or other sample areas in quaternary catchment T34A. Radionuclide dating was used to detect the presence of ^{137}Cs in the Khamopele River catchment and Mt Fletcher Dam. The use of both techniques is advantageous as it ensures that the entirety of the problem is addressed i.e. the questions of “where” and “how much” are addressed.

4.4.1. SAMPLING DESIGN

A longitudinal survey design was adopted for the data collection phase of the research. Multi-stage cluster sampling took place on three visits to the catchment to coincide with the pre-rainfall season (7 - 12 September 2010), end of rainfall season (2 - 7 March 2011) and dry season (28 - 29 July 2011). All samples were collected using a plastic spatula to eliminate contamination. Where a greater sample was needed e.g. gullies, a non-metallic trowel was used.

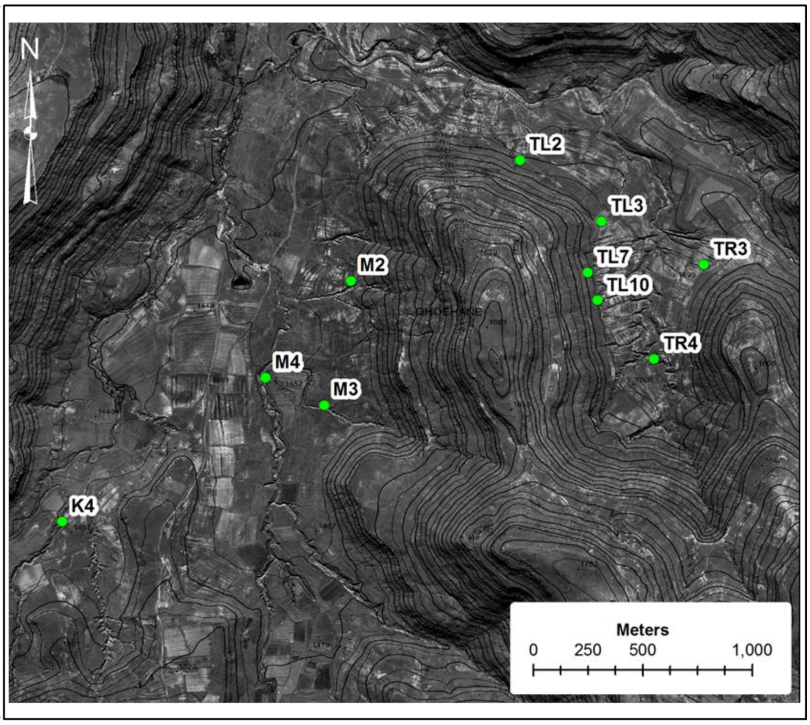
The following section describes the sampling localities, method of collection and the number of samples obtained from source areas.

Gully sidewalls

In total, 44 soil samples were collected from soil horizons exposed in gully sidewall profiles. At the site of soil collection horizons that were distinct from overlying or underlying horizons was selected and measured. The lateral persistence of the horizon was gauged and a minimum of three samples were collected from the same horizon upslope or down slope (west to east) of the first collection site. A minimum of 300 g of sample was collected. The soil was sealed in a PVC plastic bag and stored for further analysis.

Table 4.1: Summary of the number of samples collected in gullies.

Gully	Number of samples collected
TL2	3
TL3	5
TL7	4
TL10	5
TR3	4
TR4	4
K4	4
M2	5
M3	6
M4	4
SUM	**44**



Streambed material

A sample was collected at each of the confluence thalwegs in Makhoaseng catchment during the low flow months. Additional soil samples were collected in-stream in islands and point bars. A non-metallic trowel was used to collect samples on bars at the water interface (if available) and just above the watermark to get a good mix of sample. The soil sample was deposited into an empty PVC bag and sealed. A minimum of 150 g was collected for each sample. In total 30 samples were collected; 9 from bars and islands (temporary storage zones) and 21 from confluences in the catchment.

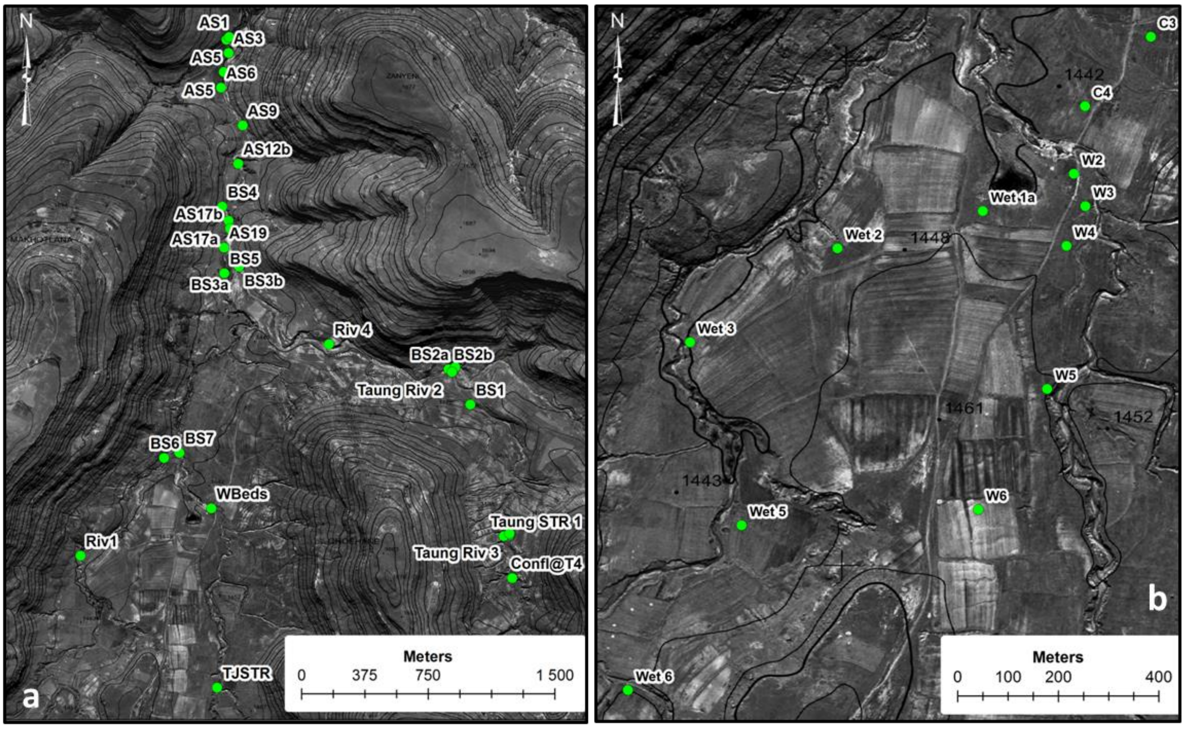


Figure 4.3: Sample locations for streambed material (a) and Mhlakeng topsoil (b) samples.

Topsoil

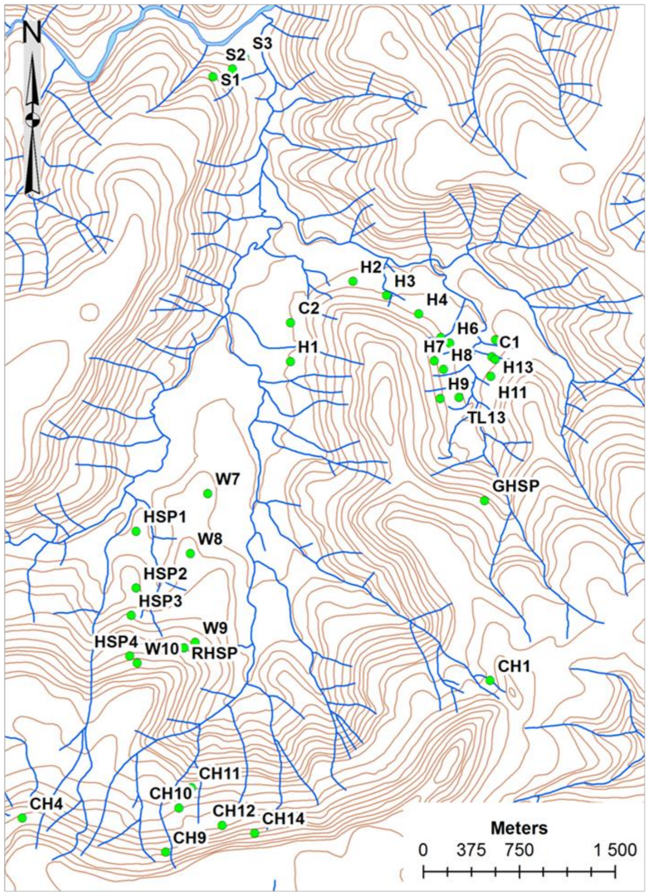
Topsoil samples were collected from the first 5 cm in the soil profile using a spatula/trowel in the Mhlakeng and the Lower Khamopele sampling areas. A number of scrapings from the surrounding area and under clumps of grass were collected to reach a minimum weight of 125 g. In total, twelve samples were collected from the catchment in a convenience sampling run (see Figure 4.3b).

Hillslopes

Hillslope samples were collected from all three sampling areas in Makhoaseng catchment at mid-slope and lower slope sections. Soil samples were also collected on slopes behind the village towards the drainage divide. Hillslope samples were collected in a similar manner to topsoil samples, ensuring intra-locality mix of sample by collecting surficial samples (approx. 5 cm) around the first scraping. A minimum of 100 g was collected at every sample site. In total 37 hillslope samples were collected.

Table 4.2: Summary of hillslope samples.

Sample Area	Number of samples collected
Taung	16
Mhlakeng	8
Lower Khamopele	6
Slopes behind village	7
Sum	**37**



Quaternary derived samples

Samples collected outside the Makhoaseng sample areas and the Khamopele River catchment were opportunistic in nature and were collected when leaving and entering the study area at the major rivers e.g. Phiri-e-Ntso, Vuvu, Tinana. Another group of samples that was collected in this manner were the basalt samples collected during a visit by Professor Rowntree to the Bell River catchment. The basalt samples characterise the Drakensberg Group in the higher altitude areas of the uMzimvubu catchment.

Samples from the main rivers were collected from instream islands, point bars and the river banks. The basalt samples were collected at the intervals 0 - 10 cm, 450 cm and 100 cm and exceeded 50 g per sample. Samples from rivers in the quaternary catchment had a minimum of 250 g in weight. In total 17 soil samples were collected, 5 basalt samples and 12 samples from the quaternary catchment rivers and banks.

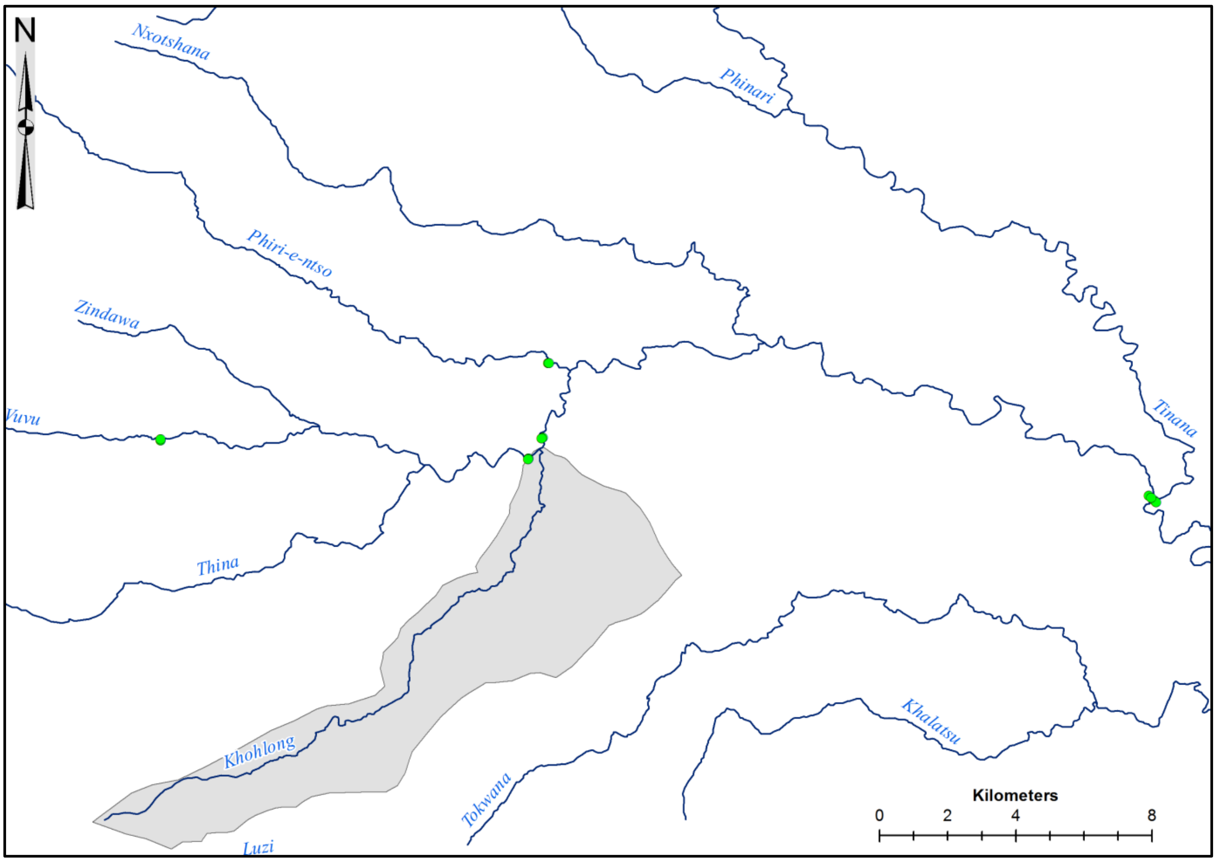


Figure 4.4: Sample locations for sediment derived outside the Khamopele River catchment (green circles indicate sample points)**.**

Cores

The Tina Dam core (TDC) was taken at location 30°37'16.79"S and 28°28'50.65"E at Mount Fletcher Dam. This was a representative sink zone area and was sampled to characterize sediment derived from quaternary catchment T34A. A Mackereth corer (see Figure 4.5a) constructed for the Rhodes University Geography Department was used to collect the 84 cm core. The Mackereth corer is a device that is used to collect surface sediments from rivers and marine environments. It is driven by pressure and soft sediment is collected in a tube that can reach depths of up to 6m (Loughran *et al.*, 2002; Goudie *et al.*, 2005).

Figure 4.5: Sampling in Mt Fletcher Dam (a) and sample preparation on site (b).

Sediment in the core was sectioned off, as shown in Figure 4.5b, from the top to the bottom at 2 cm intervals using a shaved plastic petri dish. The 2 cm core slice was placed in a PVC bag and sealed. In total forty-two 2 cm core slices were obtained with weights ranging from 50 g to 73 g.

The Tina River core (TRC) was taken at a bar (30°36'17.81"S and 28°19'1.05"E) below the confluence of the Tina and Khamopele Rivers. The TRC was taken to determine the mineral magnetic signature of sediment leaving the Makhoaseng catchment and that of the upper Tina River in the river segment. An Eijkelkamp® percussion auger with extension rods was used to collect the 88 cm core. The auger contains plastic tubing to collect the sample in the chamber with the following dimensions: 5 cm diameter and 30 cm length. In the laboratory, the core was cut into 2 cm slices using a plastic knife/spatula to avoid altering the magnetic signature of the sediments. In total, 36 soil sample sections were obtained with weights ranging from 22 g to 81 g.

Table 4.3: Summary of sample areas and number of samples collected in source area.

Source Area	Number of Samples
Tina River Core	42
Tina Dam Core	36
Hillslopes	37
Gully sidewalls	44
Streambed material	30
Topsoil	12
Quaternary 34 (samples collected outside the Khamopele River catchment)	12
Basalt	5

4.4.2. SAMPLE PREPARATION

Soil samples were dried at temperatures below 40ºC at the Rhodes University Geography Department Soils Laboratory to preserve magnetic signatures. After drying, soils were sieved and the less than 63 µm fraction was used for all magnetic and radionuclide analyses to minimize particle size effects. The organic matter content for each sample was determined using the loss on ignition method with the temperature set at 450 ºC. For samples to be tested using environmental magnetism techniques the weight of the empty pot (10 cm^3) and the pot containing the soil sample were measured and recorded. Approximately 10 g was inserted into the sample pot and a pestle, designed for use with the pots, was used to compact the samples. Cotton wool was inserted on top of the compacted soil before sealing the pot to ensure that soil was not redistributed during and before measurement. Samples were labelled accordingly and processed.

Similarly, for soils to be used for radionuclide analysis, the weight of the empty vial and packed vial were recorded. Soil samples were packed into OD PTFE vials (Foster *et al.*, 2007). Each sample was inserted separately into the detector and left to count 250 000 seconds (max). At the completion of counting, the spectra of the samples were saved and samples removed from the detector.

4.4.3. DATA ANALYSIS AND INSTRUMENTS

In total, 218 soil samples were analysed for mineral magnetic signatures. In the laboratory, χlf, χhf, ARM, SIRM and IRM_{-100} were determined. The measured variables are discussed below.

Mass Magnetic Susceptibility

The environmental magnetic technique is described in detail here as this work forms part of a growing effort by the Catchment Research Group to increase awareness of sediment fingerprinting techniques in the Geography Department at Rhodes University.

The mass magnetic susceptibility of a soil is the base measurement for mineral magnetic studies as it provides an indication of the abundance of the iron bearing minerals present in a sample (Verosub and Roberts, 1995). To measure this variable, the Bartington MS2B Dual Frequency Sensor® was used to measure high frequency (4.7 Hz) and low frequency (0.47 Hz) susceptibility in collected soil samples.

The Bartington MS2B Dual Frequency Sensor® requires a warm up period of 15 minutes at the measure (M) position before measurement can begin. The metric scale (SI units) was selected and the dial at 0.1 to achieve laboratory precision in measurements. The dial at the back of the sensor was set to Low Frequency (LF) and the instrument zeroed so that measurement could begin.

Low frequency measurements were completed first followed by High Frequency (HF) measurements. To measure magnetic susceptibility at low (χlf) and high (χhf) frequency a plastic pot was inserted into the sensor with the pot cap facing a single marked direction. The toggle switch was disabled. A measurement was obtained by pressing the (M) button and waiting for the reading on the screen after a 10 to 15 second period. The “air before” and “air after” readings were also recorded with each measurement to ensure that errors due to instrument drift were minimized. The “air before” reading is the measurement of susceptibility prior to sample insertion, the “air after” is the susceptibility reading post sample measurement. The procedure mentioned was followed for all magnetic susceptibility measurements.

After all analyses had been completed, the organic matter content of each sample was determined by igniting the sample at 450 °C for 12 to 16 hours in a muffle furnace. Thereafter, the percentage of organic matter was determined by weight differences of the sample before and after ignition. Organic matter was measured as it influences magnetic susceptibility measurements due to its diamagnetic nature. Diamagnetic materials can weaken the true content of iron bearing minerals in a given sample (Walling, 2005).

Anhysteric Remanence (ARM)

There are a number of ways that a sample can gain remanence of a field. The most common example is rocks and ice that retain Earth's magnetism e.g. remnant magnetism that reveals the historic magnetic pole direction. In environmental magnetic studies a much shorter time period is used, but the same principle applies.

Anhysteric magnetism was induced in a sample by placing it in the presence of a constant biasing field of 0.04 mT and an alternating field of 100 mT (Walden *et al.*, 1999). The biasing field is an approximate for the Earth's field and the alternating field is used to discern grain size differences. ARM was measured to determine the presence of superparamagnetic (SP) grains in the soil samples (Verosub and Roberts, 1995; Evans and Heller, 2003). SP grains are ferromagnetic and have a small grain size with a very small remanence (Evans and Heller, 2003).

The Molspin a.f demagnetiser® was used to induce ARM in the laboratory. Once the machine had been switched on, the heliport set to 100 mT, the rotation set to the "Off" position and the decay rate to C, measurements began. The soil sample was inserted into the demagnetiser via arm attachment (Walden *et al.*, 1999). The attachment allows for secure rotation of the sample. Once the sample had obtained the remanence, the "Ready" button turned red. The sample was then inserted into the pre-calibrated Rotating Magnetometer where the remanence is measured. ARM susceptibility can be expressed as X_{arm}, by using the equation in Walden *et al.* (1999):

$$X_{arm} = \text{ARM / Biasing field.}$$

Isothermal Remanent Magnetization (IRM/SIRM)

For a sample to obtain IRM it is exposed to increasing direct current fields that generally exceed those of Earth. The maximum field that can be applied is 1 Tesla and it is termed Saturation Isothermal Remanence (SIRM). SIRM is useful in determining whether magnetite and (or) haematite is present in a sample as both these minerals are iron rich and make valuable environmental tracers (Foster *et al.*, 2008). IRM can be used to determine grain size in a sample by exposing it to forward and reverse fields to obtain a hysteresis loop (Walden *et al.*, 1999). The shape of the loop, provided by the coercivity measurements, can be used to determine the domains of the sample (Evans and Heller, 2003).

To induce IRM and SIRM in the laboratory the Molspin Pulse Magnetiser ® was used. The scale was set at 1000 mT (1Tesla) to induce the maximum forward field. The induced IRM was measured using the Molspin Rotating Magnetometer ®, where the IRM in 10^{-3} Am^2 kg^{-1} was recorded. After saturation at 1 Tesla, samples were left for 24 hours. After the 24 hour period, the amount of viscous grains present was measured; this is an indicator of the rate of magnetic direction loss from the saturated sample. Lastly, samples were exposed to a small negative field of 100mT and the remanence was once again measured in the Molspin Rotating Magnometer® and recorded. The reverse and negative values were used to calculate mineral concentration i.e. S-Ratio, SIRM and HIRM.

Radionuclide Dating

The ORTEC® Multichannel Digital Analyzer System was used to measure radioactivity of samples. The radionuclide measured in this research was ^{137}Cs. The system uses a pure Germanium detector to measure emitted photons (Foster *et al.*, 2007). The machine was allowed to count for an average period of 180 000 seconds to 250 000 seconds at 661 keV. Temperature during the measurement was kept constant by liquid nitrogen at 90 ^{o}K (ORTEC, n.d.).

4.4.4. DATA CORRECTION

Mass specific magnetic susceptibility data (χlf and χhf) was corrected for instrument drift by taking an average of the “air before” and “air after” reading and subtracting it from the mass susceptibility reading. All χlf and χhf are expressed in the SI units 10^{-6} m^3 kg^{-1} (Dearing, 1999). Frequency dependent susceptibility (χfd %) was obtained by using Equations 1 and 2.

$$\chi fd = [(\chi lf - \chi hf)/ \text{mass}] \times 10 \ldots \text{(Eq 1)}$$

$$\text{and } \chi fd\ (\%) = [(\chi lf - \chi hf)/ \chi lf] \times 100 \ldots \text{(Eq 2)}$$

The organic matter content of the sample was used to obtain χlf values without the influence of diamagnetic materials (Walling, 2005). The inverse percentage value was subtracted from χlf using Equation 3.

$$\chi lf_{\text{(minero)}} = [\chi lf – (1-(\text{LOI } \% \div 100)] \ldots \text{(Eq 3)}$$

The formula was also used to calculate percentage frequency dependent susceptibility without the effects of diamagnetic materials to obtain χfd (%).

Remanence measurements were converted to ratios that are useful for the analysis of data. Sample mass specific ARM susceptibility was calculated using Equation 4 (Walden, 1999: 73):

$$\chi_{arm} = \text{ARM } (10^{-5} \text{ Am}^2 \text{ kg}^{-1}) \div 31.84 \text{ Am}^{-1} \ldots \text{(Eq 4)}$$

which takes into account the biasing field. The measured value of remanence after exposure to a magnetic field of 1 Tesla was presented as SIRM. HIRM was calculated using Equation 5.

$$\text{HIRM} = [\text{SIRM}/ (\text{IRM}_{-100} \div \text{mass})] \ldots \text{(Eq 5)}$$

This allowed for the calculation of the S-Ratio using Equation 6.

$$\text{S-Ratio} = \text{HIRM}/\ \text{IRM}_{-100} \ldots \text{(Eq 6)}$$

To detect the amount of ^{137}Cs in soil samples the spectrum analysis software GammaVision-32 was used. The saved spectra file was opened from its directory and background count was stripped using a spectrum derived from an empty waxed vial. The Library Directed and ROI Peak location methods were used to detect the ^{137}Cs peak (662 keV) and to find the net area of the peak. Once the information was recorded the date was inputted into Foster's (2005) Excel® Gamma spectroscopy macro workbooks (see Appendix D) to calculate the activity in samples. To estimate erosion rates in the catchment the Radionuclides Inventories Conversion Excel® Add-In by Walling *et al*. (2006) was used. Equation 7 was used to calculate the expected activity in the plough soil horizon in the catchment.

$$\textit{Average Concentration (mBq g}^{-1}\textit{) = Reference Inventory (Bq cm}^{-2}\textit{)} \div \textit{[Profile depth (cm) x Bulk density (g/cm}^{3}\textit{)]} \ldots \text{(Eq 7)}$$

The reference inventory was extrapolated using the average rainfall in the catchment. The bulk density was 1.34 g/ cm^3.

4.4.5. USEFUL AND APPLICABLE RATIOS

The Saturation Isothermal Remanent Magnetisation (SIRM) was used to determine the presence of haematite and magnetite. The SIRM is an indicator of the maximum remanence at the maximum induced field of 1000 mT for the Molspin Pulse Magnetiser ®. Smith (1999) provides a classification of iron oxide minerals based on SIRM values (see Table 4.4).

Dearing (1999) found that lakes in southern Sweden had elevated levels of ferromagnetic and superparamagnetic mineral concentrations. These findings indicated that surface erosion in cultivated lands contributed to the observed concentrations. A similar exercise was conducted using Dearing's (1999) plot of the various grain sizes and parent rock signatures using frequency dependent susceptibility percent ($\chi fd\%$) versus mass magnetic susceptibility (χlf).

The HIRM was used to determine the concentration of antiferromagnetic materials in the iron oxide bearing samples (Liu *et al.*, 2007). The HIRM is particularly useful in the quantification of goethite and hematite. The results of the analysis were presented in a bi-logarithmic scatterplot of HIRM versus χlf.

Thompson and Oldfield (1986) were able to use a bi-logarithmic scatterplot of χlf versus SIRM to show the concentration and domains of magnetite. This information was used by Lees (1994) who compared her database with the zonation. This scatterplot was replicated to validate the findings of the HIRM findings and to compare against Thompson and Oldfield's (1986) and Lees' (1994) findings.

4.4.6. INTERPRETATION

The data interpretation method that was adopted in this study was to seek relationships within and amongst the different source groups. This approach was used to determine whether there was causality between the source groups and whether further associations could be made. This is in line with the objectives of this chapter which is to determine whether gullies are point sources of erosion in the Khamopele River catchment. Where specific studies were used to test the hypotheses, the results were compared to the findings of said studies.

4.4.7. STATISTICAL ANALYSES

Using the statistical software package SPSS ®, a Cluster Analysis and Multivariate Analysis of Variance (MANOVA) were conducted on the data.

Cluster analysis is a widely applied statistical method to pick out similarities in collected data (Romesburg, 2004: 15). This means that data can be arranged into similar groups (Rogerson, 2010). This statistical method was used to show whether there were similarities between gullies and sink zone samples. This would help determine whether material sourced in Khamopele River catchment was found at sink zones.

The Hierarchical cluster analysis method was used to determine the number of clusters to work with (Jansen *et al.*, 2006) using Ward's method (Ward, 1963) as there were no pre-assumptions regarding the data outside the individual source groups (Romesburg, 2004). Literature indicated that Ward's method has been widely used and is advantageous as it uses variance of means to determine the number of clusters necessary (Romesburg, 2004). Its efficiency arises because it starts with all objects as single clusters containing one object, eventually yielding a cluster with all objects with the least distance of clusters merged per tier (Romesburg, 2004; Everitt *et al.*, 2011).

The cluster analysis was carried out using the following steps:

Step 1: A factor analysis was carried out using the variables: χdf%, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM, HIRM. The principal components method was used to extract the factors and the factor scores to be used in the cluster analysis.

Step 2: The Hierarchical cluster analysis using Ward's method was carried out to determine the number of clusters. Once this was established, the agglomeration cluster schedule was used to look for large changes in the coefficients in order to determine the number of clusters.

Step 3: Once the number of clusters was determined, the *k*-means procedure was used to form the clusters.

The hypotheses that were tested:

H_0: there was *no difference* in the mean χfd %, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM, HIRM with respect to the source groups i.e. Core 1, Core 2, gully sidewalls, hillslopes, Mhlakeng topsoil, streambed material, Quaternary T34A and basalt.

H_1: there *was a difference* in the mean χdf%, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM, HIRM with respect to the different source groups i.e. Core 1 (Tina Dam Core), Core 2 (Tina River Core), gully sidewalls, hillslopes, Mhlakeng topsoil, streambed material, Quaternary T34A and basalt.

To test whether there was a difference in the mean χfd%, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM and HIRM with respect to the different source groups a hypothesis was tested with MANOVA. MANOVA analyses differs from ANOVA in that the sets of means are used instead of singular means i.e. multiple dependent variables are used.

The MANOVA was carried out using the following steps:

Step 1: Box's M test was used to test for the homogeneity of covariance matrices as the number of samples collected was unequal for each source area (Coakes and Steed, 2003:17). The recommended level of significance is 0.001 (Nimon, 2012).

Step 2: Multivariate tests of significance tests were carried out to test whether there were significant group differences on a linear combination of the dependent variables. The following tests were used: Pillai's Trace criterion, Wilks Lamda, Hotelling's Trace criterion, and Roy's Largest Root.

The univariate F tests for each dependent variable indicate which individual dependent variables contribute to a significant multivariate or location effect.

Step 3: To asses more precisely where the differences between the locations were, the Least Squares Differences (LSD) multiple comparisons were used.

The hypotheses that were tested:

H_0: there was *no difference* in the mean χdf%, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM, HIRM with respect to the different source groups i.e. Core 1, Core 2, gully sidewalls, hillslopes, Mhlakeng topsoil, streambed material, Quaternary T34A and basalt.

H_1: *there was a difference* in the mean χdf%, χlf, χfd, ARM, χARM, SIRM, S-Ratio, IRM, HIRM with respect to the different locations i.e. Core 1, Core 2, gully sidewalls, hillslopes, Mhlakeng topsoil, streambed material, Quaternary T34A and basalt.

4.5. RESULTS

4.5.1. IRON OXIDE MINERAL COMPOSITION

Magnetic susceptibility (χlf) results indicated that 15% of soil samples in Makhoaseng sample area were paramagnetic. The rest of the samples were ferrimagnetic as they had χlf values greater than 0.1 x 10^{-6} m^3 kg^{-1} (Dearing, 1999). Ferrimagnetic samples were used for the analyses in this section as they are indicators of the presence of iron oxides in the environment (Dearing, 1999).

SIRM values were used to determine which iron oxides (haematite, maghaemite, magnetite and goethite) were present in the remaining 85% of soil samples. Table 4.6 below was used as a guide to classify samples into their mineral groups.

Table 4.4: Iron oxide classes (Source*:* Smith, 1999: 19).

Mineral (ferrimagnetic)	**SIRM (10^{-3} Am^2 kg^{-1})**	**Mineral (antiferromagetic)**	**SIRM (10^{-3} Am^2 kg^{-1})**
Magnetite	10 – 40	Haematite	0.2 - 0.3
Maghaemite	5 – 35	Goethite	0.01 - 1.0

An overlap in the classification between the magnetite and maghaemite SIRM values from 10 to 34.9 x10^{-3} Am^2 kg^{-1} was observed. Therefore, an additional "magnetite-maghaemite" class was added to the classification table. The magnetite-maghaemite class refers to values that lie between 10 and 35 x 10^{-3} Am^2 kg^{-1}. Values above 35 x10^{-3} Am^2 kg^{-1} were classified as magnetite and all values between 5 and 9.9 x 10^{-3} Am^2 kg^{-1} were classified as maghaemite.

Makhoaseng catchment

In Makhoaseng catchment the maghaemite mineral class had the highest number of iron-oxide rich samples followed by the goethite class (see Figure 4.6). All iron-oxide rich gully sidewall samples were in the goethite mineral class. A third of the streambed samples had goethite as their dominant mineral. All three haematite rich samples from the streambed group were collected from the confluence area of the Taung River and the south east to north-west flowing tributary in the catchment. One sample in the streambed source area group had magnetite-maghaemite mineralogy.

This sample (BS7) was collected in Mhlakeng River before its confluence with the Khamopele River as shown in Figure 4.3a.

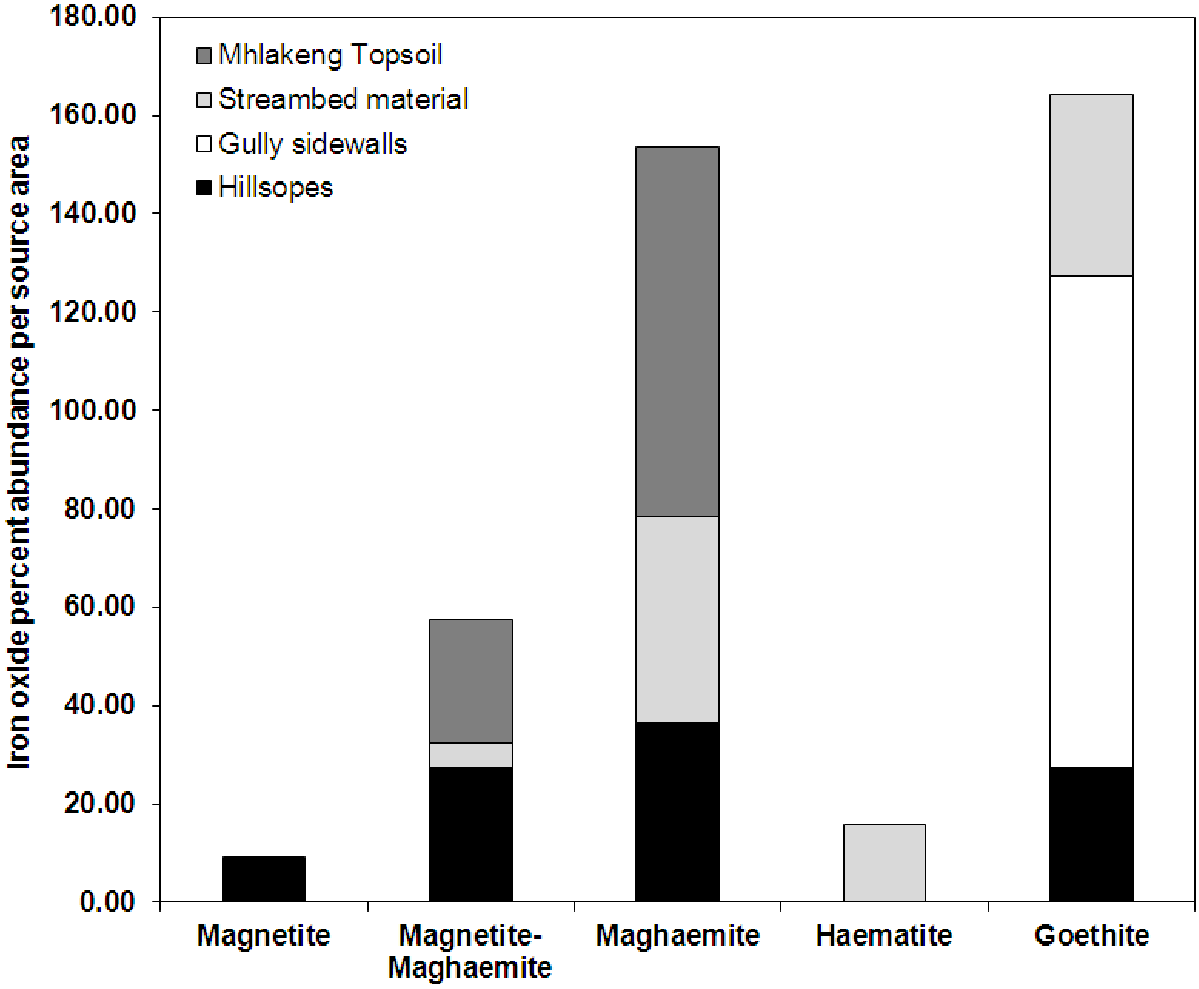


Figure 4.6: Iron oxide distribution in samples in the Khamopele River catchment.

In the Mhlakeng sample area, three samples were in the maghaemite class and one in the magnetite-maghaemite class. Streambed samples were found in all groups with the exception of the magnetite group. Interestingly, the streambed samples were the only source area that had haematite mineralogy. Most hillslope samples were in the maghaemite class. The hillslope samples showed similarities with streambed samples in that they too were present in all classes with the exception of the haematite class.

Quaternary derived sediments

Soil samples collected outside the Khamopele River catchment were strongly ferrimagnetic in nature (see Figure 4.7). The only sample that had maghaemite mineralogy was bedload from the river Phiri-e-Ntso.

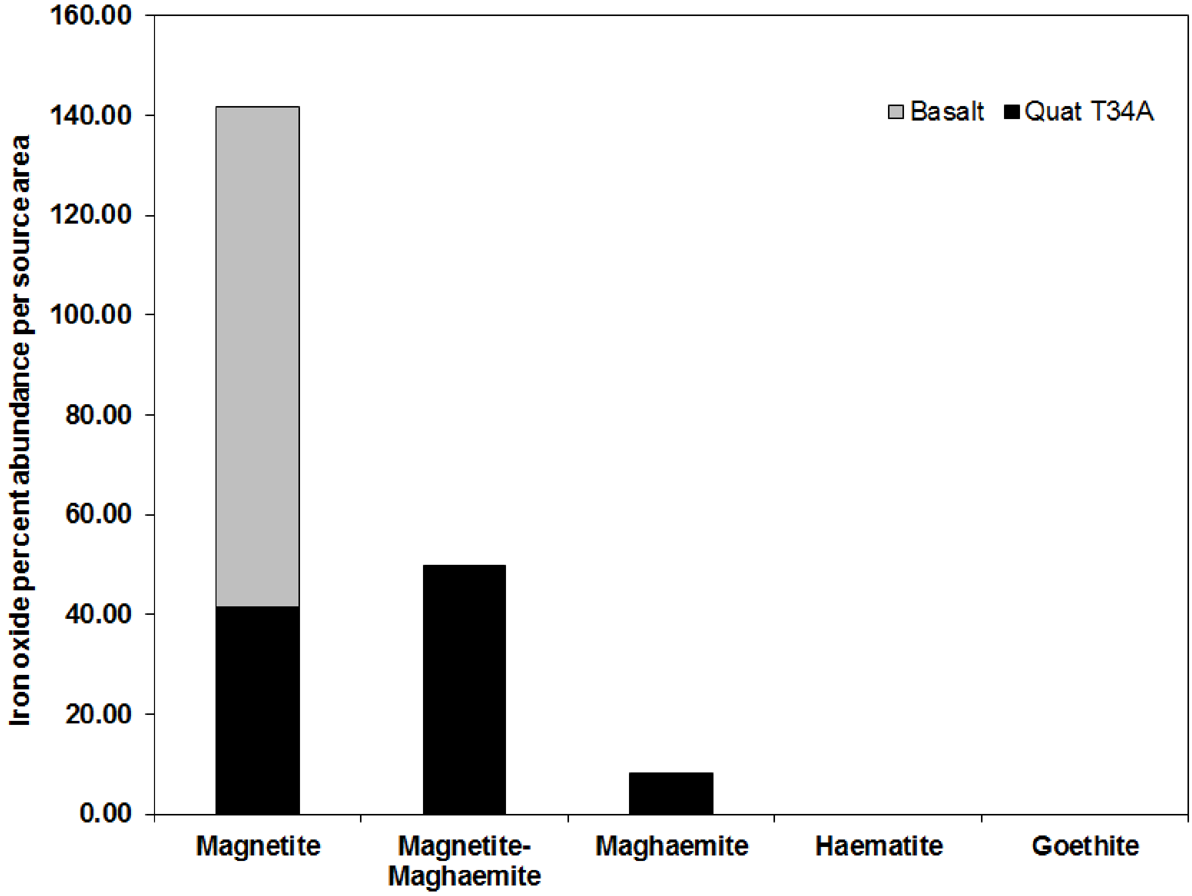


Figure 4.7: Iron oxide distribution of samples in the upper Tina River catchments.

Streambed and river bank samples collected from quaternary catchment T34A indicated strong magnetite mineralogy. The presence of magnetite was detected in all of the basalt source area samples. The maghaemite mineralogy of other samples in the quaternary catchment indicated the oxidation of iron compounds. There was no evidence of the iron hydroxide goethite and haematite was also absent from these samples.

Sink zone samples

Sink zone derived samples showed similarities to quaternary derived sediment in that none exhibited antiferromagnetic mineralogy (see Figure 4.8). The absence of goethite and haematite indicated that the full and partial oxidation process was well represented in sink samples (Chesworth, 2008).

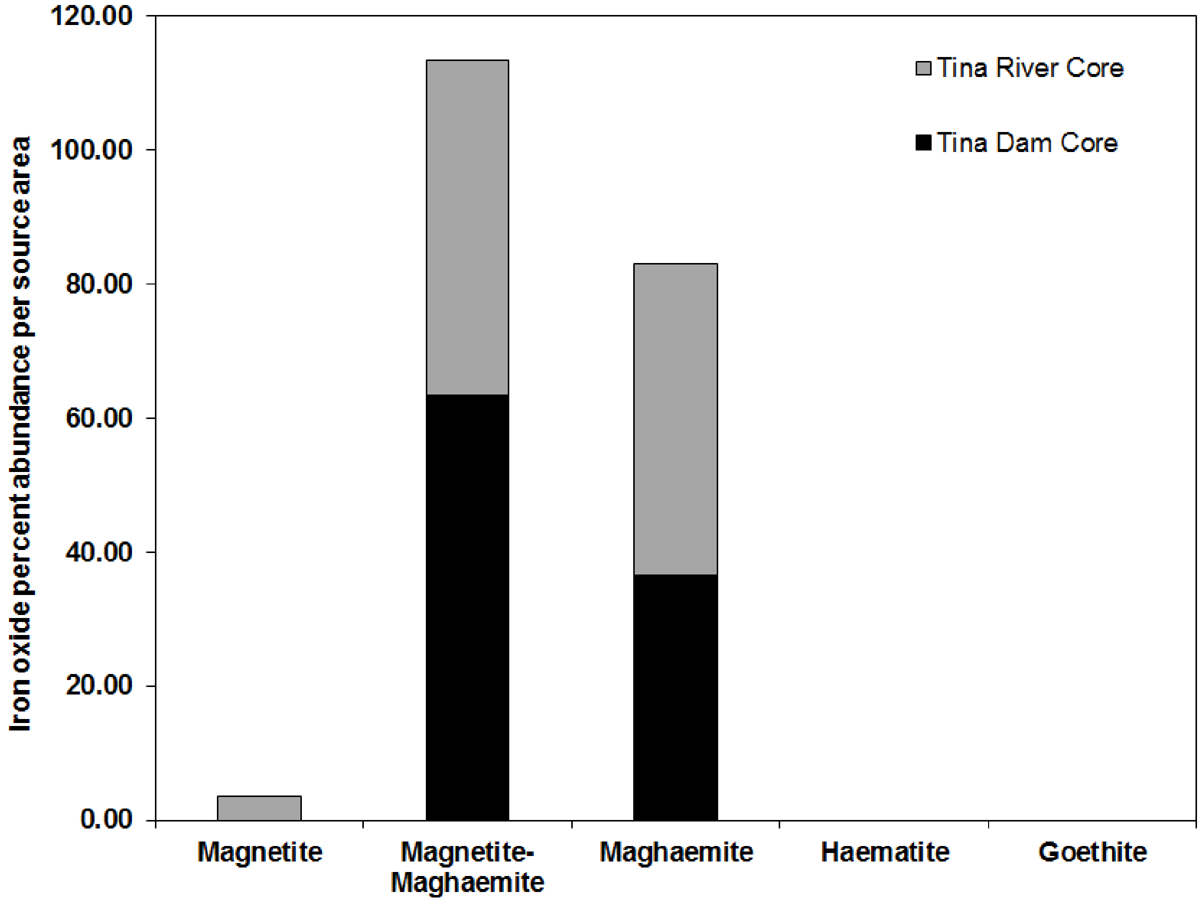


Figure 4.8: Iron oxide distribution of samples collected from the TDC and TRC.

One sample from the Tina River core showed magnetite mineralogy. This was sample TR 32 - 34 cm and it may be indicative of a high flow period that mobilised basalt rich sediment in the river system.

The Majority of sink zone samples were in the magnetite-maghaemite class. None of the iron-oxide rich samples collected from the Tina Dam core had magnetite mineralogy. This may have been an indicator of selective transport longitudinally.

Sink samples indicated ferrimagnetic behaviour and a gradual increase to stronger magnetic signatures.

All the iron oxide bearing samples from different source areas were added to one graph to determine the dominant iron oxide mineralogy and distinguish arising relationships in the collected samples (see Figure 4.9). Results show that most of the samples were largely ferrimagnetic with the maghaemite class dominant. Source area soil samples that had wholly ferromagnetic signatures were Mhlakeng topsoil, basalt, Tina River core, Tina Dam core and samples derived from river beds and banks in quaternary catchment T34A.

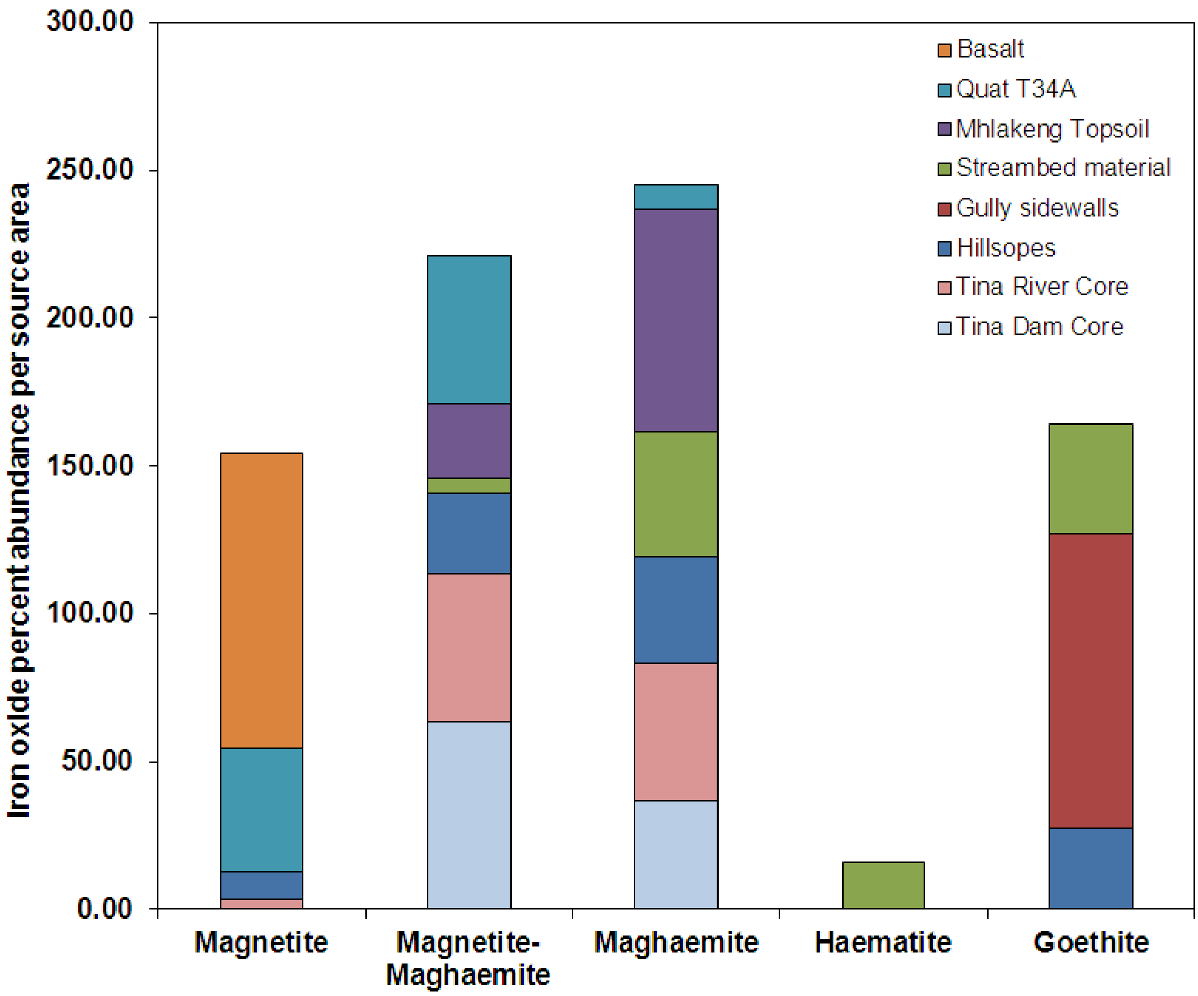


Figure 4.9: Summary of the distribution of iron oxide bearing samples.

Gully sidewall samples were the only sample group that was wholly antiferromagnetic. Furthermore, this group exclusively had goethite mineralogy. Interestingly, the only source area group to exhibit haematite mineralogy was the streambed material group. Basalt samples had the highest SIRM and all samples in this source area exhibited magnetite mineralogy. Hillslope and streambed soil samples were the only source areas to extend to four of the five mineral classes, indicating a spread from antiferromagnetic to ferromagnetic signatures or vice versa.

4.5.2. IRON OXIDE SOURCES AND GRAIN SIZE

Due to the low χlf values for catchment samples, the χfd (%) was not used to determine grain size differences using literature based χfd (%) values. Dearing (1999:47) points out that it is difficult to accurately define grain size based on χfd (%). For the purposes of this research it was deemed appropriate to use χfd (%) in conjunction with the concentration (χlf) to determine the parentage of samples as shown in Figure 4.10.

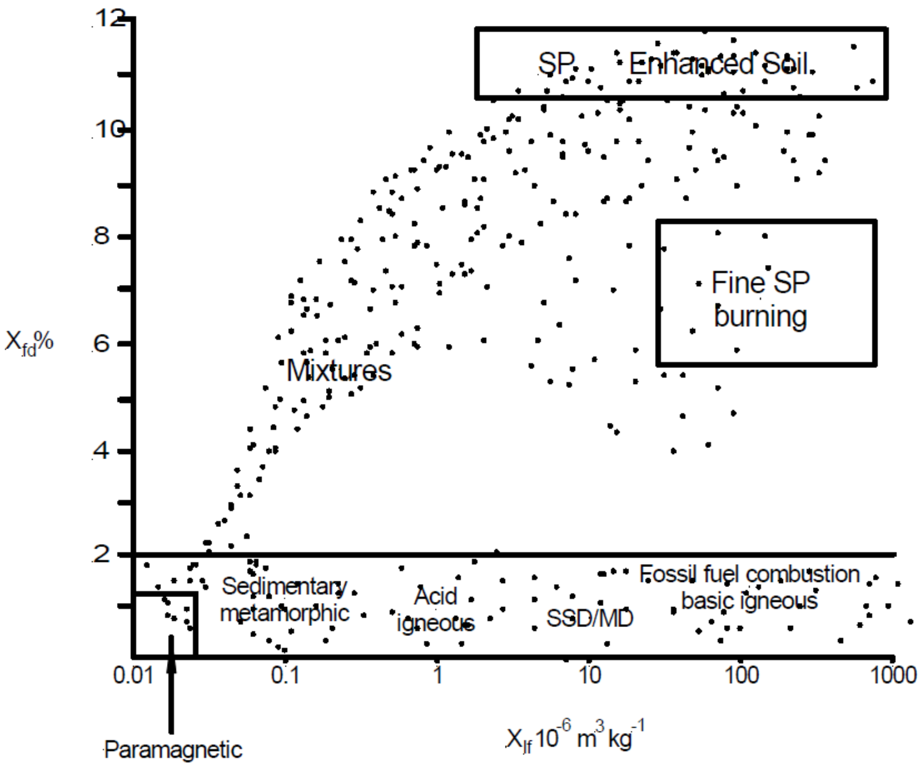


Figure 4.10: Domain differences and sources in magnetic studies (Dearing, 1999:48).

The approach addresses the objectives of this chapter to identify sediment source areas. Identified catchment sources also have an origin and some of the samples may give an indicator to the parent rock and associated grain sizes. Figure 4.10 above incorporates grain size by having the stable single domain (SSD) and multi-domain (MD) grouping at 10 x10^{-6} Am^2 kg^{-1}. Percent frequency dependent susceptibility (χfd %) is a measure of the superparamagnetic minerals in a sample; therefore the mixtures region in Figure 4.10 pertains to a mixture of SP minerals.

Makhoaseng catchment

The results of the χfd (%) versus χlf plot were overlain on Fig 4.10; the results are presented in Figure 4.11. With the exception of many Hillslope samples and some Mhlakeng topsoil samples, source groups came from sedimentary rocks. This result was consistent with the dominant sedimentary rock geology in the catchment.

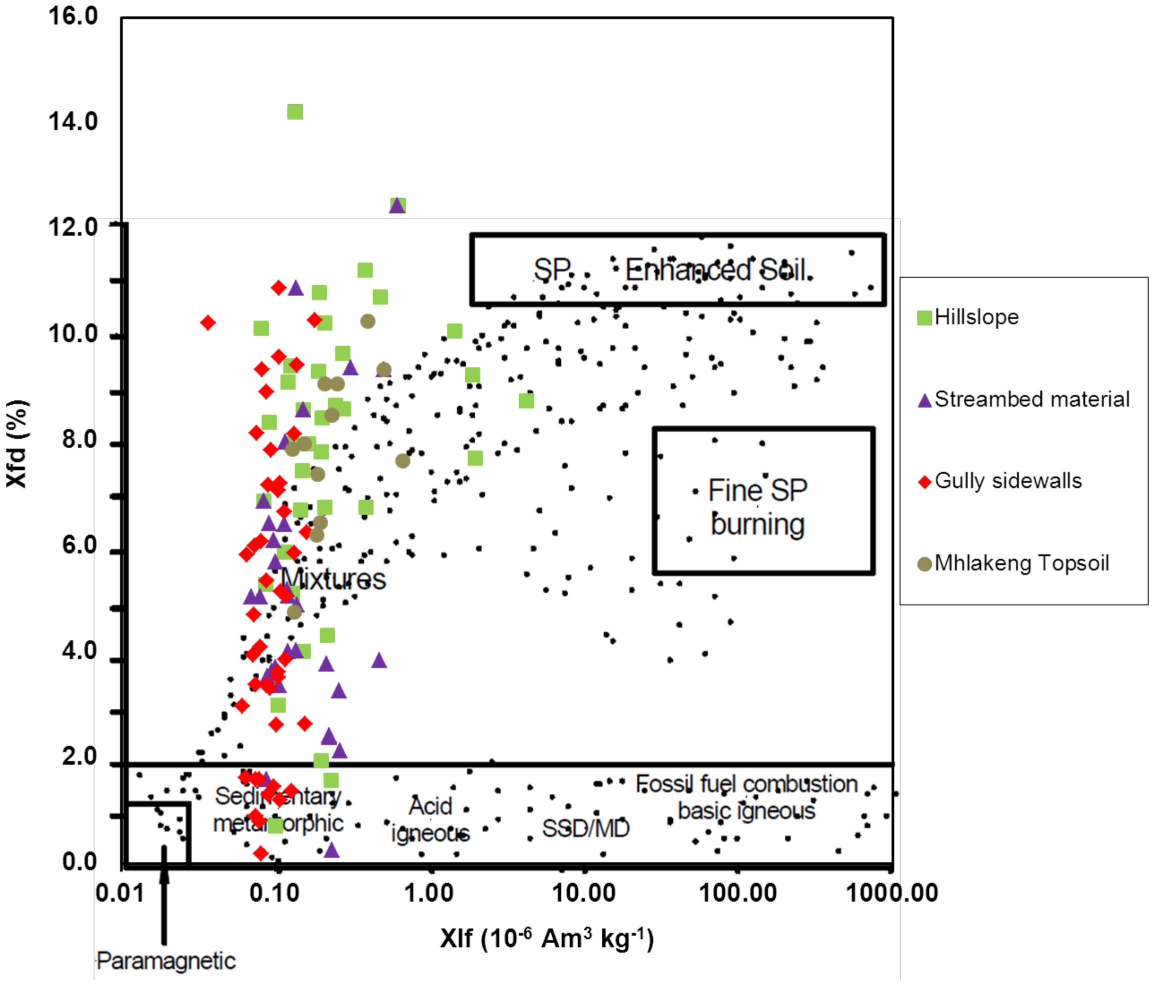


Figure 4.11: Parent rock and domain plot of the Khamopele River catchment samples.

The Hillslope samples that lie to the right of the sedimentary-metamorphic zone in Figure 4.11 included samples sourced close to the basalt and close to the dyke towards the confluence of the Tina and Khamopele Rivers. Mhlakeng topsoil samples that did not fall within the sedimentary rock grouping may indicate different parent or source material.

The topsoil samples were collected from the former wetland. Therefore, the plot may indicate differences in soils that have undergone pedogenic processes and those that have input from organic matter content from wetlands.

Soil samples that lie below the solid line at χfd (%) 2 had no SP grains. A significant number of source groups from Makhoaseng catchment showed a mixture of superparamegnetic (SP) minerals. Some of the samples did not plot within the envelope for mixtures and represent samples that do not have SP grains or where the SP fraction is dominated by fine grains (Dearing, 1999). Although superparamagnetic, these samples indicated weak remanence in sedimentary/metamorphic derived sediments.

Quaternary derived sediments

Soil samples collected outside Makhoaseng catchment indicated an increase in the concentration of ferrimagnetic minerals. Both source groups showed a move towards acid igneous parent material as shown in Figure 4.12.

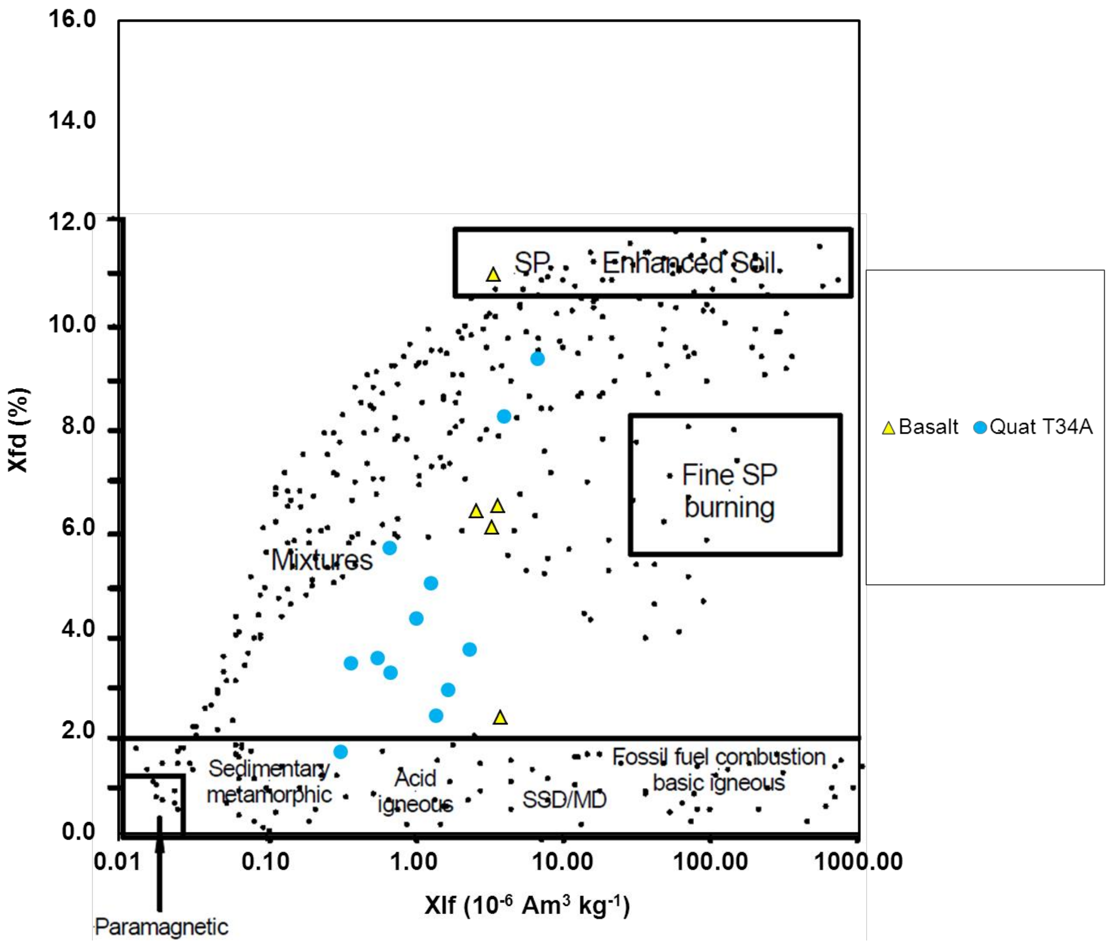


Figure 4.12: Parent rock and domain plot of quaternary derived samples.

A single sample collected in the Phiri-e-Ntso River channel plotted closest to the sedimentary/metamorphic parent envelope. It was the only sample in samples collected outside Makhaoseng catchment that had no SP grains. The cluster of QuatT34A samples between χfd (%) 2.3 and 5 % represent soil samples with no SP grains or where the SP fraction is dominated by fine grained ferromagnetic minerals (Dearing, 1999). The remaining three samples from the quaternary T34A group indicated a mixture of SP minerals. Samples from this group that plotted between χfd% 8 and 10 were sourced from the Vuvu River channel and bank.

With the exception of sample BS1 - 5 cm, the basalt samples had high χlf and χfd (%). The rest of the basalt samples were a mixture of SP grains. One sample from the basalt group was dominated by SP grains indicated soil enhancement.

Sink zones

Sediment samples from the two cores were plotted to determine their parent. Results showed that the Tina River core was a mixture of sediments that have sedimentary and igneous rock parents (see Figure 4.13).

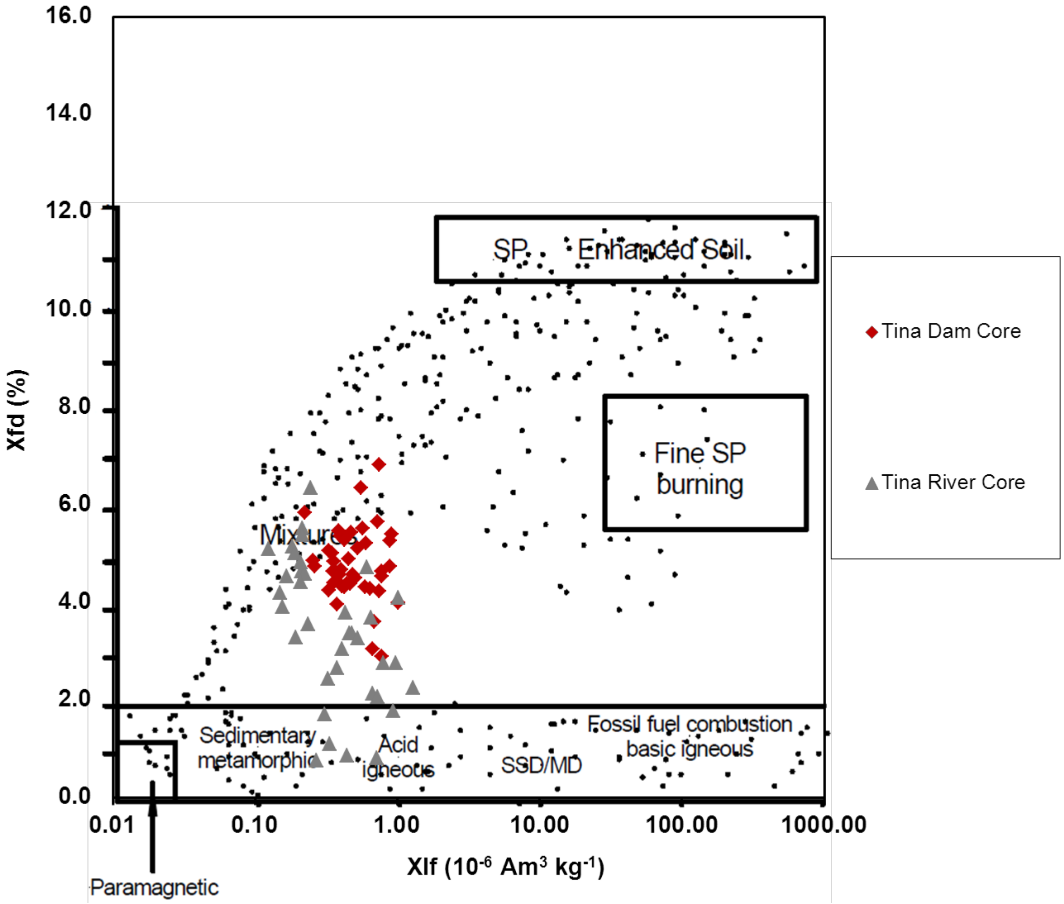


Figure 4.13: Parent rock and domain plot of core samples.

Furthermore, samples collected from the TRC included some with no SP grains. In contrast, the Tina Dam core was wholly composed of a mixture of SP grains. Where samples fell outside the envelope, these samples had a fine grained SP fraction.

The summary plot of all collected samples (see Fig 4.14) shows that the collected samples were largely a mixture of SP grains. Soils in the upper Tina River catchments were sourced from sedimentary and igneous rocks.

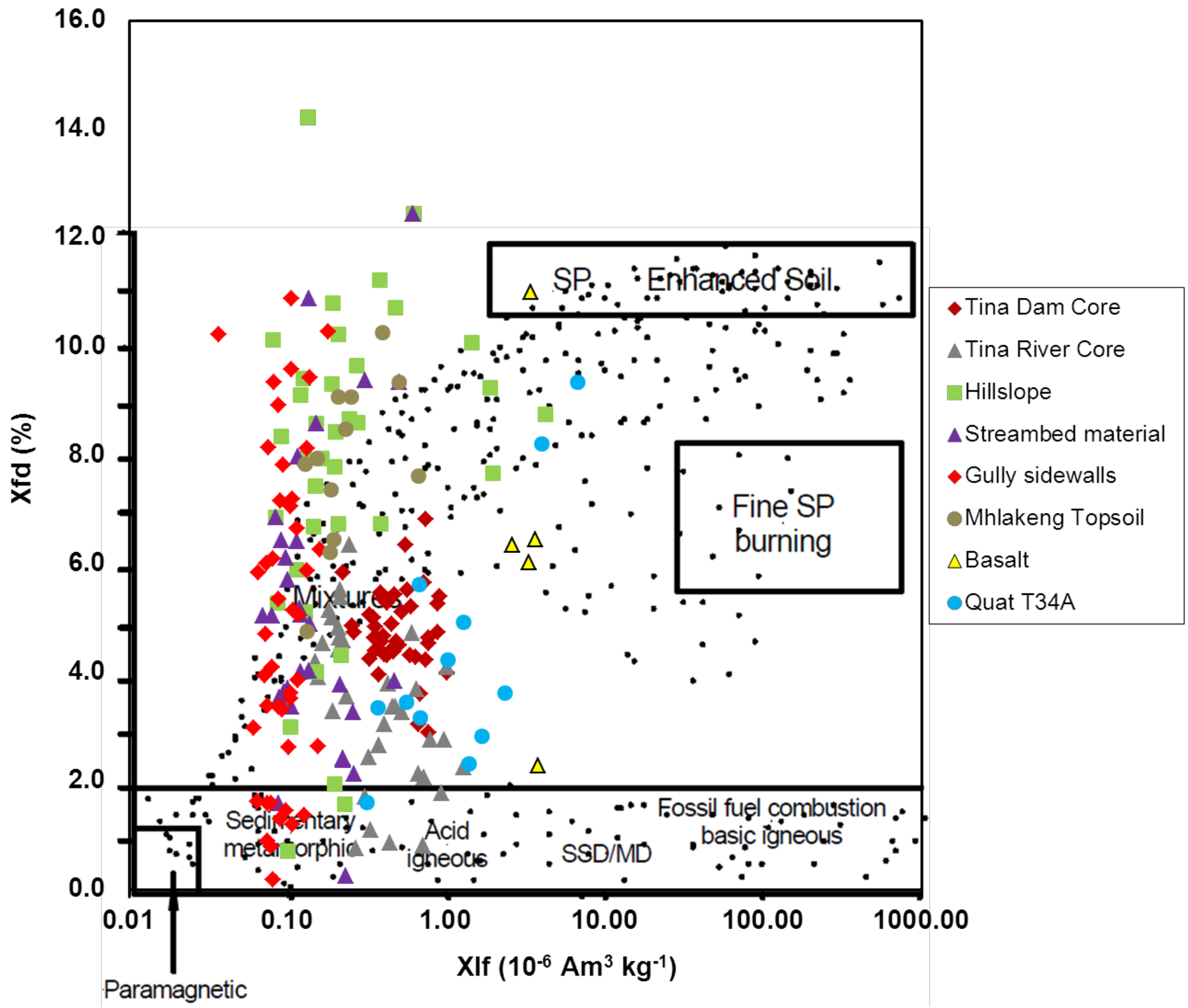


Figure 4.14: Parent rock and domain plot of all source groups.

To summarise, samples collected in this study indicated that the basalt source group was distinctly different from other source areas. Hillslope samples also showed differences to other source groups as they tended to have high χfd (%) and higher χlf values. Samples from the Tina River core showed greater concentration differences in χlf when compared to the Tina Dam core and Makhoaseng catchment samples. The samples indicate possible inter-catchment variability i.e. samples collected from outside the catchment were different to those collected in Makhoaseng catchment. Sink zone samples shared some similarities with samples collected outside Makhoaseng catchment, hillslope and streambed samples. Streambed and hillslope samples plot in similar areas as the Tina River core. Lastly, within Makhoaseng catchment there were at least seven instances where hillslope and streambed samples shared similar χlf and χfd (%) values, an indicator of similarity within Makhoaseng catchment.

4.5.3. MAGNETIC BEHAVIOUR: FERRIMAGNETS VS ANTIFERROMAGNETS

Using Equation 5, the Hard Isothermal Remanence (HIRM) was calculated to determine the quantity of antiferromagnetic minerals in the collected samples (Liu *et al*, 2007). The HIRM was compared to χlf to determine the concentration of iron bearing minerals. Bi-logarithmic graphs of the results were used in this section to present results. Samples with high HIRM indicated the dominance of ferrimagnetic minerals and those with lower HIRM indicate strongly antiferromagnetic minerals.

Makhoaseng catchment

Soil samples collected from the three sample areas in the Khamopele River catchment indicated that gully sidewall samples shared similarities with other Khamopele derived samples. Certain streambed, hillslope and Mhlakeng topsoil samples plotted in the same vicinity. However, it was observed that there were four samples from the hillslope source group which were strongly ferromagnetic in nature (see Figure 4.15). These hillslope samples were CH4, CH9, CH10 and S2. The latter sample was sourced on a burned hillslope towards the Khamopele and Tina River confluence. The former three samples were sourced from slopes behind Makhoaseng village.

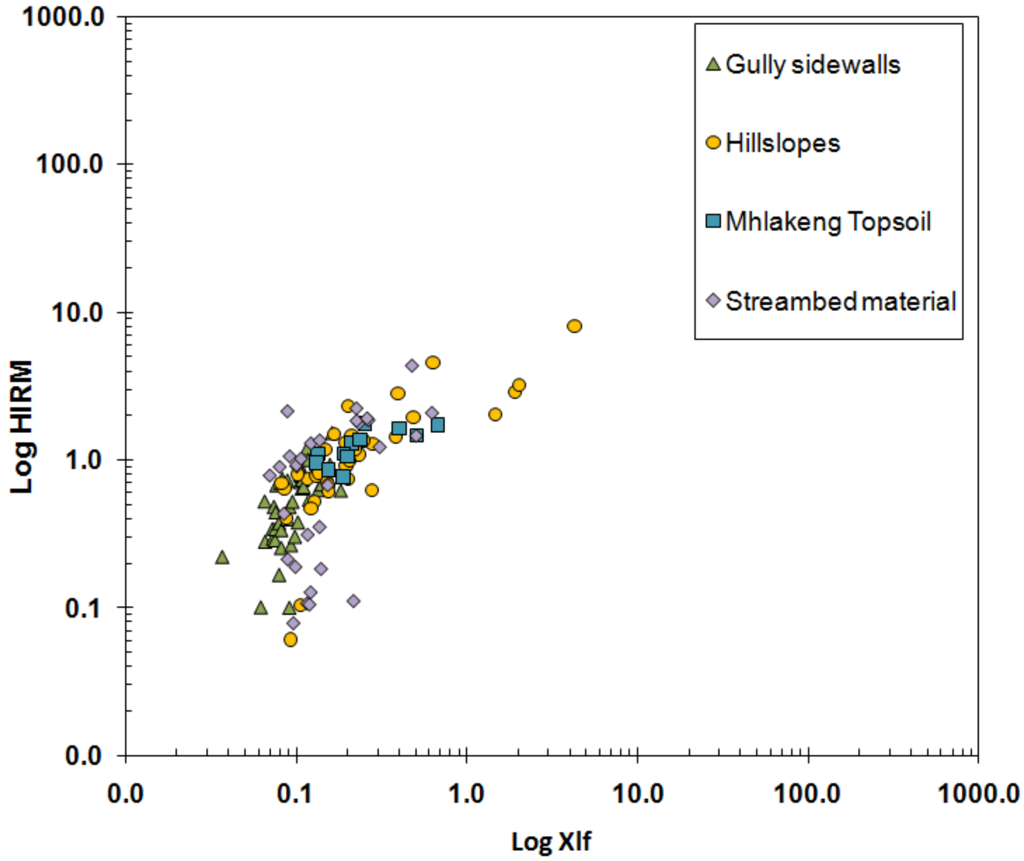


Figure 4.15: Bi-logarithmic scatterplot of magnetic behaviour in samples from the Khamopele River catchment**.**

A clear trend in the results was the similarity of hillslope and topsoil samples. Few topsoil samples shared similarities with gully sidewall samples. Streambed samples shared similarities with all three source areas. However, between HIRM 0.7 and 2, there was strong clustering of streambed samples with hillslope samples. Most of the hillslope samples collected in Taung sample area corresponded with streambed samples found at bars near the Khamopele River mouth. This was interpreted as a possible indicator of sediment movement from hillslopes to the channel in both Mhlakeng and Taung sample areas.

Intra-catchment variability

An underlying assumption in this research was that gullies were point sources of sediment in the Khamopele River catchment. This was influenced by the size and severity of erosion where gullies were present. To test the assumption, each of the source areas were separated from the cluster and compared with samples from the gully sidewalls (see Figure 4.16).

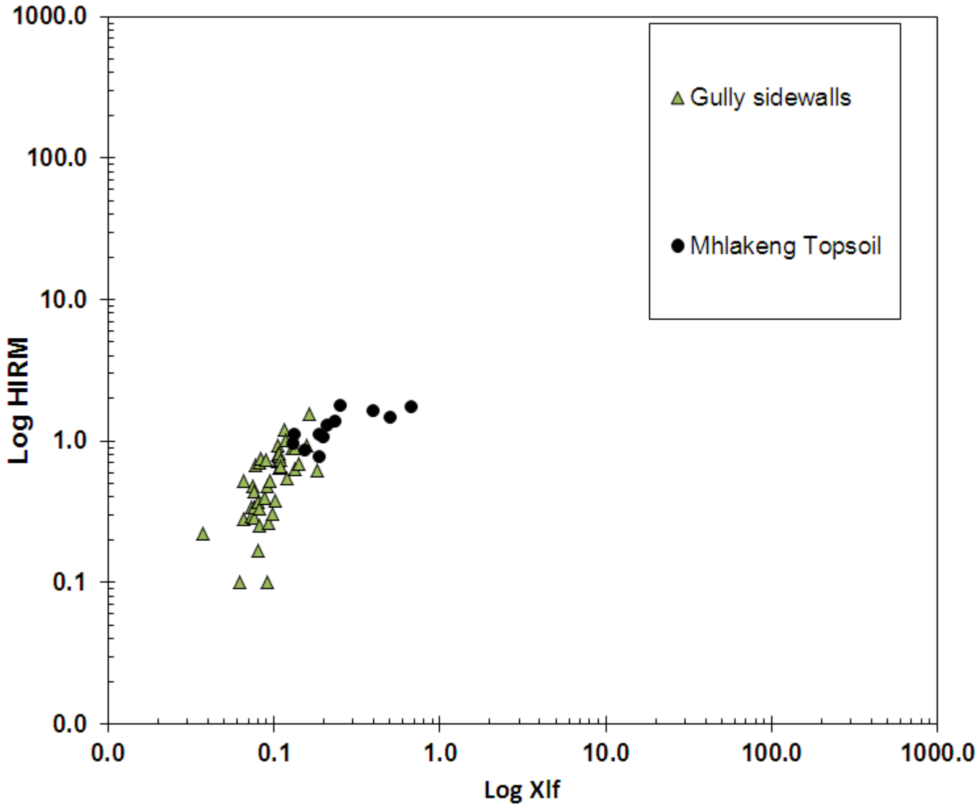


Figure 4.16: Bi-logarithmic scatterplot of magnetic behaviour in the Mhlakeng Topsoil source group.

The first stage was to compare topsoil samples from Mhlakeng sample area to the gully sidewall samples. Three samples from both groups overlapped. The first match was from topsoil sample Wet 6 and gully sample M4B. Wet 6 was collected from a former agricultural plot in the middle of Mhlakeng sample area (see Figure 4.3b). Sample M4B was the second horizon in the gully sidewall profile in Mhlakeng River. The overlap of these two samples suggests that significant erosion or cultivation has occurred to expose the second soil horizon as topsoil at this present time. This may also point to the erodibility of the second horizon.

The second overlap was between topsoil sample W4 and gully samples M3D (190 cm - 260 cm) and TL3D. W4 was collected between the connected (M2 and M3) gullies on the left bank of the Mhlakeng River when facing downstream. Gully TL3 was the gully where the tunnel was found. Its fourth soil horizon (110 cm – 185 cm) was identical in mineral composition to the topsoil sample W4. Interestingly, the topsoil sample matches the fourth horizon of both gullies. However, these gullies were found in different sample areas i.e. the Taung and Mhlakeng sample areas.

Sample M3D was collected downstream of the gully M3, its similarity with W4 suggests that lower soil horizons were exposed in Mhlakeng sample area, thus indicating surface horizon removal and subsequent horizon exposure. The correlation with a soil horizon in Taung sample area suggests that soil horizons share similar depositional history. Overall, topsoil samples indicated an increase in ferrimagnetic minerals when compared to gully sidewall samples.

Hillslope samples in Makhoaseng catchment showed good overlap with gully samples between HIRM 0.1 and 1 (shown in circle in Figure 4.17a). Thereafter, there was a clear separation of hillslope and gully samples. The samples which had high HIRM and χlf values were those samples that were collected in the mid-slope region behind the village and the Taung and Mhlakeng sample areas. Interesting relationships within the hillslope samples are those of TR4D and H6 and TL3A and H1. Geographically, gully TR4 lies opposite where sample H6 was collected. The two are separated by a river. Their similarity may indicate lateral extension (east to west) of soil horizons or the topsoil sample was transported from further upslope where the mineralogy is similar to that of TR4D. This may also indicate the amount of erosion that has taken place on the left hand bank of the Taung River when compared to the right hand side. Had erosion and deposition rates been similar, sample H6 would not be a surface layer. It would be a soil horizon, such as TR4D.

TL3A represented the first horizon in the gully where a tunnel was found. It shared near-identical mineralogy with a sample collected in Mhlakeng sample area. If one were to draw a horizontal line from where the topsoil sample was collected, across the ridge (west to east) into Taung sample area the first gully is TL3. This result further indicates possible sequential layering of soil horizons in Mhlakeng and Taung sample areas.

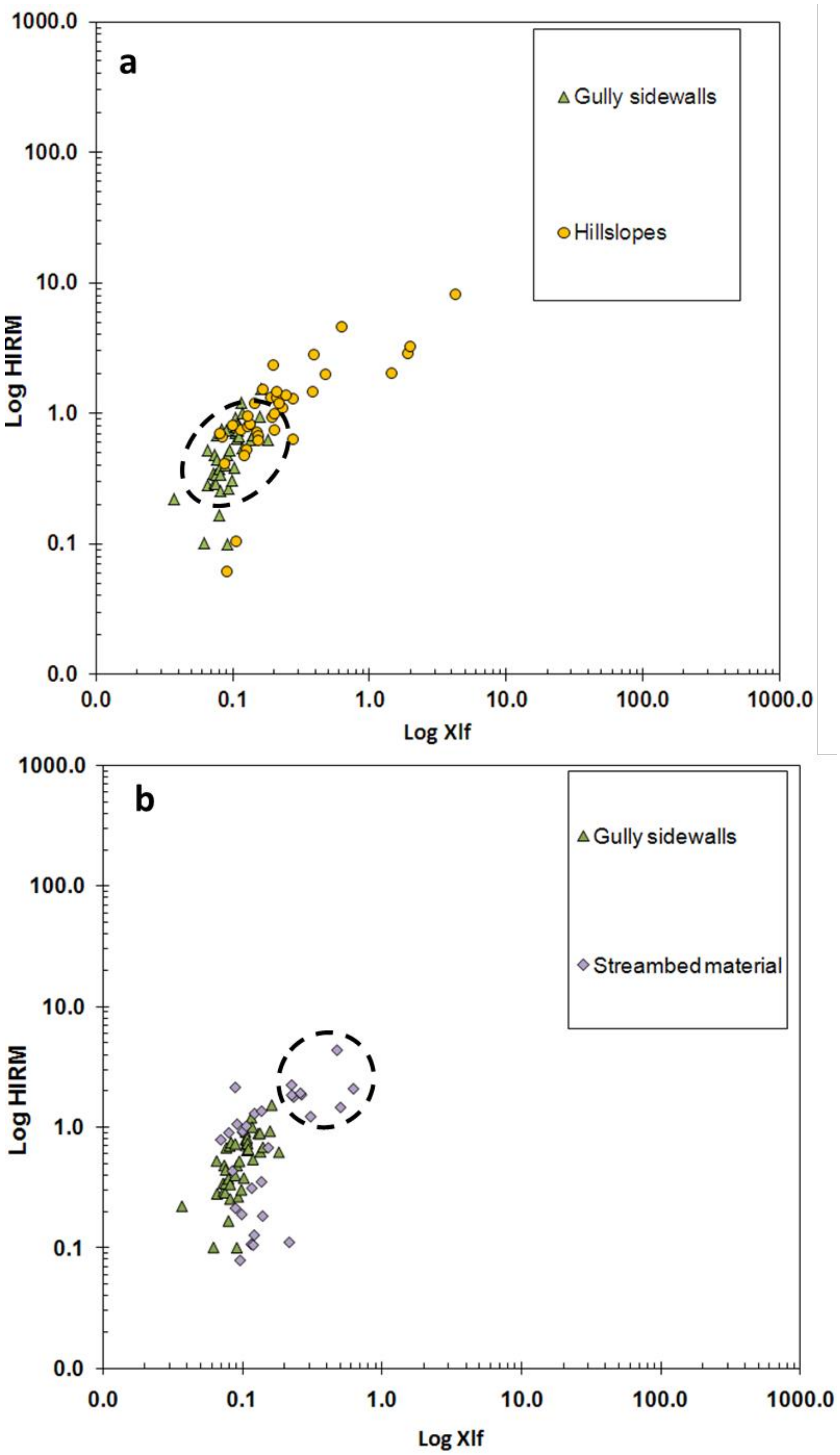


Figure 4.17: Bi-logarithmic scatterplot of magnetic behaviour in the hillslope (a) and streambed material (b) source groups.

Streambed samples indicated good overlap with samples from gullies in the catchment between HIRM 0.06 and 1 (see Figure 4.17b). However, there was a separation of nine samples. These samples coincided with confluence points in the Lower Khamopele, Mhlakeng and Taung Rivers. Three of the samples represented samples collected in the lower reaches of the Khamopele River towards the mouth.

Quaternary derived sediments

The basalt and quaternary derived source groups were similar in that they both had high HIRM, thus indicating the strong presence of ferrimagnetic minerals. However, there were apparent differences in the source groups. For example, the basalt samples did not overlie any Quaternary catchment derived samples (see Figure 4.18).

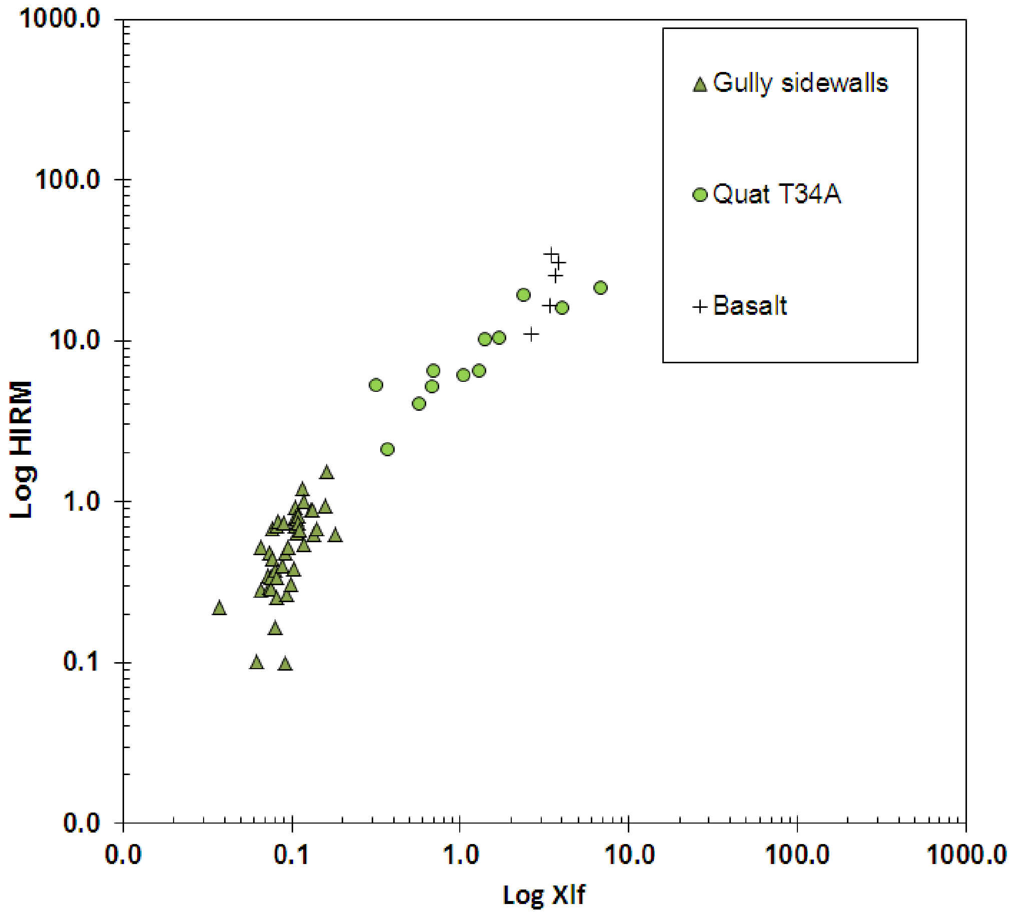


Figure 4.18: Bi-logarithmic scatterplot of magnetic behaviour in the quaternary derived source groups.

A sample collected from the Tinana River catchment footslope, plotted close to the basalt sample that was collected at 0 to 10 cm in the soil profile. Overall, samples collected outside the Makhoaseng catchment were ferrimagnetic in nature and shared no similarities with gully sidewalls.

Sink zones

Samples collected from the deposition zones were compared with the gully sidewall samples (see Fig 4.19).

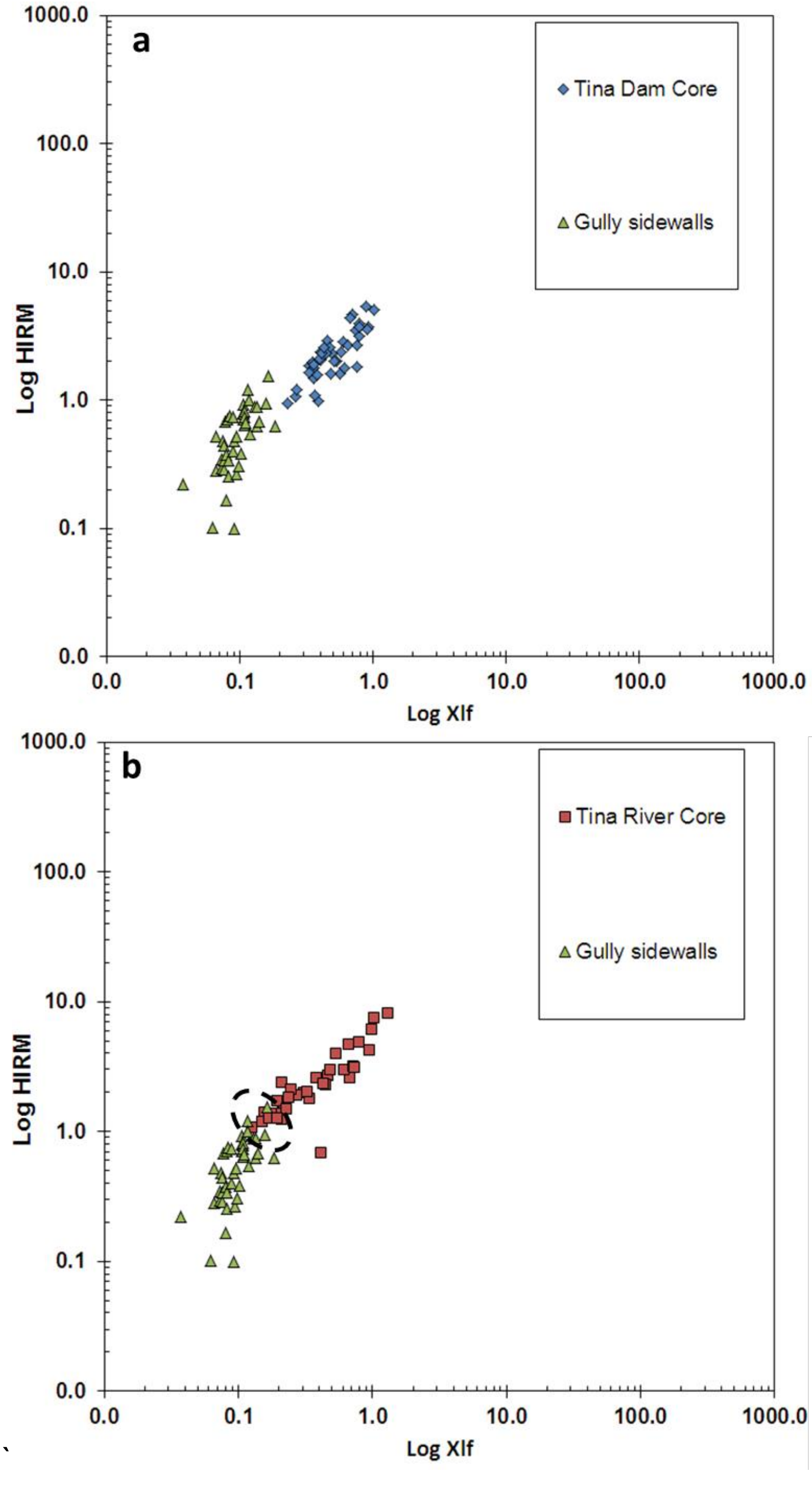


Figure 4.19: Bi-logarithmic scatterplot of magnetic behaviour in the Tina Dam (a) and Tina River (b) cores.

Results indicated that both TRC and TDC had a mixture of ferromagnetic and antiferromagnetic minerals. Soil samples collected from the TDC shared no similarities with gully sidewall samples. In contrast, there were three TRC samples that overlapped with gully sidewall samples. This was plausible as sediment from the Khamopele River catchment is discharged into the Upper Tina River, where the core was collected. The gully samples M3F, TR4D and TL3E, which coincided with TRC samples, correspond to the lowermost soil horizons in Taung and Mhlakeng sample areas. The corresponding TRC samples were TR 8 - 10 cm, TR 24 - 26 cm and TR 46 - 48 cm. These samples were interspersed in the top half of the TRC.

To gain an understanding of the catchment interactions, all the source groups were plotted in one graph (see Figure 4.20). Results clearly indicated that the sink zone samples were a mixture of the other source groups. Another evident pattern was the strong HIRM of samples collected outside Makhoaseng catchment and hillslope samples. The aforementioned groups had moderate to strong ferrimagnetic minerals.

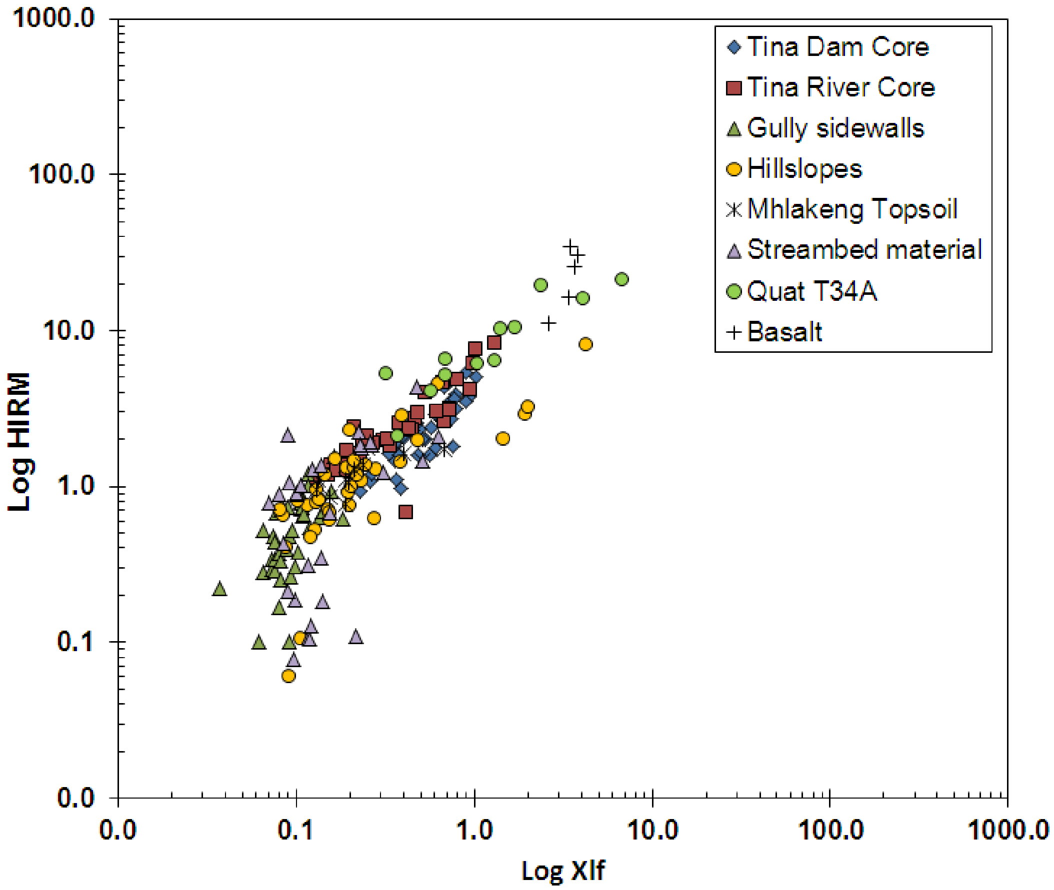


Figure 4.20: Summary bi-logarithmic scatterplot of magnetic behaviour of the collected samples**.**

Samples collected from the gully sidewalls and streambeds were generally antiferromagnetic in nature. With the exception of basalt samples and four hillslope samples, every source group shared similarities with one or both of the sink zone samples. This indicates that the sink zones were devoid of basalt. Two samples from the TRC showed strong ferrimagnetism i.e. the presence of magnetite. In contrast, the TDC was largely antiferromagnetic with few samples in the ferrimagnetic class. Interestingly, the core samples showed a strong clustering together with similar HIRM and χlf. This may be an indicator of the inputs into the sink zones in the Upper Tina River catchment

In summary, the results indicated that sink zones contain differing contributions from the source groups in the Khamopele River catchment and the quaternary catchment. To tease out these relationships further, Section 4.6.4 investigates the composition of the two and a similar exercise was conducted for sink zone samples with graphical representations of the relationships between the source groups and the sink zone samples (see Figure 4.23a to Figure 4.23f).

4.5.4. INTRA-SINK ZONE VARIATION

Another indicator of the ratio of ferromagnetic to antiferromagnetic minerals is the S-Ratio. It is the inverse of the HIRM and was calculated using Equation 6. In contrast to the HIRM, the S-Ratio has a range between 0 and 1.0. The maximum (1.0) represents soft magnetite/haematite; low concentrations represent mineral assemblages dominated by goethite/haematite. The S-Ratio, together with χlf, was used to ascertain trends in the sink zone samples.

Tina Dam Core (TDC)

Results indicated that the TDC was predominantly silty in texture with layers of interbedded clay and fine sand (see Figure 4.21). The observed texture was representative of the sink environment of Mt Fletcher Dam. The organic matter content generally exceeded 6 % with a marked decrease towards the base of the core.

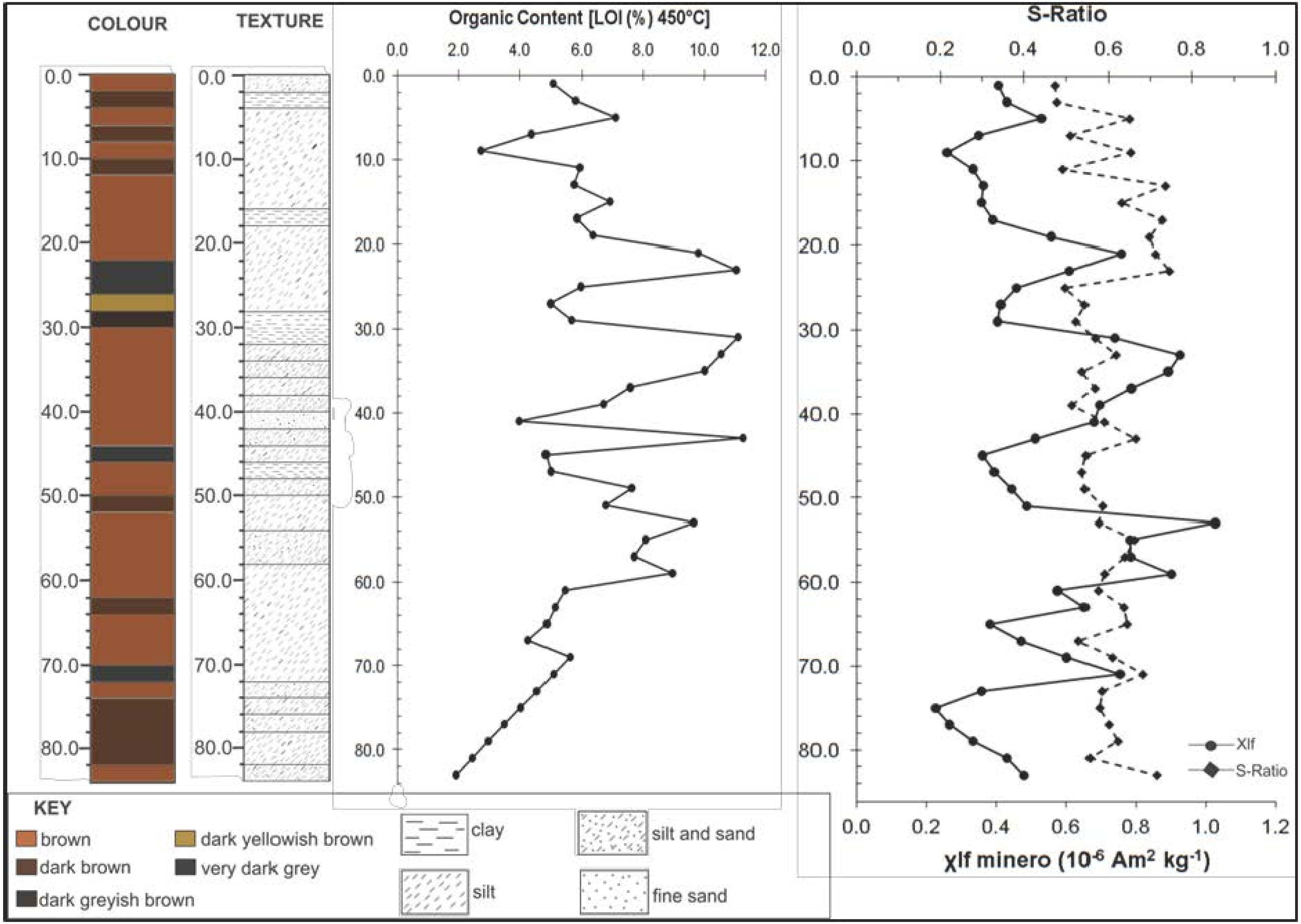


Figure 4.21: Soil profile of the Tina Dam core showing textural, colour and magnetic properties.

Three peaks in the organic matter chart were observed at 23 cm, 31 cm and 43 cm respectively. They show a possible relationship between χlf and organic matter content. The fine sand layer at 40 cm to 42 cm had the lowest organic matter content. The concentration of magnetic minerals (χlf) observed in this layer was also low. This again points to a relationship between organic matter content, grain size and the concentration of iron bearing minerals.

The low frequency mass susceptibility (χlf) trend showed a near cyclical distribution of iron bearing minerals down core. The χlf peak occurred in a silt layer at 53 cm at 1.026×10^{-6} m^3 kg^{-1}. Other χlf peaks occurred at or near the interface of two layers of differing textures. The S-Ratio graph shows that there was a good mix of hard and soft minerals as most of the samples were between 0.5 and 0.6. Overall, the core was marked by an increase in soft minerals (maghaemite/magnetite) as only four samples were below the 0.5 benchmark.

Tina River Core (TRC)

Results from the TRC indicated that texturally the core was dominated by medium sand particles (see Figure 4.22).The abundance of the sand fraction was also attributed to the sampling location, a bar in the Tina River. The organic matter content did not exceed 10 % for any of the sections in the core. Few samples exceeded 5 % and those that did were texturally finer than the rest of the core i.e. silt and fine sand. The rest of the core samples seldom exceeded 3 % organic matter content outside the high 26 cm to 54 cm zone.

Low frequency mass (χlf) susceptibility was variable down core. The uppermost 0 cm to 4 cm section had high χlf values followed by a gradual decrease until a peak χlf at 33 cm (1.25×10^{-6} m^{-3} kg^{-1}). The peak area which lies between 25 cm to 47 cm corresponded with the highest organic matter content sections in the core. A decreasing trend of χlf with alternating peaks no greater than 1.0×10^{-6} m^{-3} kg^{-1} continued until the end of the core. The lowest χlf values coincided with the boundaries of medium silt and medium sand. The lower section of the core was texturally coarse and represented river gravels and sand which had high χlf values. The S-Ratio followed a similar trend to χlf with the distinct phase peaks. The S-Ratio trend shows that there was a dominance of hard (goethite/haematite) minerals.

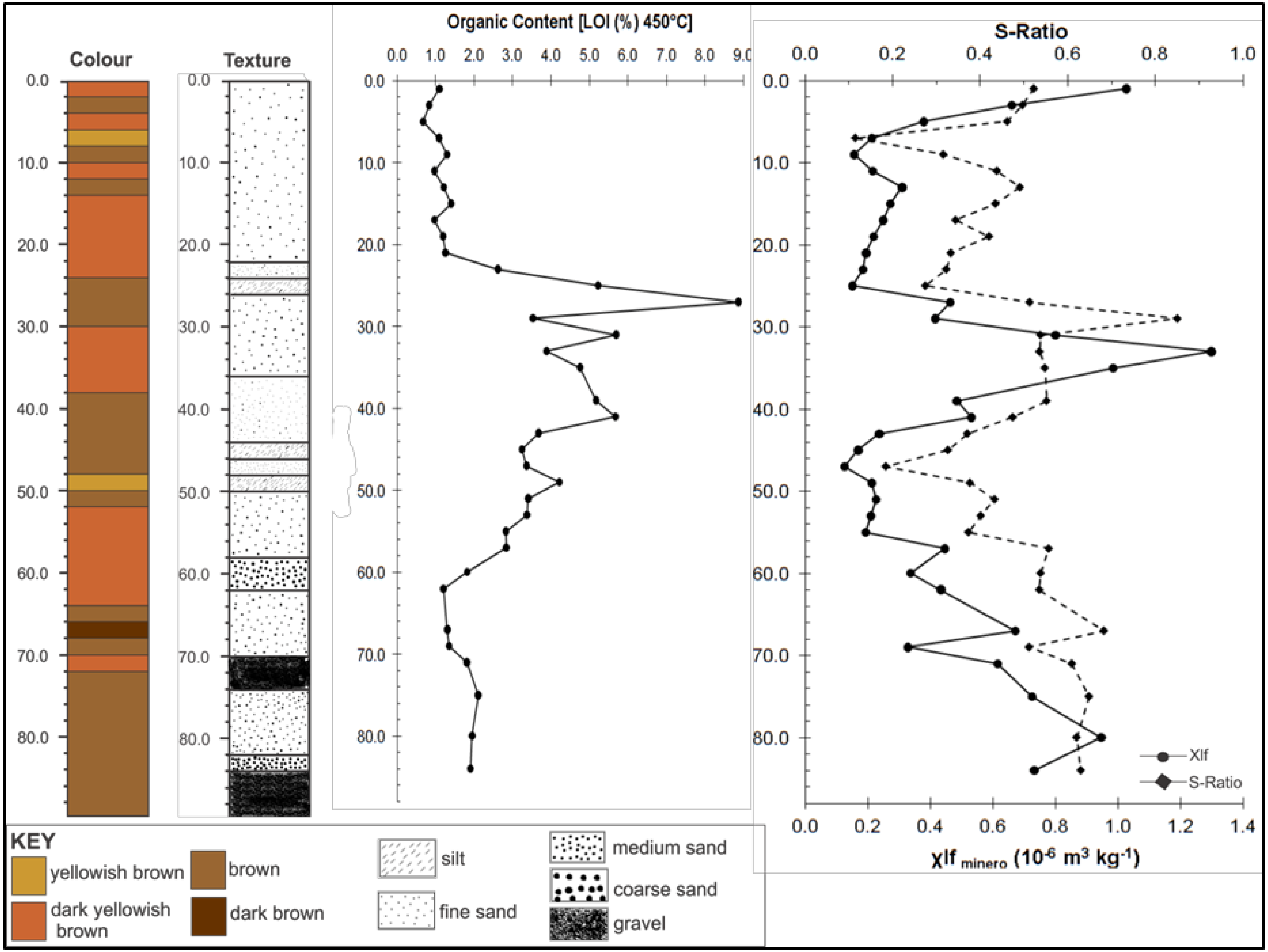


Figure 4.22: Soil profile of the Tina River core showing textural, colour and magnetic properties.

This section provides a description of the different source group interactions with the two cores. The results are depicted in Figure 4.23a to 4.23f.

Gully sidewalls

The results show that gully sidewall samples shared no similarities with samples collected from the TDC (see Figure 4.23a). However, these samples did share similarities with the TRC.

Mhlakeng Topsoil

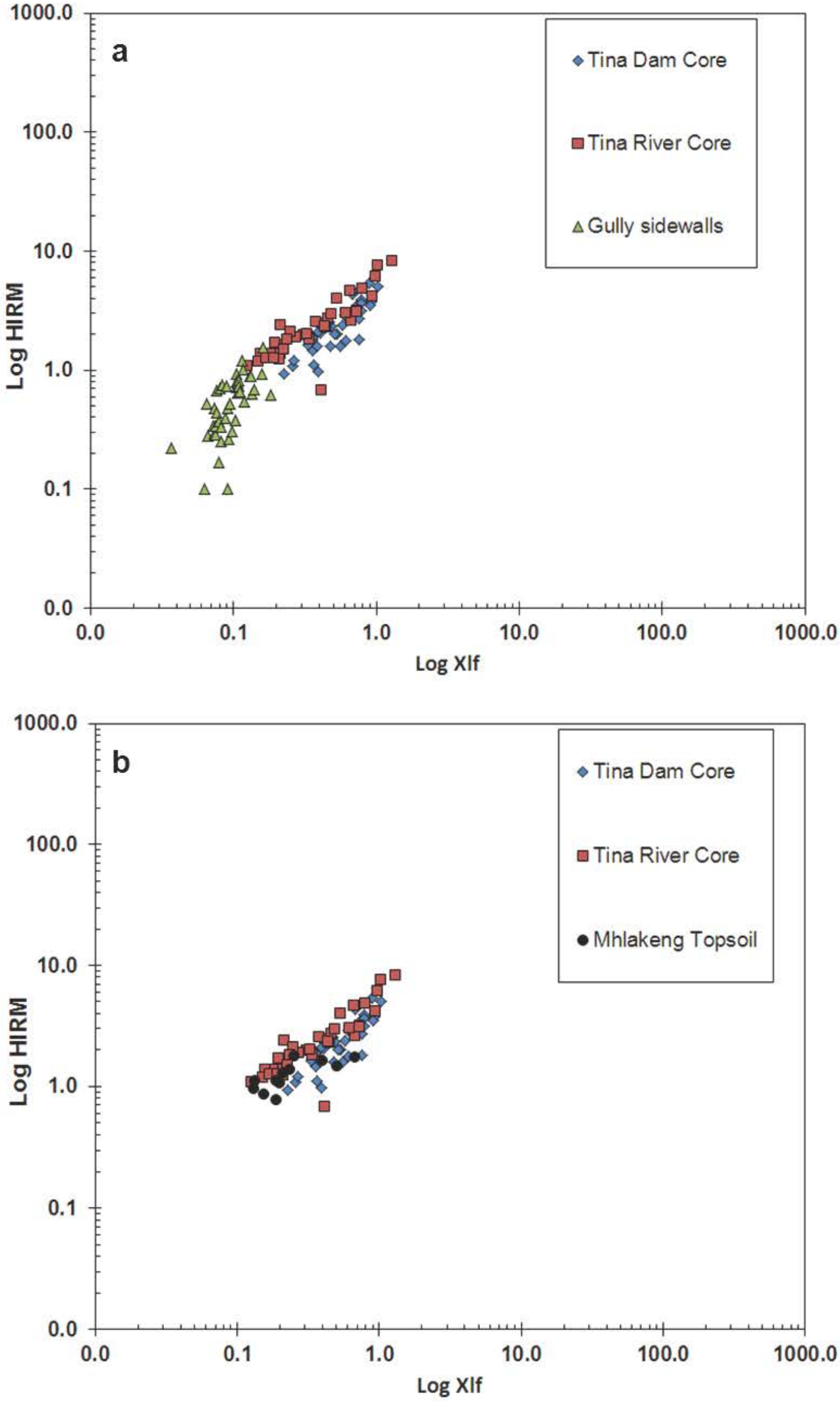
Topsoil samples shared similarities with both cores but more topsoil samples plot in the same vicinity as the TRC (see Figure 4.23b). Interestingly, there were three samples which coincided with samples collected from Mount Fletcher dam. This may be due to grain size effect and the ease of transporting topsoil downstream. The topsoil samples showed good overlap with the sink zone samples and were wholly encased within the envelope of the two sink zone source groups.

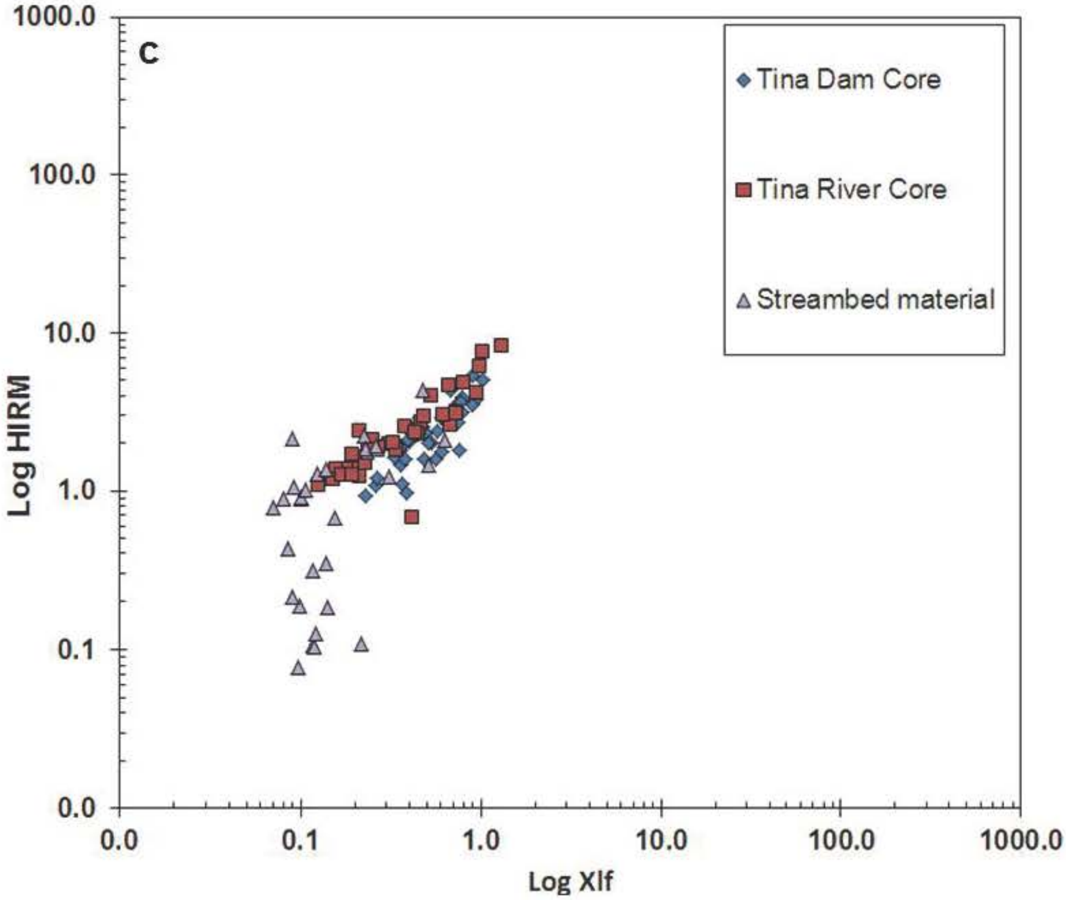
Streambed material

Besides the low cluster of antiferromagnetic samples in the streambed source group, most samples in the group plotted in the same vicinity as the two cores. An obvious characteristic of streambed samples was their low χlf (see Figure 4.23c).

Hillslopes

Similar to streambed samples, hillslope derived samples indicated a spread in the data (see Fig 4.23d). There were two groups which did not share the characteristics of other soil samples. One of these groups consisted of two samples (Ghsp and Rhsp) which had antiferromagnetic minerals i.e. low HIRM. Both samples were collected near the drainage divide in the Taung sample area and collected where there was exposed bedrock. The second group had four samples and had high HIRM and χlf when compared to the rest of the hillslope samples. The highest three samples were collected behind the village (south on Figure 2.1). The last sample in this group was collected after veld burning on a hillslope towards the confluence of the Tina and the Khamopele Rivers.


a
Tina Dam Core
Tina River Core
Gully sidewalls
Log HIRM
Log Xlf
1000.0
100.0
10.0
1.0
0.1
0.0
b
Tina Dam Core
Tina River Core
Mhlakeng Topsoil
Log HIRM
Log Xlf


c
Tina Dam Core
Tina River Core
Streambed material
Log HIRM
Log Xlf
1000.0
100.0
10.0
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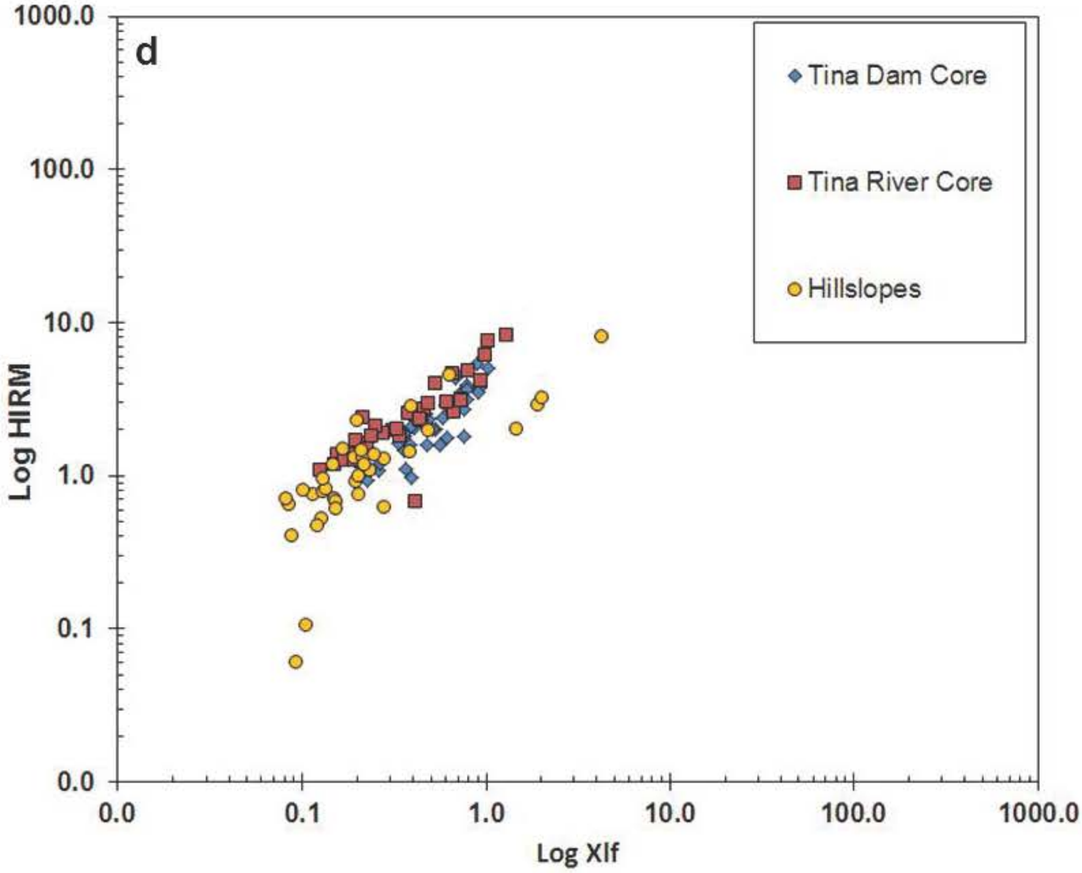

d
Tina Dam Core
Tina River Core
Hillslopes
Log HIRM
Log Xlf
1000.0
100.0
10.0
1.0
0.1
0.0
0.0
0.1
1.0
10.0
100.0
1000.0

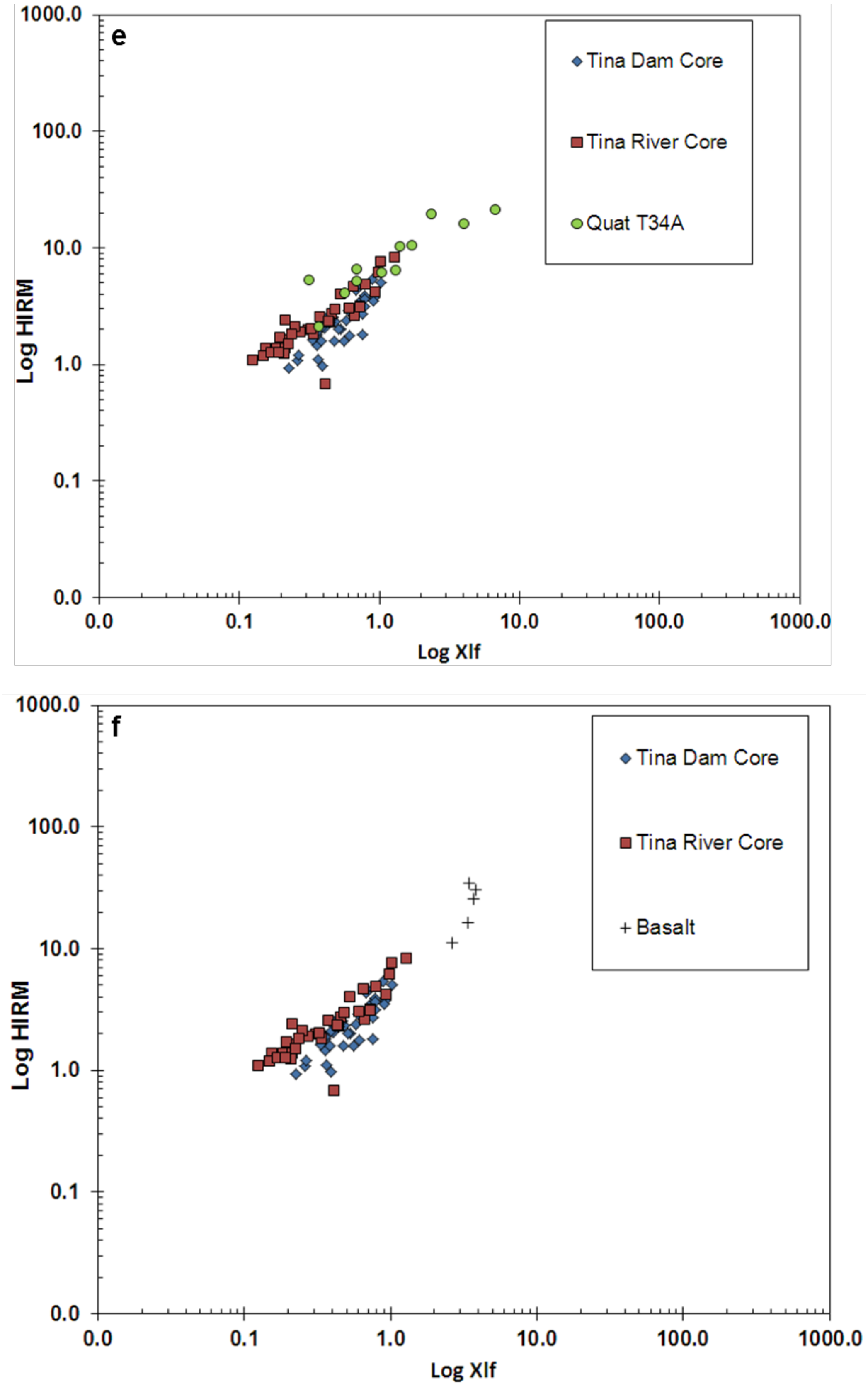


Figure 4.23: Bi-logarithmic scatterplot indicating magnetic behaviour in gully sidewall (a), Mhlakeng topsoil (b), streambed material (c), hillslopes (d), upper Tina River quaternary catchments (e) and basalt (f) source groups in contrast to core samples.

Quaternary derived sediment

Soil samples collected outside the Khamopele River catchment had similar mineralogy to samples collected from the sink zones, particularly samples from the TRC. Three samples collected in quaternary catchment T34 shared the same mineralogy as the TRC. Two of the samples, Lower Tina River and Lower Tina bank, were collected in the same reach as the TRC. They correspond with the sections 34 to 36 cm and 40 to 42 cm in the TRC. The remaining sample was collected on a bank of the Phiri-e-Ntso River. The mineralogy of the aforementioned sample matched the 2 to 4 cm of the TRC. Overall, the samples collected outside the Khamopele River catchment had moderate to strong ferrimagnetic mineralogy.

Basalt

The basalt source group was distinctly different from the two cores. The five basalt samples had a high concentration of iron bearing minerals and high HIRM. The basalt samples were wholly ferrimagnetic and indicated that basalt was not present in depositional zones in the catchment.

4.5.5. MINERAL AND VOLUME CONCENTRATION

The final indicator that was used to separate out the source groups was the Saturation Isothermal Remanence (SIRM). The SIRM represents the magnetisation when the maximum field is induced in a sample. It was an indicator of the volume concentration of magnetic minerals (Lees, 1994). It is compared to χlf, which is an indicator of the concentration of iron minerals in a sample. All the results are presented in a bi-logarithmic plot of χlf vs SIRM.

This section follows a different presentation style in that the all the source areas are presented first and then investigated separately (see Figure 4.24). The labels depicted on the bi-logarithmic are those used in Thomas and Oldfield (1986).

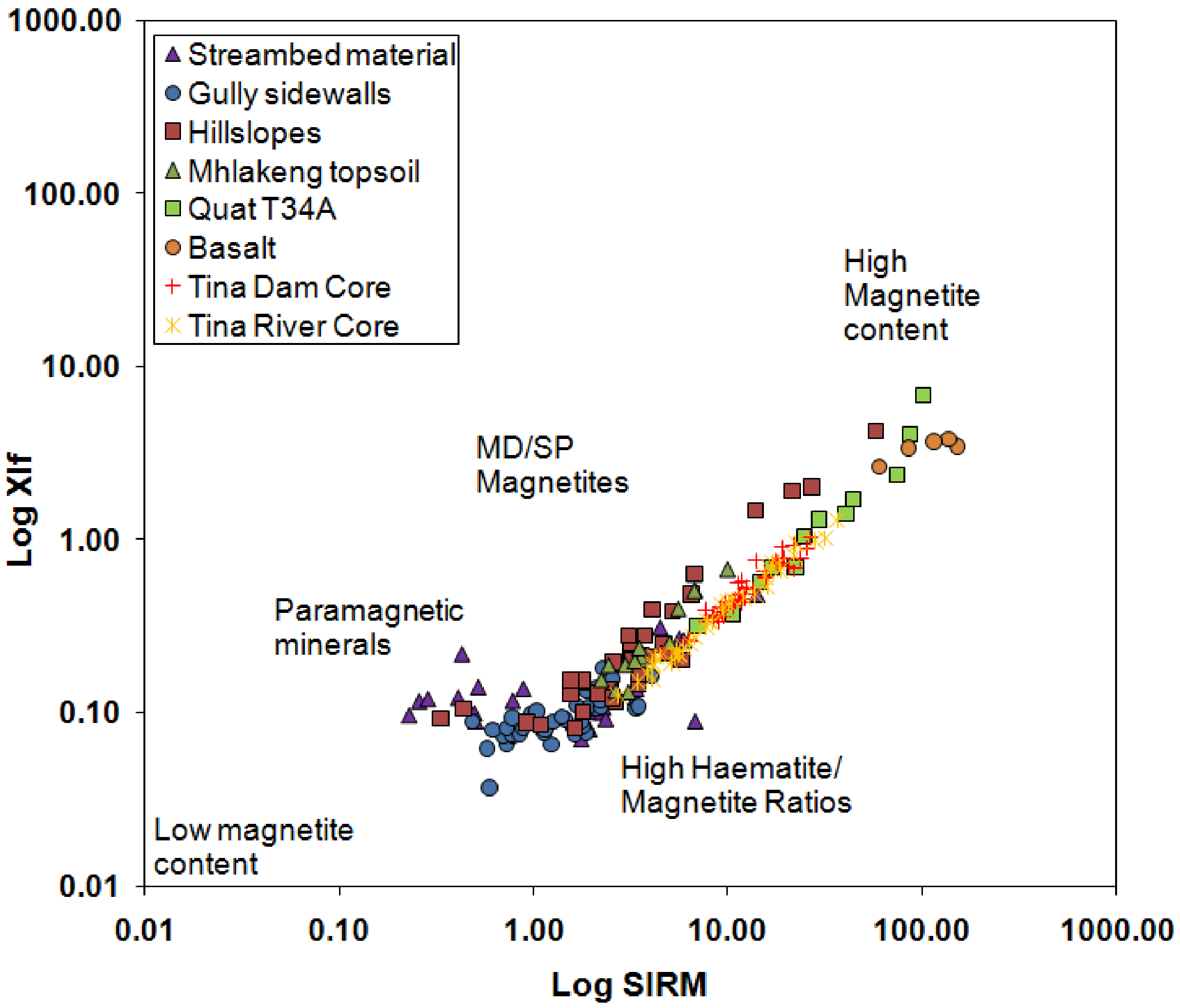


Figure 4.24: Summary bi-logarithmic graph of magnetic concentration.

The results indicated that samples collected in the study were a mixture of paramagnetic, ferrimagnetic and antiferromagnetic minerals. Samples that most represented paramagnetic minerals were streambed samples from Mhlakeng and Taung sample areas. One streambed sample (AS1) collected at the Tina and the Khamopele River confluence had haematite mineralogy.

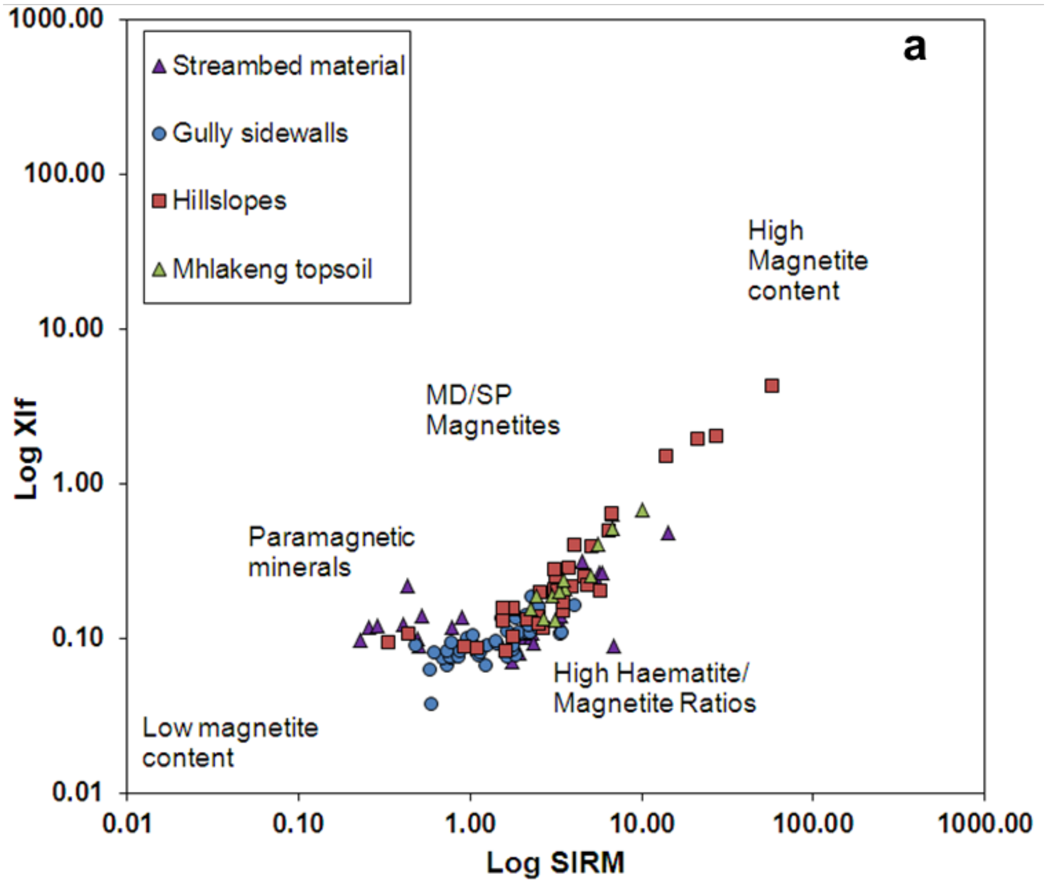
Samples collected from rivers in quaternary T34A and basalt had higher concentrations of magnetic minerals and high volume concentrations of the same minerals. These samples generally had maghaemite and magnetite mineralogy. Hillslope samples with highest magnetite content were collected behind the village (three samples) and the sample (S2) collected after veld burning.

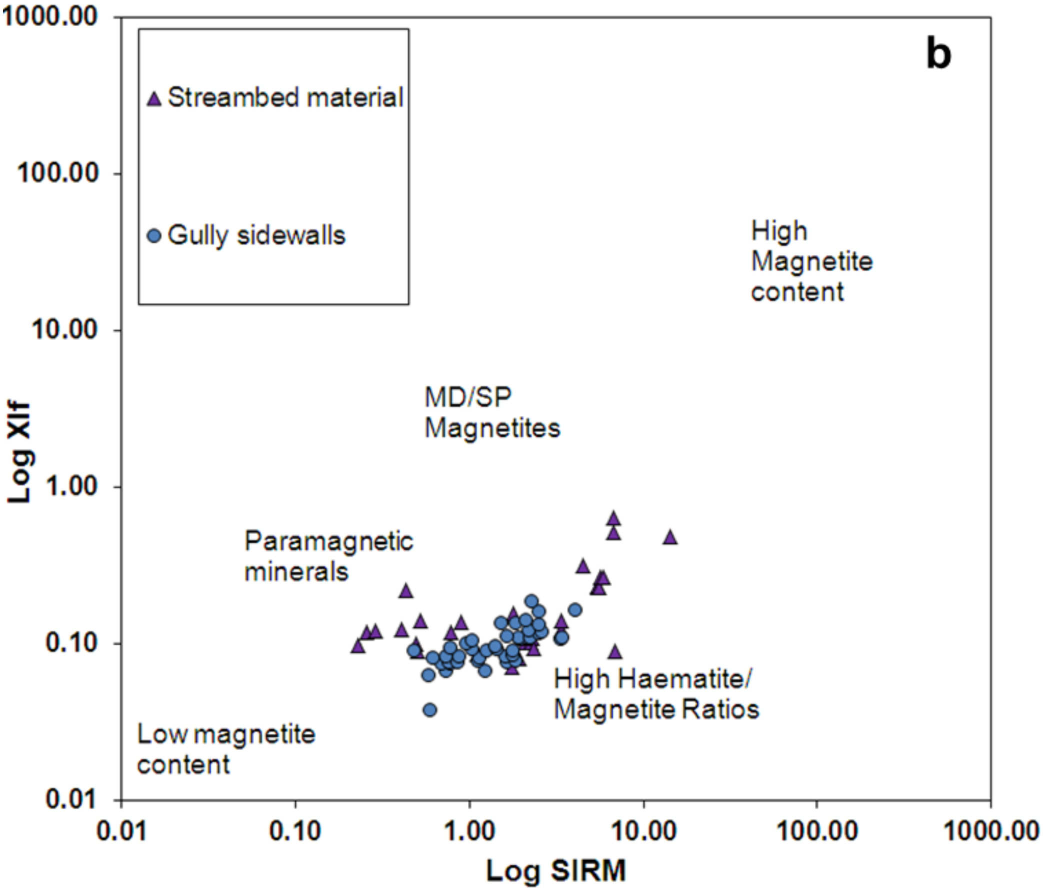
Makhoaseng catchment

Concentration and volume concentration results from Makhoaseng catchment indicated that there were four hillslope samples which had high magnetite contents (see Figure 4.25a). These samples have been mentioned above. Two streambed samples were outside this cluster i.e. they had high SIRM. One of these samples BS7 (high SIRM) was collected in the river channel in the Lower Khamopele sample area. The second sample, AS1, was collected at a bar at the confluence of the Tina and Khamopele rivers.

A closer look at samples collected from streambeds in Makhoaseng catchment showed that only eleven (37 %) samples coincided with gully samples in the scatterplot area (see Figure 4.25b). There were two breakaway groups within the streambed samples. The first group was between χlf 0.09 and 0.14 in the scatterplot. The second group was between SIRM 7 and 20. These samples represented the opposite ends in terms of volume concentration in streambed samples. The streambed samples were antiferromagnetic in nature with samples from the second group indicating increasing ferrimagnetic content.

The same parameters (SIRM and χlf) were applied to topsoil samples collected in the Mhlakeng sample area (see Figure 4.25c). Three topsoil samples (C3, Wet 1a and Wet 6) coincided with gully samples in the scatterplot. Interestingly, with the exception of sample C3, the two topsoil samples matched gully samples TR3A and TR4A which were from Taung sample area. These samples had similar magnetic concentrations as the uppermost soil horizons in the adjacent Taung sample area gullies. Sample C3 shared similar SIRM and χlf as sample M3F. This sample was collected from the sixth soil horizon (200 cm – 260 cm) in gully M3 in Mhlakeng sample area. This apparent disjuncture in deposition sequence may indicate soil loss in the catchment or the redistribution of soil horizons by anthropogenic related activities such as farming, brickmaking and stocking.


a
Streambed material
Gully sidewalls
Hillslopes
Mhlakeng topsoil
High
Magnetite
content
MD/SP
Magnetites
Paramagnetic
minerals
High Haematite/
Magnetite Ratios
Low magnetite
content
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00
Log Xlf
Log SIRM


b
Streambed material
Gully sidewalls
High
Magnetite
content
MD/SP
Magnetites
Paramagnetic
minerals
High Haematite/
Magnetite Ratios
Low magnetite
content
1000.00
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
100.00
1000.00
Log Xlf
Log SIRM

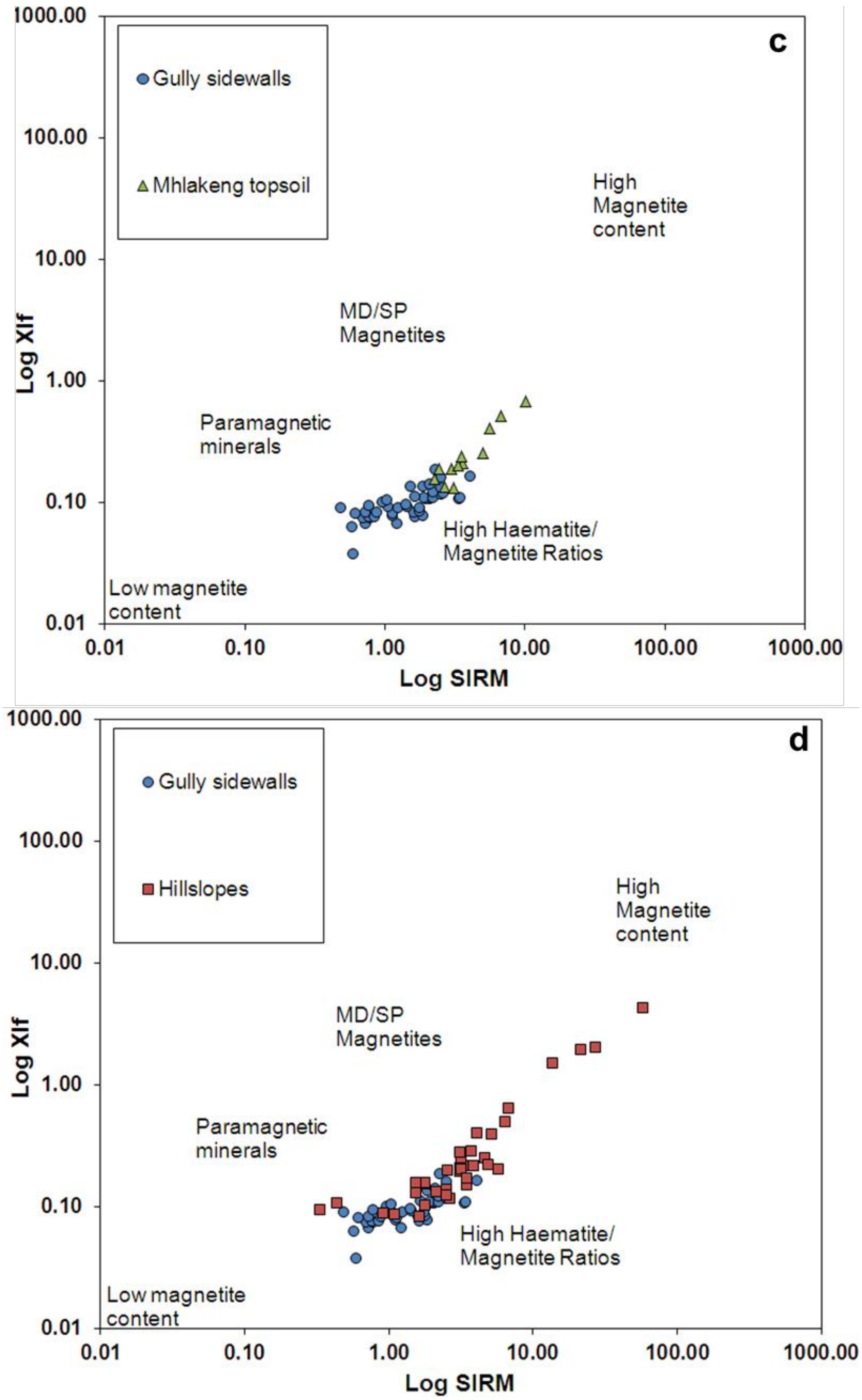


Figure 4.25: Bi-logarithmic graph of magnetic concentration in the Khamopele River catchment samples (a), and gully sidewall samples (b), Mhlakeng Topsoil catchment samples (c) and hillslope samples (d).

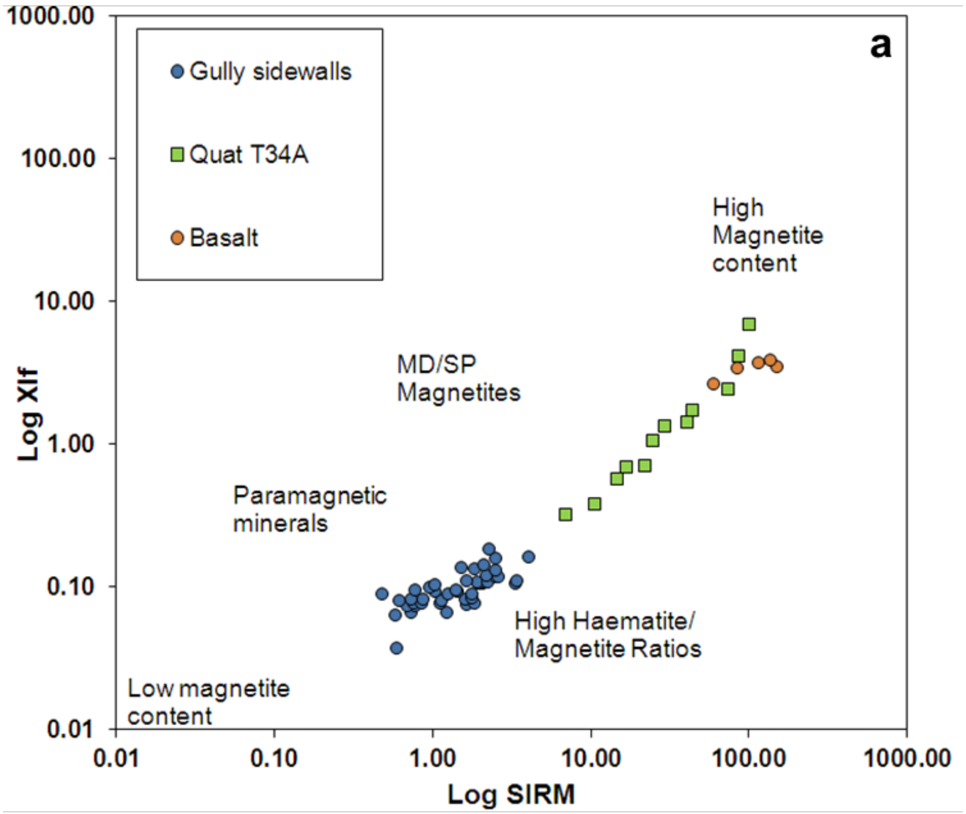
Lastly, hillslope samples were compared with gully sidewall samples (see Figure 4.25d). There were two hillslope samples that had low χlf and SIRM, they represented 5 % of hillslope samples. These samples were Ghlsp and Rhlsp collected at the rim of Taung sample area i.e. upper slopes of Taung sample area. There were 21 samples that shared similar concentration and volume concentration as the gully samples. These samples account for 38 % of all hillslope samples. The remaining 57 % of samples indicated increasing ferrimagnetic concentration and indicated separation from the gullies. Therefore, approximately 40 % of hillslope samples collected in Makhaoseng catchment shared similar mineralogy as samples collected from gully sidewalls. Hillslope samples that were similar to gully sidewalls were predominantly from Taung sample area. This may be an indicator of the transport rates and mechanisms in the Taung sample area.

Quaternary derived sediments

Soil samples collected from banks and channels in quaternary T34A (see Figure 4.26a) showed distinctly different mineral concentrations and volume concentrations of magnetic minerals to gully sidewall samples. There was no overlap of samples collected from quaternary T34A, basalt and the gully sidewall samples. These samples clearly indicate the antiferromagnetic (gully sidewalls) and ferromagnetic (basalt and quaternary T34A) groupings.

Sink zones

In contrast to samples collected at river channels and banks of the quaternary catchment, samples in depositional environments did not have a clear break from gully samples (see Figure 4.26b). In fact, three samples from the TRC overlapped gully samples TL3E and M3F. The aforementioned gully samples represented the lowest soil horizons in the gully profiles. They provided evidence of sediment mobility as a result of under-cutting in gullies. Gully sample M3F was collected in Mhlakeng sample area and has similar magnetic concentration as the TRC in section 46 to 48 cm. Gully sample TL3E shares similar mineralogy as the TRC in sections 8 to 10 cm and 44 to 46 cm.



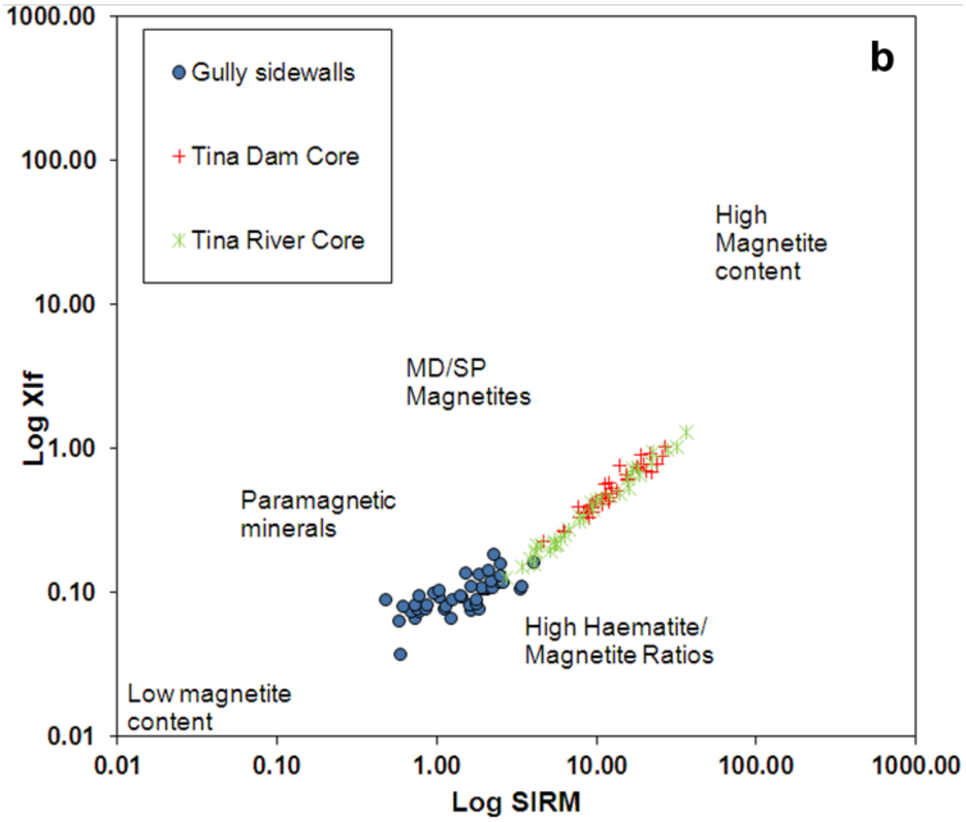


Figure 4.26: Bi-logarithmic graph of magnetic concentration in upper Tina River quaternary catchment samples (a) and cores (b).

None of the samples collected from TDC matched samples from gully sidewalls. This indicates that samples from Mt Fletcher Dam have different mineralogy and concentration when compared to gully sidewall samples.

In summary, out of 218 samples collected in the study 128 soil samples positively indicated the presence of iron oxides. The 128 samples represent 59 % of all magnetic samples. Results indicated that the magnetite-maghaemite class had the largest combined iron oxide mineralogy. Source areas that were excluded from this class were the basalt and gully sidewall samples. They indicated the opposite mineralogies with basalt samples indicating the highly ferrimagnetic magnetite and gully sidewalls the antiferromagnetic goethite class. Samples from sink zones indicated a good mix of ferrimagnetic and antiferromagnetic minerals. They also had strong clustering indicating similarity in mineralogy.

4.5.6. STATISTICAL RESULTS

Cluster Analysis Results

Step 1: The factor analysis showed that two factors constituted the variation in the data. This was indicated by factors that had total Eigen values above 1 in Table 4.5.

Table 4.5: Total Variance in study samples**.**

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	**6.456**	71.736	71.736	6.456	71.736	71.736
2	**1.199**	13.326	85.061	1.199	13.326	85.061
3	.777	8.630	93.692			
4	.443	4.925	98.617			
5	.074	.825	99.441			
6	.024	.270	99.712			
7	.017	.184	99.895			
8	.008	.090	99.985			
9	.001	.015	100.000			

Extraction Method: Principal Component Analysis.

These two factors account for 85.06 % of the variation in the data. These factors were extracted and factor scores were used in the cluster analysis. The first factor consisted of χlf, ARM, IRM, χARM, SIRM, χfd, HIRM whilst the second factor was made up $\chi fd\%$ and the S-Ratio as shown in Table 4.6.

Table 4.6: Component Matrix

	Component	
	1	2
χlf	**.986**	.018
ARM	**.960**	.098
IRM	**.959**	.120
χ_{ARM}	**.956**	.090
SIRM	**.951**	-.118
χ_{fd}	**.912**	.244
HIRM	**.911**	-.094
$\chi_{fd\%}$	.121	**.882**
S-Ratio	.385	**.554**

Extraction Method: Principal Component Analysis.

Step 2: The factor scores from the model were saved and used in the Hierarchical cluster analysis. The agglomeration schedule indicated that three clusters were required (see Table 4.7).

Table 4.7: Final cluster centres.

	Cluster		
	1	2	3
REGR factor score 1 for analysis 1	-.09144	-.34164	4.23629
REGR factor score 2 for analysis 1	-.63470	1.06775	.36287

Step 3: The change in the correlation coefficients was greatest from stage 216 to 215 (see agglomeration schedule in Appendix F) i.e. 124.460 - 100.508 = 23.952, further supporting the use of three clusters. The number of cases in each cluster was as follows: Cluster 1 = 133, Cluster 2 = 76 and Cluster 3 = 9. The results of the cluster analysis on all collected samples are summarized in the *k*-means cluster analysis shown in Figure 2.28.

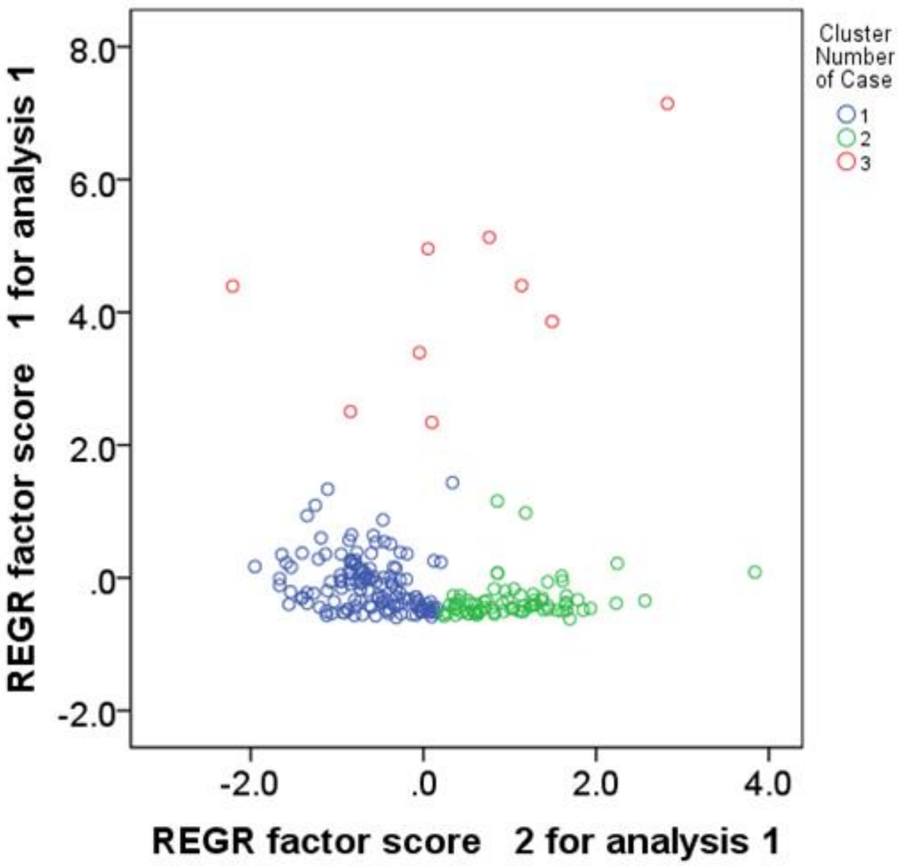


Figure 4.27: *k*-means cluster of catchment derived samples.

The results from the *k*-means cluster analysis were symbolised to indicate the different source groups (see Figure 4.29). Results indicated that cluster 1 largely consisted of samples collected from the two cores and samples collected in quaternary T34A.

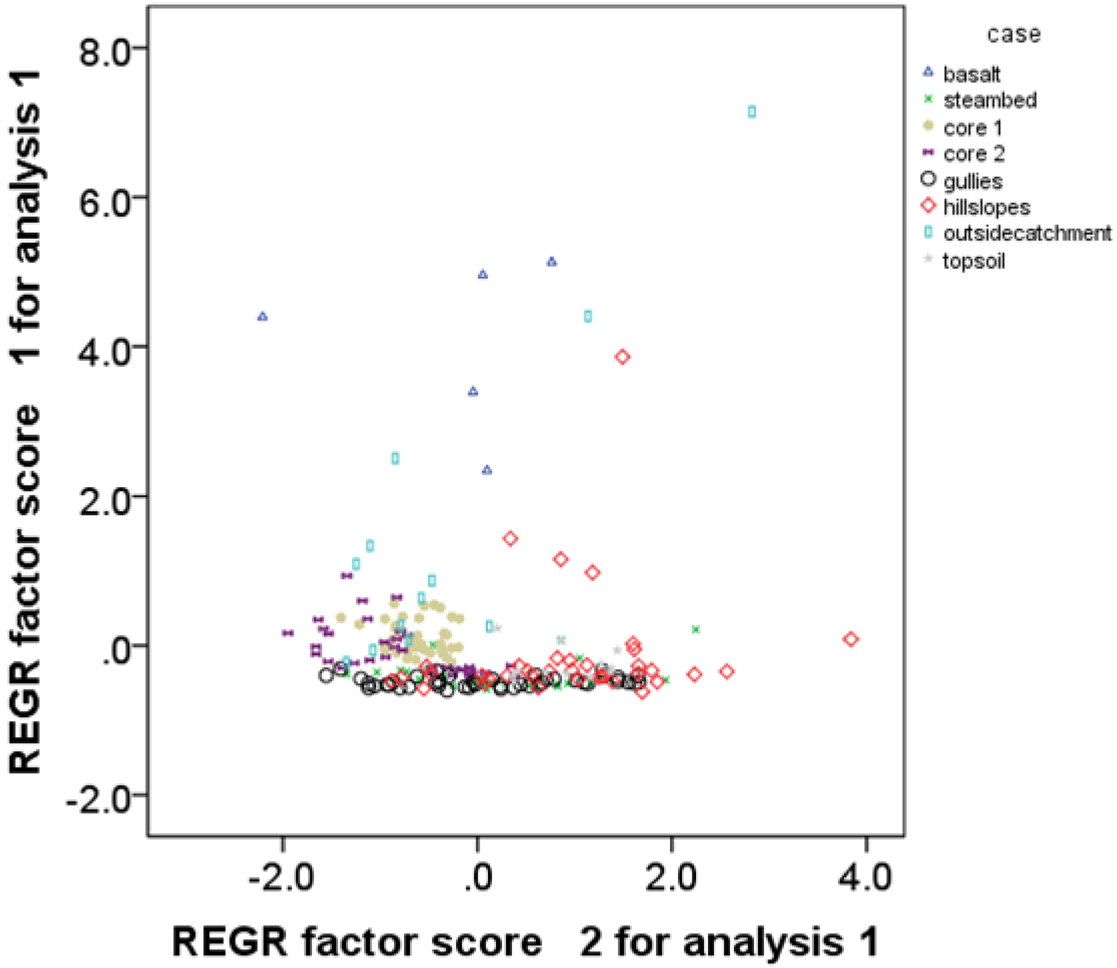


Figure 4.28: *k*-means cluster of source groups**.**

Cluster 2 largely consisted of samples collected from hillslopes, gullies, streambed and topsoil samples from Mhlakeng sample area. Cluster 3 consisted of basalt, samples from the quaternary catchment and a small proportion (0.5 %) of hillslope samples. With the exception of three samples from Core 2, all samples from sink zones were in cluster 1.

The cross tabulation shown in Table 4.8 summarizes the cluster breakdown per source area.

Table 4.8: Cluster Analysis for magnetic study samples.

			Ward Method clusters			Total
			1	2	3	
SOURCE AREA	Basalt	Count	0	0	5	5
		% of Total	.0%	.0%	**2.3%**	2.3%
	Streambed material	Count	16	14	0	30
		% of Total	7.3%	**6.4%**	.0%	13.8%
	Core 1	Count	42	0	0	42
		% of Total	**19.3%**	.0%	.0%	19.3%
	Core 2	Count	33	3	0	36
		% of Total	**15.1%**	1.4%	.0%	16.5%
	Gully sidewall	Count	23	21	0	44
		% of Total	**10.6%**	**9.6%**	.0%	20.2%
	Hillslopes	Count	9	27	1	37
		% of Total	4.1%	**12.4%**	**.5%**	17.0%
	Quat T34A	Count	9	0	3	12
		% of Total	4.1%	.0%	**1.4%**	5.5%
	Mhlakeng topsoil	Count	1	11	0	12
		% of Total	0.5%	5.0%	.0%	5.5%
Total		Count	133	76	9	218
		% of Total	61.0%	34.9%	4.1%	100.0%

Results indicated that 61.0 % of the data from all the locations was similarly grouped in cluster 1. Only 34.9 % of the data was in cluster 2 whilst 4.1 % of the data was grouped into cluster 3. The difference between cluster means was determined using a one way ANOVA. The results are shown in Table 4.9.

Table 4.9: ANOVA results.

		Sum of Squares	df	Mean Square	F	Sig.
χfd%	Between Groups	888.936	2	444.468	132.703	.000
	Within Groups	720.110	215	3.349		
	Total	1609.046	217			
χlf	Between Groups	107.346	2	53.673	333.267	.000
	Within Groups	34.626	215	.161		
	Total	141.973	217			
χfd	Between Groups	586825.430	2	293412.715	182.851	.000
	Within Groups	345000.589	215	1604.654		
	Total	931826.019	217			
ARM	Between Groups	10.909	2	5.454	257.953	.000
	Within Groups	4.546	215	.021		
	Total	15.455	217			
χARM	Between Groups	10844.696	2	5422.348	283.306	.000
	Within Groups	4115.007	215	19.140		
	Total	14959.704	217			
SIRM	Between Groups	71139.467	2	35569.734	386.997	.000
	Within Groups	19761.141	215	91.912		
	Total	90900.609	217			
S-Ratio	Between Groups	2.696	2	1.348	41.741	.000
	Within Groups	6.944	215	.032		
	Total	9.640	217			
IRM	Between Groups	21374.577	2	10687.289	351.236	.000
	Within Groups	6541.944	215	30.428		
	Total	27916.521	217			
HIRM	Between Groups	3032.422	2	1516.211	287.788	.000
	Within Groups	1132.726	215	5.268		
	Total	4165.148	217			

At the 5 % significance level H_0 was rejected as the p-values were less than 0.05. This indicated that there was a difference in the cluster mean χlf %, χlf, χfd, ARM, χ_{ARM}, SIRM, S-Ratio, IRM, HIRM with respect to the different sources.

b) MANOVA RESULTS

Step 1: Box's M test was used to test for the homogeneity of covariance matrices. The results are shown in Table 4.10.

Table 4.10: Box's Test of Equality of Covariance Matrices.

Box's M	4836.797
F	14.558
df1	270
df2	11943.118
Sig.	.002

Since the p-value was 0.002, it was concluded that there was dissimilarity of variance within the MANOVA as 0.002 is greater than the recommended test level of significance of 0.001.

Step 2: Multivariate tests of significance were carried out to test whether there were significant group differences on a linear combination of the dependent variables (Table 4.11). Pillai's Trace criterion was used as it able to provide nuance when there has been a violation of assumption (Van Dyke *et al.*, 2010).

Table 4.11: Multivariate Tests [c]

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	.938	338.458[a]	9.000	202.000	.000
	Wilks' Lambda	.062	338.458[a]	9.000	202.000	.000
	Hotelling's Trace	15.080	338.458[a]	9.000	202.000	.000
	Roy's Largest Root	15.080	338.458[a]	9.000	202.000	.000
group	Pillai's Trace	1.909	8.667	63.000	1456.000	.000
	Wilks' Lambda	.049	12.877	63.000	1143.783	.000
	Hotelling's Trace	5.932	18.857	63.000	1402.000	.000
	Roy's Largest Root	4.165	96.268[b]	9.000	208.000	.000

a. Exact statistic

b. The statistic is an upper bound on F that yields a lower bound on the significance level.

c. Design: Intercept + group

Since the Pillai's statistic was significant at the 5 % level, this was interpreted as a significant multivariate group or location effect i.e. location effects are significantly different. This indicated that TDC, TRC, gully sidewalls, hillslopes, Mhlakeng topsoil, streambed material, quaternary T34A and basalt were significantly different.

Since all the p-values were less than 0.05 and even to a corrected Bonferroni-type adjustment of significance, the p-values were all significant and it was concluded that there was a difference in the mean χfd%, χlf, χfd, ARM, χ_{ARM}, SIRM, S-Ratio, IRM, HIRM with respect to the different source area sample groups.

Step 3: In order to asses where the differences between the locations were, the Least Squares Differences (LSD) multiple comparisons were used. The results are summarised in the Table 4.12. Grey shading indicates that there was significant difference at the 5 % level.

Table 4.12: Least Squared Differences of χlf for all magnetic study samples (significance at the 5 % level represented in grey shading).

	TDC	TRC	Gullies	Hillslopes	Topsoil	Streambed material	Quat T34	Basalt
TDC								
TRC								
Gullies								
Hillslopes								
Topsoil								
Streambed material								
Quat T34								
Basalt								

Table 4.12 shows that besides the gully samples being different from the TDC, no other relationships could be established within the Khamopele catchment source area samples. This was because the values of the samples collected in quaternary T34A and Basalt had higher χlf than other source areas.

To determine whether the high χlf samples had an impact on the LSD results, these two source area groups were removed from the comparison (see Table 4.13).

Table 4.13: Least Squared Differences of χlf for samples excluding Basalt and samples collected outside the Khamopele River catchment (significance at the 5 % level represented in grey shading).

	TDC	TRC	Gullies	Hillslopes	Topsoil	Streambed material
TDC						
TRC						
Gullies						
Hillslopes						
Topsoil						
Streambed material						

The results indicated that in terms of χlf, source areas that were similar to the TDC were the TRC and hillslope samples. In addition to the aforementioned source groups, the TRC was similar to topsoil samples collected in Mhlakeng sample area.

Gully samples were different to both cores and hillslope samples. Gully samples were similar only to topsoil and streambed samples. Hillslope samples were similar to one source area in the Khamopele River catchment. This source area was topsoil from Mhlakeng sample area. Interestingly, similarities between sediment deposited in both sink zones and hillslopes existed.

Topsoil samples were similar to all sample areas except samples collected from the TDC. Soil samples collected instream in Makhoaseng catchment showed significant differences from samples collected in TDC, TRC and hillslopes. Streambed samples were most similar to samples collected from the gully and Mhlakeng topsoil source groups.

In summary, results from the environmental magnetic tracing analyses revealed that gully sidewalls samples were different to other iron oxides as they were the only group to exhibit goethite mineralogy. The difference of the gully sidewall source group to the quaternary derived sediments and TDC was further highlighted by the HIRM and SIRM comparisons to χlf. The LSD statistical analysis showed that gullies were similar to only two source groups, the Mhlakeng topsoil and streambed material groups. In addition, only three samples from the gully sidewall group matched soil from the TRC. Statistical results indicated that there was a significant difference at the 5% level between gully samples and the TRC. This implies that eroded sediment in catchments similar to the Khamopele River catchment was sourced from soil eroded from hillslopes and topsoil. These source groups were statistically similar to the TRC and TDC.

4.5.7. GAMMA SPECTROSCOPY RESULTS

Sixty three soil samples were analysed for ^{137}Cs and their source area breakdown is shown in Table 4.14. Most of the soil samples were collected in the Khamopele River catchment to test whether soils in the catchment had remnant ^{137}Cs. Most of the samples that were used were collected from the various sampling efforts in Makhoaseng catchment. Plough layer samples (0 cm – 20 cm) were collected to specifically test for the presence of ^{137}Cs in Taung sample area. The hillslope samples represent those collected in the Khamopele River catchment i.e. behind the village and Makhoaseng catchment. Their depth was 0 cm - 5 cm. Confluence samples were collected during the low flow period from the confluences of rivers in Makhoaseng catchment. Badland samples represent samples from Makhoaseng catchment and represent the interfluve and gullies. Their depth was 10 cm – 15 cm. Core samples are represented by locality, “TR” denotes samples collected below the confluence of the Khamopele and Tina Rivers. Samples with a prefix “TC” represent samples that were collected from Mt Fletcher Dam.

Table 4.14: Source areas and samples tested for ^{137}Cs.

Source area	Sample ID	
Hillslopes (n =6)	Rhlsp BGL11$_{HILL}$ CH11 Ghlsp CH1 CH12	
Confluence samples (n = 18)	BS1a BS4 TJSTR BS2a BS5 Z1 BS2b BS6 BS3a BS7 BS3b Taung R2	
Plough Layers	Taung LHS0 Taung LHS1 Taung RHS1 Taung RHS2 Taung RHS3	
Badland areas (n = 13)	BGL3 BGL3UNIC BGL7$_{top}$ BGL2$_{top}$ BGL3$_{lwst}$ BGL10A BGL3$_{GF}$ BGL7$_{bottom}$ BGL10$_{bottom}$ BGL13$_{top}$ BGR3 BGR3$_{mid2}$ CS1	
Cores (n = 26)	*Tina Dam core* (n = 19) TC 0 – 2 cm TC 2 – 4 cm TC 4 – 6 cm TC 6 – 8 cm TC 8 – 10 cm TC 10 – 12 cm TC 12 – 14 cm TC 14 – 16 cm TC 20 – 22 cm TC 32 – 34 cm TC 44 – 46 cm TC 36 – 38 cm TC 52 – 54 cm TC 60 – 62 cm TC 66 – 68 cm TC 70 – 72 cm TC 74 – 76 cm	*Tina River core* (n = 7) TR 2 – 4 cm TR 6 – 8 cm TR 24 – 26 cm TR 32 – 34 cm TR 42 – 44 cm TR 46 – 48 cm TR 80 – 82 cm

Using the Excel® Add-In by Walling *et al.* (2006) the reference inventory for ^{137}Cs the catchment was estimated to be 513.08 Bq m^{-2} for 2011. Using the catchment reference inventory, the expected concentration for the plough layer (20 cm) was calculated using Eq 8.

Average Concentration (mBq g^{-1}) = Reference Inventory (Bq cm^{-2}) ÷ [Profile depth (cm) x Bulk density (g/cm^3)] ... (Eq 8)

Where the

Reference inventory = 0.0513 Bq cm^{-2}
Profile depth = 20 cm, and;
Bulk density = 1.34 g/cm^3

The result shows that the average concentration for the removal of 20 cm of the plough layer was 1.9 mBq g^{-1}.

Caesium-137 was found in three samples only, these samples are shown in Table 4.15. Z1 was a streambed sample from the Mhakeng River, CH1 was a hillslope sample near a drainage line (see Table 4.2) and TC 0 - 2 represents the top 2 cm of the TDC.

Table 4.15: ^{137}Cs concentrations of catchment samples**.**

Sample code	Cs-137 mBq g-1	Cs-137 Error
TC 0 - 2 cm	0.13	0.06
Z1	2.17	0.55
CH1	2.91	0.52

Using the results from Equation 8 above, the concentration of ^{137}Cs in sample CH1 was used to determine the difference in soil removal from the reference condition using the calculation below. Sample CH1 was used as it was the most autochthonous of the three ^{137}Cs samples.

	Concentration		Profile Depth
Reference	1.9 mBq g^{-1}	=	20 cm
CH1	2.91 mBq g^{-1}	=	x

CH1 profile depth = 30.63 cm

Results indicate that the concentration of ^{137}Cs is 1.01 mBq g^{-1} greater than the reference condition, thus translating to approximately 31 cm soil removal which is 11 cm greater than the plough layer.

Since the number of samples that tested positive for ^{137}Cs were very low, the calculations used to determine the erosion rates based on a core were abandoned as there was lack of a representative sample size. Therefore, since only 4.76 % of the tested samples indicated the presence of ^{137}Cs, it can be deduced that the Khamopele River catchment has experienced extensive soil erosion eradicating the topsoil layer in most of its areal extent.

Both core samples indicate a lack of ^{137}Cs. This can be interpreted as the absence of ^{137}Cs in the catchment area i.e. the supply of ^{137}Cs has been exhausted or was low in the catchment. Secondly, Foster *et al*. (2006) have shown that sediment size plays an important role in the adsorption of ^{137}Cs i.e. clays adsorb ^{137}Cs better than sands. The soil texture of samples in the Khamopele catchment was largely sandy. The TDC, which was closest to the catchment, was also sandy in texture. The TDC had a finer texture. The less than 63µm (coarse silt and less) fraction was used for analyses as this was the fine fraction of soil. Results show that even with this fraction ^{137}Cs was not detected. This may be a result of the ^{137}Cs being part of the fine sediment load (suspended/washload) as pointed out by Ely *et al*. (1992). Thirdly, the TDC sample which tested positive for ^{137}Cs was very low at 0.13 mBq g^{-1}. Krause *et al*. (2003) caution in accepting values slightly above zero for erosion rates due to increased detector limit errors. The detection limit for the gamma spectrometer was 0.7 mBq g^{-1}. Lastly, the lack of ^{137}Cs points to the slow vertical migration of ^{137}Cs in the soil profile. In this chapter it has been shown that gullies were not the main source erosion but have been in the past. Had there been vertical migration of ^{137}Cs

it would be present in the gully samples, this is not the case indicating the removal of a significant topsoil layer in the Khamopele River catchment.

Summary

The results section has provided useful insights to the source group interactions within the Khamopele River catchment and selected sink zones in the upper Tina River catchment. Environmental magnetic tracing has yielded results that have highlighted the differences and similarities of samples in the different source areas. Radionuclide results showed that the Khamopele River catchment was depleted in ^{137}Cs and this may point to high erosion rates in the catchment. The environmental magnetic tracing technique has been more useful in this context, showing that radionuclide techniques need further refined exploration.

4.6. DISCUSSION

Iron Oxide Mineral Composition

In Makhoaseng catchment, maghaemite and goethite dominated the mineralogy. Goethite was exclusively found in gully sidewall samples. Taylor and Eggleton (2001) suggest that valleys, the terrain unit within which gullies were located, were goethite rich as they have moisture. Chesworth (2008) found that older soils have an abundance of goethite and haematite. Gullies were found in colluvium and the presence of goethite and haematite may be an indicator of the deposition process over time. Maghaemite is derived in two ways (see Figure 4.1), the oxidation of magnetite and thermal alteration of iron oxides that occurs with organic matter i.e. fires (Taylor and Eggleton, 2001; Chesworth, 2008). Goethite was the main iron oxide that transforms to maghaemite post-fire as the reduced iron oxide changes to maghaemite i.e. changes from iron hydroxide (goethite) to iron oxide (maghaemite).

The presence of haematite in soil samples was limited to streambed samples, particularly the confluences. One of the explanations is that goethite dehydrates to haematite (Taylor and Eggleton, 2001). Streambed samples were collected during the dry season and haematite production is exacerbated by warm dry temperatures (Chesworth, 2008). The other explanation is that haematite, at 5.3, has the highest specific gravity of all iron oxides (Farndon, 2012). Therefore, it would not be easily transported when compared to goethite which has a specific gravity that lies between 2.9 and 4.3 (Farndon, 2012).

Samples derived from quaternary catchment (T34A) were ferrimagnetic and did not have antiferromagnetic minerals. This may be a result of the parent rock and the location of the collected sample i.e. river beds and banks.

It is interesting to note that one sample in the TRC had magnetite and that the TDC had no magnetite. This may indicate the proximity of the sample location to Drakensberg Group Basalt. Specific gravities of magnetite and maghaemite might also address the discrepancy as magnetite has a specific gravity of 5.1, whereas maghaemite has one of 4.9 (Gross, 1965). It is likely that fluvial transport processes would more easily move maghaemite. The lone representation of magnetite in the core is a possible indicator of a heavy flow event that was able to deposit magnetite. Alternatively, its presence is limited due to the selected grain size class for this study i.e. less than 63µm.

Iron oxide classification indicated that the maghaemite mineralogy was dominant in most sample areas except for Quaternary derived sediments. The abundance of maghaemite mineralogy further indicated the dominance of ferrimagnetic minerals in the collected samples. Source areas that indicated partial antiferromagnetic behaviour were hillslope and streambed material.

Results from the iron oxide analysis indicated that two source areas had distinctive signatures. They were the basalt and gully sample groups. These source areas represent opposite magnetism i.e. basalt indicates ferrimagnetic mineralogy and gully sidewalls antiferromagnetic mineralogy. Basalt samples were wholly composed of magnetite whereas gully sidewall samples were wholly composed of goethite. The rest of the samples from the Khamopele River catchment shared similarities in mineralogy with other Quaternary derived sediments.

Source areas in Makhoaseng catchment that shared similarities with sink zone samples were Mhlakeng topsoil, streambed material and hillslope samples. These source areas indicated zones of mobility in the catchment i.e. they represent easily mobilised sediment.

Mineral Grain Size versus Concentration

Results from section 4.5.2 show Makhoaseng catchment was host to a number of samples that exhibited a mixture of SP grains in their composition. However, there were also many samples that did not plot in the "mixtures" envelope depicted in Figure 4.10. Attention is drawn to those samples that exceeded χfd (%) 10 that would otherwise qualify as SP grain dominated samples (Dearing,1999). These samples were from three source areas in Makhoaseng catchment: gully sidewalls, hillslopes and streambeds.

Soil samples collected from Mhlakeng topsoil were the only group not to have a sample plot in the sedimentary/metamorphic rock parent area. Perhaps the difference arose because of the saturation that the Mhlakeng topsoil has undergone as part of the wetland soil and the contributions of organic matter, whereas the other source groups were directly derived from the weathering of parent rock.

Quaternary derived sediments indicated that some of the samples were sourced from acid igneous rocks. This finding is disputed as the lithology of the upper Tina River catchment indicates that the igneous rocks are of a basic nature i.e. basalts and dolerites and not acidic e.g. granite. Interestingly, the sample collected from the Phiri-e-Ntso River channel was the only sample that had no SP grains and also showed linkages to sedimentary parent rock. This was inconsistent with the group findings as most of the samples clustered together at χfd (%) 2 to 6. The other two samples to fall outside this cluster were from the Vuvu River channel and bank. The high χlf of these samples was attributed to the Vuvu River being at the top of the geological sequence therefore having bed material and soils influenced by rocks of the Drakensberg Group.

Basalt samples showed range in χfd (%) values but not in χlf, as a result they depicted the extreme ranges of SP grain contributions. One basalt sample had high χfd (%) and was wholly dominated by SP grains. In contrast, one sample was in the group where the SP fraction was dominated by fine grained ferrimagnetic minerals or had no SP grains. The other three basalt samples plotted in a group indicating a mixture of SP grains. All basalt samples had magnetite as the dominant iron oxide. However, these results suggest that there were grain size considerations even within a seemingly homogenous iron oxide class.

Sinks zone samples generally had their χfd (%) range between 2 and 6, indicating a mixture of SP grains (Dearing, 1999). This result was expected as the TRC and TDC represent sink zones, therefore a mixture of grains dependent on the transporting event or delivery process. The TRC exhibited some of the most interesting findings i.e. there were samples that had no SP grains and there were contributions from both sedimentary and igneous rocks. This is plausible as the TRC samples were collected a short distance from where the Vuvu and Tina Rivers join, thus the igneous contribution. The sedimentary parentage is attributed to the eroded sediment from Upper Tina River catchments similar to the Khamopele River catchment.

Magnetic Behaviour: Ferrimagnets vs Antiferromagnets

Results of the comparison of different source groups with gully sidewall samples revealed that in the Khamopele River catchment, hillslope samples with the highest HIRM and χlf were collected outside Makhoaseng catchment. These samples were within the broader the Khamopele River catchment i.e. slopes behind the village and hillslopes towards the Tina River confluence.

Two resulting relationships were observed. The first was the similarity of the gully sidewall samples with the streambed material group. The second was the similarity of Mhlakeng topsoil and hillslope samples. Both these relationships were logical in that hillslope samples are moved by wind and runoff for a distance. Upon deposition, hillslope samples will form the surficial layer in that environment unless disturbed by anthropogenic activities. Gully sidewalls erode and sediment is mobilised from the gully floor to the nearest fluvial system. Transport mechanisms seem to dictate the similarities of the aforementioned source groups.

The observed similarity of samples collected from Taung and Mhlakeng sample areas suggest similar colluvial depositional history. These results show evidence of the geologic Law of Superposition and the Principle of Original Horizontality, but in this case manifest in unconsolidated sediments.

Streambed samples that showed differences to the rest of the samples in the group were from confluence sites. Perhaps the higher χlf was a result of the accumulation of sediments at confluence sites. Quaternary catchment derived sediments showed a distinct difference to gully sidewall samples. These two groups did not have samples that had similar mineralogy. This finding was also true for the TDC. However, the TRC had three samples with similar HIRM and χlf as the gully sidewall samples. This was thought to be a proximity factor i.e. the TRC was much closer to the outlet of the Khamopele River catchment than Mt Fletcher Dam.

Results indicated that gully samples shared similarities with source groups collected from the Khamopele River catchment. The TRC was the only other source group that shared similarities with the gully sidewall samples. Sink zone samples shared similarities with other source groups from the Khamopele River catchment, in particular the hillslope, streambed and topsoil samples. Quaternary derived sediments do not share similarities with the gully samples.

Intra sink-zone variation

The TDC textural pattern showed that high organic matter percentages correspond with silt and clay layers. Texture findings in TRC indicated that sand layers were depleted in organic matter. The TRC was predominantly sandy in nature and this was reflected in organic matter contents which seldom exceeded 5 %. The TDC on the other hand had organic matter contents well in excess of 5 %. A few TDC samples were above 10 % whereas the TRC had no samples that exceeded 10 % in organic matter content.

The organic matter and texture patterns were indicative of the depositional environment in which these two cores were found. The TRC was located on a point bar in the upper Tina River segment and was subject to flow fluxes during local rainfall events. Furthermore, the river segment wherein the TRC was collected represents the transitional zone and lacks a floodplain (Rowntree and Wadeson, 1999). The confined nature of the channel and the river segment location in the greater Umzimvubu River system indicates that the river has high energies and has high flow velocities. The coarse nature of the core possibly indicates the size fraction of sediment mobile during the wet season. Overall, the TRC location indicates a deposition-transport zone that is influenced by seasonal longitudinal connectivity in the river system.

In contrast, the environmental setting for the TDC was a dam. Regulation structures such as dams represent barriers to longitudinal connectivity in a river system. The location of TDC represents a man-made sink and is unlikely to be influenced to the same extent by isolated rainfall events due to lag effects/ dissipation of energy downstream. The first indicator of location differences was the texture of the core which was finer than the TRC. Dams are energy dissipating structures, similar to log steps, which promote deposition behind the dam wall and incision at the front (Marston, 1982). Therefore, the silty texture profile with fine sand intercalations in Figure 4.21 was characteristic of this environment. Soil colour was also noted to be different in the two sink zones. The TDC which had higher OM content had darker colours than the TRC.

The second indicator was the differences in $\chi lf_{(minero)}$ of the two cores. The TRC had three distinct high $\chi lf_{(minero)}$ zones and the rest of the core had low $\chi lf_{(minero)}$. This indicates a grouping of high iron bearing minerals at those zones. The TDC on the other hand has periodical $\chi lf_{(minero)}$ pattern with a moderately distributed $\chi lf_{(minero)}$ range between 0.2 and 1.0 x 10^{-3} m^3 kg^{-1}. This showed that TRC experienced pulses of deposition, possibly from high rainfall events and seasonal changes. The TDC on the other hand may be showing relatively consistent flow velocities and environment.

The S-Ratios of the cores showed that the TRC had a mixture of goethite/haematite and magnetite/maghaemite mineralogy. The TDC had increasing magnetite/maghaemite mineralogy. This indicated that the TRC was influenced by local sediment systems such as those from the Khamopele and Vuvu catchments (T34A). The Vuvu and Khamopele Rivers have their sources in basaltic rocks (Figure 2.7) and these rocks have high $\chi lf_{(minero)}$ which can explain the punctuated $\chi lf_{(minero)}$ peaks in the TRC. The TDC may represent the contribution of diffuse sources of sediment i.e. combined effects of sub-catchments in T34A, T34B and T34C (Tinana River catchment). All the rivers draining into the Mt Fletcher dam have their sources in Drakensberg basalt. Therefore, the enhanced $\chi lf_{(minero)}$ signature may be a reflection of the combined transport of iron rich material downstream.

The HIRM vs Xlf comparison of the different source groups to the two cores revealed that the basalt samples shared no similarities with the TRC and TDC. Three samples from the gully sidewalls shared similarities with samples collected from the TRC. Again, none of the TDC samples shared similarities with gully sidewall samples. There are two plausible explanations for the observed absence of basalt in the TDC; the first is that the basalt samples were not collected from the upper Tina River catchment but the adjacent Bell River catchment. The second explanation relates to the specific gravity of magnetite making its transport to Mt Fletcher less likely due to Hjulstrom's (1935) assertion that velocity dictates the transport of particles in fluvial systems i.e. maghaemite and goethite are more likely to be mobilised than magnetite rich basalt. The low frequency of gully sidewall overlap with the TRC soil samples suggests that there were impediments to the efficient and effective transport of sediment derived from side wall collapse in the Khamopele River catchment. The presence of islands in the catchment in both the wet and dry season may explain the lag in deposition or, simply, the gullies sidewalls were not the main sources of eroded sediment in the Khamopele River catchment. Furthermore, the analysis showed that Mhlakeng topsoil, hillslope and streambed samples shared similarities with both cores. This suggests that eroded sediment in the upper Tina River catchments was derived from topsoil and hillslopes. Streambed samples are already in a transport zone and their movement within the fluvial system is continuous into temporary and permanent sinks.

Mineral and volume concentration

Findings from the SIRM vs χlf analyses were similar to the HIRM vs χlf results. The basalt and quaternary derived samples did not share similar mineralogy with the gully sidewall samples. Hillslope samples that exhibited high SIRM and χlf were those that were close to the basalt cap in the Khamopele River catchment i.e. samples collected on slopes behind Makhoaseng village. The last sample of the four, S2, indicates possible enhancement of the magnetic signature as the sample was collected after grassland burning.

Gully samples shared similar mineral and volume concentrations with sediment from the Khamopele River catchment. Quaternary derived sediments showed no overlap with the gully sidewall samples, suggesting a lack of gully derived material in the sediment load of rivers in the upper Tina River catchment.

Statistical analysis

The LSD tables indicated that quaternary derived sediments were different to the TRC and TDC sediments. This finding was consistent with findings from the SIRM and HIRM analyses in section 4.5. Another shared finding was the significant difference between gully sidewall samples and the TDC. Furthermore, gullies exhibited significant differences to the TRC.

Both cores shared similarities with hillslope and Mhlakeng topsoil samples. The TDC was similar to the TRC and hillslope groups. The TRC was similar to the TDC, hillslope and Mhlakeng topsoil groups. Gully sidewall samples showed similarities with the Mhlakeng topsoil and streambed groups. This again suggested similarities across Taung and Mhlakeng sample areas in colluvium depositional history and sequence. Mhlakeng topsoil samples were most similar to the TRC, gully sidewall and hillslope samples. The gully similarity may have been a result of soil horizons exposed as a result of erosion and previous cultivation in the valley bottom areas of the Khamopele River catchment. Streambed samples were most similar to the gully sidewall and Mhlakeng topsoil groups. This was plausible as undercutting and sidewall collapse in gullies can contribute to streambed material. Topsoil is generally the first layer to be eroded during a heavy rainfall event. Therefore, the similarity of this group and the streambed group was logical when transport processes are considered.

Radionuclide tracing

The findings from the radionuclide tracing exercise indicated that the Khamopele River catchment was ^{137}Cs poor. The three samples showed evidence of ^{137}Cs do not have clear spatial correlations to explain the detected ^{137}Cs levels. The TDC, in which high ^{137}Cs was expected, had a single ^{137}Cs sample confirm the presence of the radionuclide. The two samples collected from the Khamopele River catchment show no clear linkages to the observed measurements except that CH1 was collected where there was significant gradient change from the rest of the terrain unit. Sample Z1, a confluence sample may indicate accumulation of ^{137}Cs from eroded topsoil in the catchment.

The application of radionuclide tracing techniques in the catchment has shown that the Taung sample area has been stripped of its topsoil horizon. No trace of the plough layer exists, suggesting degradation rates in excess of 20 cm over 50 (±) 5 years in the Taung sample area. Hillslope sample CH1 shows that degradation has indeed been in excess of 20 cm as the estimate is approximately 31 cm topsoil removal from the site.

4.7. LIMITATIONS

The collected samples were not representative of the whole catchment. The upper Khamopele catchment is not well represented as the bulk of this research was focused in the Taung sampling area where aerial photographs and oral history had indicated that the area had severe levels of degradation.

The sites were selected based on the primary assumption that gullies were the main sources of erosion in the catchment. Therefore, sampling efforts were focused on covering gullies in Makhoaseng catchment.

The sample depth of the dam core was 84 cm. Mt Fletcher Dam was built in 2008, thereby only allowing limited interpretation of the sediment history as eroded sediment from 1956 would not be detected from a basal core.

4.8. CONCLUSION

In conclusion, the environmental magnetic tracing results indicated that the Khamopele River catchment has iron oxides which can be used to establish source areas. The results show that sediment derived from hillslopes and topsoil in Taung and Mhlakeng sample areas provides the main source of eroded sediment from the Khamopele River catchment. Streambed samples were also found to be sources of eroded sediment found in sink zones, but this is largely due to their location i.e. transfer zone.

Insufficient evidence exists to show that gullies were localised sources of erosion in the catchment as only three gully samples shared similar magnetic signatures as the sink samples from TRC. Evidence of magnetic signatures similar to gullies was not found in the TDC. Soils collected outside of Khamopele River catchment did not share similar magnetic signatures with the gully samples. This finding presents the following possibilities for gullies in the catchment. The first that gullies were transport limited source areas. Secondly, that the gullies are now inactive and thirdly, that gully sediment is carried as washload thus not depositing in the dam.

The use of ^{137}Cs in the Khamopele catchment indicated that significant erosion has taken place in the catchment, eroding at least 20 cm from the Taung sample area surface area. The ^{137}Cs detected in topsoil was low thus minimizing the robustness and validity of the ^{137}Cs tracing method in this study.

CHAPTER 5

GENERAL SUMMARY

5.1. INTRODUCTION

The aim of this research was to assess the extent of erosion in the Khamopele River catchment and determine whether sediment derived from Khamopele River catchment contributes to sedimentation in Mount Fletcher Dam and the upper Tina River. Physical, anthropogenic and land use factors were considered key factors in the initiation and continuation of soil erosion in the Khamopele River catchment. This chapter presents a summary of the findings of this research and the outputs of the stated objectives of the study. The chapter is structured by objective.

5.2. SUMMARY OF FINDINGS

5.2.1. Anthropogenic factors promoting soil degradation in the Khamopele River catchment (Objective a)

Human disturbance of the natural environment is dependent on the location of the environment and the availability of resources. In Chapter 2 of this study it was found that the location of the Khamopele River catchment in the Eastern Escarpment mountains meant that the catchment had high gradient. The gradient meant that slope would play an important role in promoting sediment removal from hillslopes and gully development. Furthermore, precipitation data for the region showed that rainfall during the study period was conducive to soil detachment and transport as the region as a whole was experiencing a wet cycle. The precipitation, erodible geology and well drained soils in the Khamopele River catchment indicated that in its natural state the catchment would be susceptible to erosion. The human component would compound and further induce conditions necessary for the observed scale of soil erosion.

The location of the catchment in the former Transkei homeland presented the legacy of degraded land in such areas. The activities which the community engage in i.e. farming, stocking and brick making, had a negative cumulative impact on the marginal land the residents use. For example, the rotational grazing system, where in the summer months cattle are allowed to graze in the higher lying areas, creates tracks that line hills slopes and promote compaction and rapid detachment of soil. Veld fires were also a problem as the burning frequency meant that the first rains mobilised most of the sediment.

Soil conservation suggestions by participants were those that were common in Land Care projects e.g. vegetating slopes and inserting rocks in gullies (terracing). The reduction of veld fires was seen as a step towards increasing the resilience of the ecosystem. Spring burning is common in the grassland biome (Maloti Drakensberg Transfrontier Project, 2007) because of *Themida triandra*, burning makes the grass more palatable. However, a more sustainable solution must be found. Vetter (2007) finds that chiefs used to regulate the burning frequency. Blignaut *et al*. (2010) suggest that burning should take place only once every two years.

Chapter 2 highlighted the struggle that exists to balance resource use and resource protection. Objective *a* was addressed in Chapter 2 as the above mentioned factors were found to promote soil degradation. The anthropogenic factors indicated that, if future rehabilitation works seeks efficient use of resources to mitigate erosion, some of the issues regarding resource use in communities such as Makhoaseng need to be carefully considered.

5.2.2. Physical factors influencing soil degradation in the Khamopele River catchment (Objective b)

Chapter 3, introduced the type and extent of erosion in the Khamopele River catchment. The desktop study indicated that gullies were a persistent problem in the catchment. To address the stated objective, gullies were quantified using location, morphology and sidewall form. Furthermore, gullies were classified using Dardis *et al's* (1988) classification. Using Dardis *et al's* (1988) classification, Type 6, 7 and 8 gully forms were found to be dominant in Makhoaseng catchment. Gullies were largely concentrated in the valley sides of the catchment with sloping and vertical sidewalls.

Gullies

Whitford *et al*. (2010) explain that gullies are part of a cycle marked by three phases; namely, initiation, stabilization and accretion. Gullies in the catchment were present on foot slopes with slope angles between 5º and 10º. The observed gullies were valley-side and valley-bottom gullies. A number of small bank gullies were also observed, particularly in the Mhlakeng and lower Khamopele River. The deeply entrenched gullies (2.5 m onwards) were Type 6 and 7 gullies that had vertical and sloping side walls. Gullies in Mhlakeng and Taung sample areas were generally trapezoidal. However, the fluting/pinnacles made the cross sectional area on either sidewall irregular.

Kosov *et al*. (1978) established that the initiation of a gully takes five percent of its life time. During this stage gullies attain most of their present length (Whitford *et al*., 2010). The stabilization phase is marked by lateral extension, sidewall collapse and infrequent transport of sediment from the gully floor (Sidorchuk, 1999; Whitford *et al*., 2010). Sidewall collapse was the most observed sign of active gullying in the catchment. The lateral extension of gullies was evident in aerial photographs as linear gullies coalesced into branched gullies. Furthermore, the gully heads in the lower Taung sample area had extended laterally and merged with neighbouring gully heads. The dominance of sheet erosion in the catchment indicated that overland flow was the most effective agent of transport. This implies that gully erosion is a less dominant method of transport within the catchment and limited to the footslope regions. Gully erosion is dependent on the wetting of sidewalls and sediment on the gully floor, thus necessitating a heavy rainfall event whereas overland flow can be Hortonian or saturation overland flow (Parsons and Abrahams, 1992).

Based on the findings of this study, gully erosion was not responsible for sediment production in the Khamopele River catchment. High rainfall events played a major role as sediment from hillslopes and topsoil was readily moved by these rainfall events. The sandy loam nature of soils in the catchment favoured sheet/rill erosion in the hillslopes (Poesen *et al*., 2003). These factors contributed to the limited transport of gully derived sediment.

Connectivity

The Landscape Connectivity Framework was also used to represent the interactions at sub-catchment level. Lateral and longitudinal connectivity were most pronounced, with longitudinal connectivity allowing for the movement of sediment into the Tina River. Hillslope-channel coupling was high in the Taung sample area. Variable degrees of connectivity were found in the Mhlakeng sample area. Some of the largest potentially connected systems were found in this sample area. Sidewalls were eroding in the catchment but it took a while for that sediment to reach the Tina River. In terms of connectivity, this makes the catchment a partially connected system. The occurrence and extent of sand bars in the Mhlakeng and Khamopele Rivers supports this finding. The connectivity of systems in Makhoaseng catchment was dependent on rainfall. No evidence of wind erosion was found. Therefore, most transport occurs during the wet season or when a rainfall event of significant magnitude occurs in the catchment. Blankets were present on the catchment in the form of bedrock steps. They caused sediment to move intermittently in the channel and pools.

Soil

An investigation of the soil properties showed that the A and O horizons were absent in Makhoaseng catchment. This was an indicator of the extent of erosion within this catchment. This finding was further supported by the absence of ^{137}Cs in the topsoil in the catchment. Soil texture results indicated that the catchment consisted of sandy soils. Some of the soil forms associated with the textures found were the Avalon, Kroonstad, Constantia, Cartref, Katspruit and Hutton Forms. Soil test results indicated that there was a proportional relationship between organic matter content and aggregate stability with 86.7 % of samples having less than 5 % organic matter. Cameraat and Imeson (1999) and Billi and Dramis (2003) also observed that there was a dependent relationship between organic matter and aggregate stability in their gully investigations. The organic matter differences extended to the cores where the TDC had more organic matter and the TRC less than 5 % outside the organic matter enriched zone (26 cm to 54 cm).

The erodibility of soils in the Khamopele catchment may be a characteristic of the Molteno Formation derived soils in the Eastern Cape. Le Roux *et al*. (2008) also observed that duplex soils of the Molteno Formation were highly erodible in Quaternary T35. Some of the factors contributing to the erodibility of soils in the catchment include the predominant texture being loamy sand to sandy loam, low organic matter contents, low aggregate stability and low electrical conductivity. According to Hazelton and Murphy (2007) the approximate clay content of loamy sand and sandy loam is 5 - 15 %, making them subject to dispersion.

The erodibility of soils in the catchment was compounded by the degree and extent of sub-surface influence on the gullies. Evidence of dispersion, piping, tunnelling and mottling was found in the catchment. Goldsmith and Smith (1985: 3) observe that tunnelling is more likely to occur in areas that have a distinct wet and dry season and "shallow groundwater levels". Furthermore, Goldsmith and Smith (1985) find that the dissolution of plagioclase makes sodium available in the soil. Plagioclase is a paramagnetic mineral (Dearing, 1999). The electrical conductivity results indicated that soils in all three sub-catchments were non-saline. This was in agreement with the plagioclase argument but it seems unlikely that the catchment would be deficient in salts as piping and tunnelling are symptomatic of dispersive soils (Paige-Green, 2001, Hazelton and Murphy, 2007). Could the contributions from overland, subsurface and groundwater flow have leached sodium from the soil profile? Hutton Form soils are known to be well drained soils (Materechera, 2009; Fey, 2010). Or does the lack of salinity point to an incomplete investigation as Sodium Adsorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) tests were not conducted? Whether it is the former or the latter, the colour of the soil provides some direction to the physical properties of soils in the catchment (Erskine, 2012).

Soils in the catchment adhere to the AGIS' (2010) general classification of soils in this catchment i.e. red-yellow well drained soils. Very few soils in the catchment exhibited the red moist colour as per AGIS' (2010) description of soils. Most of the soils in the catchment seemed to be yellow-brown apedal in nature instead of red. Fey (2010) observes that acidic soils in humid areas tend to be yellow in colour instead of red due the iron hydroxide goethite, which is an alteration product of haematite. The dehydration of goethite brings the reddish colour in soil (Butler, 1992), this may occur during the dry season with the correct temperatures. The environmental magnetic tracing studies revealed that Taung sample area was dominated by the goethite mineral assemblage. All of the gullies examined in the catchment had goethite as the main iron bearing mineral.

Calcrete nodules were found in the Mhlakeng and the Lower Khamopele sample area. Calcrete nodules are an indication of three things; namely, a distinct wet and dry season, leaching of organic matter/$CaCO_3$ and groundwater processes (Rowe and Maher, 2000; Zhou and Chafetz, 2009). They form as part of the pedogenic process and can form in sub-humid areas like Makhoaseng catchment (Khadkikar *et al.*, 2000). The most important thing that calcrete nodules show is that a (palaeo-) soil has been removed as they form at the base of soil horizons i.e. *in situ* (Rowe and Maher, 2000). According to Khadkikar *et al.*, (2000) and Achyuthan *et al*. (2009) calcrete nodules are commonly found in the Vertic A soil horizon. Hence, it can be deduced that calcrete nodules indicate a stripped A-horizon in the Mhlakeng and the Khamopele sub-catchments. Van Niekerk *et al*. (1999) observed that soils of the Hutton Form had ferromanganese nodules that were largely goethite and haematite in the lower layers.

Geomorphic controls

The Taung sample area was shown to be an area of saturation by geologic/structural control. Cross sections showed that the Taung gullies had formed on a perched water table. The underlying Molteno Formation mudstones had very low porosities making the lowest soil horizons saturated with water. The two dykes also formed a water trap in the Taung sample area, forcing groundwater to come to the surface at the contact. In the wet season the dual action of these structures combined with high levels of precipitation made this catchment a hotbed for the formation of pipes and tunnels.

Lastly, the 500 000 m^3 Mount Fletcher dam was reported to have an estimated 70 % loss of storage capacity in 2011 (Naude *pers.comm, 2011*). A visit to the dam revealed that the dam has never been flushed since its construction in 2008, thus explaining the siltation problem.

The four factors (soil, gully morphology, connectivity and geomorphic controls) stated in Objective *b* were addressed in Chapter 3. The findings are used to explain the interactions in the study area and the observed contrast of the scale of erosion across the three sample areas.

5.2.3. Utilisation of environmental magnetism and gamma spectroscopy techniques to identify sediment source areas (Objective c)

Chapter 4 presented contemporary tracing and dating techniques. Iron oxides were shown to be particularly useful for environmental tracing purposes. The radionuclide Ceasium -137 was selected to determine the extent of erosion in the catchment.

The use of oxides to distinguish between source areas showed that there was a distinct difference in gully derived samples and those sourced from basalt. The former was antiferromagnetic in nature and the latter ferrimagnetic. The difference of these two source groups was persistent for all environmental magnetism tests, thus indicating different mineralogies between the two source groups. Sink zones were found to be composed of topsoil, hillslope and streambed material.

The mineral and concentration results showed that samples collected in this study predominantly have a sedimentary parent rock with some igneous rock mineralogy. Mhlakeng topsoil samples did not fully adhere to either sedimentary/metamorphic or igneous parentage, pointing to soils of the former wetland which were organic matter rich.

The similarity of Taung sample area hillslope samples and Mhlakeng streambed samples suggested that the two sample areas had undergone similar deposition and erosion histories.

Mineral magnetic results indicated that sheet erosion of hillslopes and topsoils was the likely source of soil erosion in Makhoaseng catchment as hillslope samples showed the most overlap with other catchment derived sediment. Mineral magnetic signatures also revealed that samples collected behind the village had some of the highest low frequency mass magnetic signatures. This was largely due to their proximity to the basalt rocks and a concealed dyke. Another factor could be the slope percentage as slopes in this area were in the range of 22% to 33%. This leaves very little potential for water to remain *in situ* at such angles as it preferentially moves down slope, thereby making saturation less of a problem in this area. This means that goethite is not formed in this area of the catchment and so increases the iron oxide concentration at the site.

The lack of ^{137}Cs in the catchment showed that a minimum of 20 cm has been eroded. This figure indicates the widespread surface erosion in Khamopele River catchment.

In the concluding parts of the Chapter 4, the *a priori* assumption that gullies in the Khamopele River catchment were the main sources of sediment deposited in downstream sinks was not supported. Gullies in the catchment were headed towards the stabilisation phase (Sidorchuk, 1999; Whitford *et al.*, 2010) as evidenced by sidewall collapse; however, their transport limited nature due so unmoved collapsed sidewalls means that sediment derived from gullies is seldom found in the sink zones.

5.3. LIMITATIONS OF THE STUDY

One of the main limitations in this research was the lack of rainfall data for the catchment. Although spatial interpolation techniques are available, the continual and accurate monitoring of weather provides a strong database for research. For example, using the Fourier Index catchment specific erosivity results could have been achieved.

The incomplete analysis of soil texture with the sedigraph was a limiting factor but the Land Type Survey (Land Type Survey Staff, 1972 – 2006) confirms the findings of loamy sand and sandy loam textured soil in the catchment.

Radionuclide concentrations were low indicating a lack of ^{137}Cs in the landscape. The prerequisite for a reference site in the Khamopele River catchment was a disadvantage which pointed to weaknesses in using as a ^{137}Cs radionuclide tracer. A recent paper by Parsons and Foster (2011) has shown that ^{137}Cs cannot be used with confidence in all settings to determine erosion rates in catchments.

Increasing sample sizes from the Lower Khamopele and Mhlakeng sample areas would have provided stronger evidence for the linkages that exist in the catchment. A control or paired catchment approach in the upper Khamopele would have benefited the study as over time the “observed” and “normal” states could have been tracked for future research.

Lastly, the SAR and ESP tests would have provided more definitive answers with regards to dispersion percentages and electrical conductivity of soils in the catchment.

5.4. CONCLUSION

The study aimed to assess the extent of erosion in the Khamopele River catchment and determine whether sediment derived from the Khamopele River catchment contributed to sedimentation in Mount Fletcher Dam and the upper Tina River. Results show that sediment derived from gullies in the Khamopele River catchment was absent in Mount Fletcher Dam. However, some of the soil eroded from gullies in the catchment does contribute to sedimentation in the upper Tina River as signatures from catchment derived soils were found in the Tina River core. The main sediment sources in the Khamopele River catchment were hillslopes and topsoil. Sheet erosion was therefore the dominant carrier of sediment in the catchment.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

This study set out to assess the extent of erosion in the Khamopele River catchment and determine whether sediment derived from the Khamopele River catchment contributed to sedimentation in Mount Fletcher Dam and the upper Tina River. The research showed that within the catchment:

-The Taung sample area was host to the highest amount of gully erosion but environmental magnetic tracing results indicated that sheet erosion was the dominant type of erosion in the catchment.

- The A and (or) O horizons had been stripped, indicating the intensity of erosion in this catchment. The absence of radionuclide tracers and the presence of calcrete nodules on topsoil provide evidence for the removal of the uppermost soil horizon.

-Soils in the catchment were acidic loamy sands to sandy loams that were influenced by overland and sub-surface flow.

-Soil erosion by piping in the Taung sample area was accelerated by a perched water table that may have been the result of dolerite dykes.

Matching sediment from the sink zones to the source areas in the catchment showed that:

- The Tina Dam Core (sink zone) samples showed some similarities with the Khamopele River catchment derived soil samples, indicating a similar source area for sediment at Mount Fletcher Dam.

-The Tina River Core (sink zone) samples showed similarities with hillslope, streambed and topsoil soil samples from Makhoaseng catchment. Suggesting that sediment derived from these source areas was mobile.

In conclusion, the mineral magnetic signatures were able to detect iron oxide and concentration differences between source and sink zones showing that environmental magnetism was a valid approach in distinguishing source areas in catchments. Eroded sediment in the upper Tina River predominantly was sourced from hillslopes and topsoil in the Khamopele River catchment. ^{137}Cs proved to be an ineffective tracer in this study due to the limited number of topsoil samples that had the radionuclide.

The soil erosion problem in this catchment will require a solution that is cognisant of the inherent physical factors, land management and anthropogenic activities.

6.2. RECOMMENDATIONS

Hillslopes were identified as sensitive spots in the Khamopele River catchment. Vegetation cover was decreasing in these areas as sheet erosion was increasing on hillslopes. To restore ecosystem services attention should be focused on the slopes in the catchment. Planting grasses and having trees near drainage features are ways in which water can be trapped in the catchment.

Gullies that can be rehabilitated in the catchment are those in the Mhlakeng and the Lower Khamopele sample areas. Some of these gully systems have not incised to connect with the river channel and gabions can be inserted. The friable nature of the Molteno Formation may pose problems for fixed structures such as gabions in the Taung sample area. Furthermore, the exposure of bedrock and subsurface water influences in Taung sample area can cause problems if gabions are inserted. Increasing vegetation cover on bare slopes and stone walls (no clamping) within the gullies may provide some stabilisation.

A review of the grazing management needs to be considered for the catchment. There needs to be a single path to the pastures at the drainage divide as it will be easier to control erosion at one site instead of many cattle tracks.

The successful implementation of a Payment for Ecosystem Services (PES) programme in the upper Tina River catchment depends on a willing buyer and willing seller principle. If communities are to be approached to begin restoration and stewardship programmes, there have to be open channels of communication between the managers and community members. Where possible, research must aim to empower the very communities it seeks to serve otherwise it creates a dependency. This can be done is simple ways such as having someone shadow or assist the researcher in the field. This fosters camaraderie, trust and transparency. Furthermore, this provides a meeting point for scientific and indigenous knowledge where communities can better address environmental problems.

In this project, local assistants were used from the pilot phase to the sample collection. In the early phases, knowledge from the elderly in the community confirmed the site selection and allowed the researcher to gain insights on the changes in land use in the catchment as shown in Chapter 2. During the data collection period, young adults accompanied the researcher in the field. Although there were plenty of questions in the field, there did not seem to be widespread sharing or assimilation of the research or erosion mitigation strategies discussed. This may be a result of the community having lived with the erosion for so long that they are accustomed to it. Or, that the community seeks additional resources to help initiate rehabilitation works.

Future studies in the Mount Fletcher southern Drakensberg region

-A comparison of two catchments of differing geology in the application of environmental magnetic and tracing (^{210}Pb or OSL) studies in the upper Tina and Tinana River catchments.

- An assessment of fluvial geomorphology in the Tina River during the winter and summer months.

-*Catchment Visions*: Future studies scenario formulation based on community perceptions of degradation.

-*Catchment Visions*: Scenarios for upper Tina River catchments based on hydrological, climatic, sediment yield and vegetation changes.

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