A SPATIAL ASSESSMENT OF RIPARIAN VEGETATION DENSITY AND IMPLICATIONS FOR STREAMBANK EROSION IN RELATION TO LAND TENURE IN THE MGWALANA CATCHMENT, EASTERN CAPE PROVINCE, SOUTH AFRICA

By

Asakhile Maxama

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Supervisor: Prof Vincent Kakembo

DECLARATION

I, *Asakhile Maxama, 214125939,* hereby declare that the treatise/dissertation/thesis for a *Master of Science (Geography)* to be awarded is my own work and that it has not been previously submitted for assessment or completion of any postgraduate qualification to another university or for any other qualification.

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ABSTRACT

Riparian vegetation provides an array of various ecosystem functions and has significantly shaped the conditions of catchments. It has strong controls on fluvial geomorphology and erosion processes. The Mgwalana catchment has been intensively studied over the years and the current environmental condition of the study has been linked to land use history. The catchment has been subjected to land use/cover changes (LUCC) over the years. However, spatial variations in riparian vegetation, their implications for stream bank stability and the contribution of land tenure systems to stream channel degradation are poorly understood.

The study sought to assess the implications of the spatial variations in riparian vegetation density for stream bank erosion in relation to land tenure on a catchment scale. Land tenure units comprising the catchment of study are traditional and betterment villages (communal lands), and former white commercial farms. A three-pronged approach using GIS and remote sensing, field investigations and laboratory procedures for soil analysis was employed in this study. Variations of riparian vegetation density in the catchment were mapped using ArcGIS for the two land tenure units to assess the spatial variations of riparian density along stream reaches and to determine the spatial relationship between land tenure units and riparian vegetation diminution. Other mapped shape files include sediment accumulation zones to analyse the spatial relationship between riparian vegetation density and sediment sinks. LUCC classification and analysis of the Normalized Difference Vegetation Index (NDVI) were carried out in IDRISI Selva, using Landsat 8 TM imagery of 2018 to represent the current spatial riparian vegetation variations in the catchment.

Field investigations were conducted to determine the coupling among hillslope gully erosion, riparian vegetation density and sink areas; and to assess physical characteristics of soil. This would permit an assessment of the implications of riparian vegetation for stream bank erosion and sediment accumulation within the tenure units. Soil samples were taken from scantily and densely vegetated stream reaches, as well as measurements of channel widths and depths. Analyses of soil physical properties *viz*; grain size distribution, bulk density, soil texture and aggregate stability were done.

Results demonstrated that a sparse riparian vegetation distribution was consistent with the communal villages, confined to the upper catchment area. Dense riparian vegetation distribution was consistent with former commercial farms in the lower catchment area. NDVI values were lower (-0.14) in communal villages and higher (0.22) in the former commercial farms. A high spatial correlation was noted among sediment sink zones, scanty riparian vegetation density and land tenure units. There were more sediment sinks in communal areas, where sparse riparian vegetation was dominant. The opposite is true for former commercial farms, where dense riparian vegetation distribution persists.

Stream widths assessed along scantily vegetated channel reaches were significantly higher ($p=0.008$; $p<0.05$) than those observed along densely vegetated reaches. There was no significant difference in stream depths ($p=0.31$; $p>0.05$). Grain size distribution showed a higher coarse output along scantily vegetated reaches compared to densely vegetated ones. Densely vegetated channel reaches recorded the highest sand and lowest silt content. No significant difference was observed in the clay content ($p=0.79$; $p>0.05$). Mean weight diameter (MWD) was 1.3 and 0.5 in densely and scantily vegetated reaches respectively. This denotes stable soil aggregates on the one hand and poor ones on the other.

Variations identified in the present study reflect considerable lapses in land stewardship in the communal villages. Robust land rehabilitation and management policies must be enforced in these areas to restore riparian vegetation and curb stream bank erosion, as well as excessive sedimentation on channel beds.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Riparian vegetation is a fundamental component of landscape systems, which exerts strong controls on fluvial geomorphology (Simon, *et al*. 2004). Riparian vegetation is composed of forests and shrubs and is described as a transitional zone between the aquatic and terrestrial ecosystems (Scott *et al*. 2009). The transitional zone provides an array of ecosystem functions that ensure the regulation of geomorphic processes and nutrients between these two ecosystems. Yuan *et al*. (2009) observes that ecosystem functions provided by riparian zones include diminishing nutrient and sediment loads that could have adverse effects on stream bank erosion. Li *et al*, (2009) concur that riparian areas are essential as they reduce the negative impacts of land-use practices along streams by providing hydraulic and geotechnical shear strength. Riparian habitats also provide refuge and shelter for wildlife in urban and rural areas and simultaneously act as corridors of movement for wildlife and plant species between communities. However, a surge in disturbances that have disrupted landscape connectivity has diminished this function.

Riparian vegetation is shaped by both naturally occurring and anthropogenic disturbances (Tang & Montgomery, 1995). Whereas naturally occurring disturbances include wind, rain, and sedimentation processes, anthropogenic disturbances range from structural developments and land-use practices that impact negatively on riparian zones. According to Naiman *et al.* (2008), the structure and composition of riparian communities is determined and influenced by the river channel slope and the flow of water. Riparian vegetation communities are dynamic; their composition is determined by the ambient conditions along stream channels that exhibit favourable conditions for them to germinate and establish themselves (Hupp & Osterkamp, 1996).

Anthropogenic disturbances have resulted in the removal of riparian vegetation along the stream and river channels for agricultural purposes in different parts of the world. This is attributed to the productive nature of riparian ecosystems of the landscape (Mureti, 2014).

Historically, aboriginal communities relied heavily on riparian zones for basic resources such as water, wood, food, and shelter. Early land stewardship along these zones is evidently seen through African communities settling along the Nile River, where they practiced agriculture and other activities that supported their livelihoods. Furthermore, early European settlers exploited riparian zones as waterways for transportation and trade routes (Mureti, 2014). In recent years, riparian vegetation degradation has been occurring at a much faster rate. Dillaha *et al*. (1989) state that riparian vegetation diminution as a result of agriculture is due to the resources found in these areas and the economic incentive that underpins riparian zone conversion. Riparian zones have the most fertile soils and are simultaneously convenient sources of water for irrigation purposes. Other additional reasons for riparian vegetation diminution are urbanization and the manipulation of hydrologic regimes (National Research Council, 2002). The latter consideration significantly influences the integrity of the riparian systems. This has taken the form of construction of dams and inter-basin diversions and water transfers. The degree of riparian vegetation diminution could also vary with land tenure differences.

Land tenure systems impose an important influence on the degree to which land is put to use for either economic or social development (Bassey, 1990). There are distinct rules and regulations associated with land tenure that are used to control and manage natural resources, such as riparian vegetation. It is important to note that land tenure systems are driven and shaped by socio-economic and political changes. They vary through settings that prompt either private or communal land ownership (Phuhlisani NPC, 2017). A general consensus is that privately owned land or secure land tenure exhibits and follows strict land conservation regulations, consequently minimizing degradation. The opposite is deemed for communally owned land. These are assertions that may not necessarily apply to every part of the world.

South Africa is ecologically diverse and is encompassed by eight terrestrial biomes (Holmes, *et al*. 2005). Land tenure is unique and is rooted in its colonial and apartheid past. Historically, a very small percentage of land was distributed to black homelands, which were communally owned and under-resourced (Hoffman & Todd, 1999). White privately owned commercial farms comprised the other land tenure system. Trends in riparian zone degradation in South

Africa are similar to those in many parts around the world, where riparian vegetation removal is engendered by the desire to expand settlements and agricultural land.

Riparian vegetation diminution gives rise to increased stream bank erosion and instability (Duan, 2001). This culminates in increased excess sediment delivery from hillslopes and accumulation on channel beds, which degrades riparian ecosystems even further. Findings made by Thapa (2015) indicate that the removal of the riparian vegetation zone leads to excessive stream bank erosion and contributes significantly to the bank failure problem in rivers. This underscores the need for regular riparian vegetation management and monitoring.

The implementation of riparian vegetation management is carried out by creating riparian buffer zones. According to Monaghan *et al*. (2008) and Parkyn (2004), buffer zones are the best environmental management tool, considered as the 'first line of defence' against degradation. Riparian buffers trap contaminants released from surrounding land-use practices and facilitate the deposition of suspended particles immersed within the buffer soil profile. Sediment is considered the largest source of contamination in streams (Cooper, 1993).

Riparian buffers have demonstrated a decrease in the effect of land use impacts on the riparian environments by reducing sediment accumulation and sediment transportation in rivers and streams (Fennessy & Cronk, 1997; Hoffmann *et al*., 2009). According to Phillips & Daly (2008), riparian buffers have categorically induced bank stabilization and reduced the susceptibility to erosion. However, their maintenance requires monitoring from time to time.

Monitoring is carried out to evaluate the success of previous management approaches and to maintain changing environments against rapid land-use advances. Vegetation monitoring can be carried out through field visits and aerial photo interpretation techniques. More recently, remote sensing and GIS techniques have become more appropriate as monitoring tools. This is due to the advancement of satellite imagery, enabling high spatial resolution between 20 and 30m and lately up to between 1 and 5 m. This approximates to the use of aerial photographs (Goetz, 2006).

1.2 Problem statement

Rural catchments in many communal areas of the Eastern Cape Province are characterized by degradation of the riparian zone, which has resulted in progressive stream bank erosion and failure, as well as sediment accumulation on stream channel beds. Spatial and temporal variations of such degradation phenomena are poorly understood. Mgwalana, one of such severely affected catchments constitutes the area of the present study. Severe erosion and increased sediment delivery in the catchment are linked to the land-use history of the area, typified by land tenure variations and land-use changes during specific time periods.

Riparian zone management and restoration have been widely carried out in the Eastern Cape Province of South Africa. However, robust management frameworks remain elusive, particularly in the rural communal catchments. Ensuring improved management of riparian systems demands the explicit and integrated consideration of crucial processes at a range of spatial and temporal scales. Therefore, an attempt is made in the present study to elucidate the importance of riparian vegetation and its implications for stream bank processes. This is done by identifying and mapping variations in riparian density in the Mgwalana catchment and making management recommendations that would suit the local conditions. This should assist in the curbing of riparian vegetation degradation and restoration of riparian systems.

1.3 Aim of the study

The cardinal aim of the study is to assess the spatial variations in riparian vegetation density and determine their implications for stream bank erosion in the Mgwalana catchment.

1.4 The objectives of the study

The objectives of this study are:

- To assess spatial variations in riparian vegetation density along stream channels in the Mgwalana catchment.

- To analyse the coupling among hillslope gully erosion, sink (sediment accumulation) areas, and riparian vegetation density.
- To establish the spatial relationship between land tenure systems, land use/cover, and riparian vegetation diminution.
- To determine the implications of the spatial variations of riparian vegetation density for stream bank erosion.

1.5 Research questions

- What is the effect of the coupling among hillslope gullies, sediment sinks and riparian vegetation density?
- How are spatial characteristics related to land tenure systems, land use/cover and riparian vegetation?
- Is there a direct link between spatial variations of riparian vegetation density and stream bank erosion?

This chapter serves as a brief introduction to the importance of riparian vegetation in effecting stream bank and channel processes, as well as the benefits of ensuring its integrity and restoration. The available literature on the geomorphic importance of riparian vegetation is reviewed in Chapter 2. The historical and environmental setting of the study area is presented in Chapter 3. Chapter 4 presents the methods of data collection relevant to achieving the aim and specific objectives of the present study. The results of the study are presented and analysed in Chapter 5. A discussion of the results is presented in Chapter 6. Recommendations that should assist in the curbing of riparian vegetation degradation in the Mgwalana catchment and restoration of riparian systems are also made. A general conclusion is presented in the last chapter.

CHAPTER 2
LITERATURE REVIEW

2.1. Introduction

This chapter firstly gives a general overview of riparian zones and describes the biogeography of riparian vegetation which indicates the conditions different types of riparian vegetation inhabit. Secondly, the functions of riparian vegetation on ecosystems and catchments such as being sources of sediment sinks, facilitating biological corridors, and the implications of riparian vegetation on fluvial processes are discerned. Thirdly, the effect of land use on riparian vegetation is discussed, which interlinks with streambank erosion. A detailed note and review are given on streambank erosion, entailing the factors that induce it such as bank geometry, channel morphology, vegetation, the composition of bank material, and the implications of soil properties for streambank erosion. Lastly, a brief review of remote sensing as a tool to monitor vegetation and a note on the Normalised Difference Vegetation Index which is pertinent to this study is given.

2.2. Background information of riparian zones

Scott *et al*. (2009), describes riparian zones as transitional zones between the aquatic and terrestrial ecosystems. These transitional zones provide an array of ecosystem functions that ensure the efficient regulation of nutrients between these two ecosystems' habitats. According to Yuan *et al*. (2009), ecosystem functions provided by riparian zones include the control of sediment loads that have adverse effects on streambank erosion. Furthermore, Li *et al*, (2009), state that riparian areas are essential due to their ability to reduce the negative impacts of land-use practices on streams. Riparian habitats also provide refuge and shelter for wildlife in urban and rural areas, simultaneously acting as corridors of movement of wildlife and plant species between communities (National Research Council, 2002). In recent years, riparian vegetation has been removed along the streams and rivers for agricultural purposes in different parts of the world.

Riparian vegetation is shaped by both naturally occurring and anthropogenic disturbances (Tang & Montgomery, 1995). Naturally occurring disturbances include wind, rain, and sedimentation processes and anthropogenic disturbances range from structural developments and land-use practices. Allan (2004) states that anthropogenic activities are currently the biggest threat to riparian zones. According to Naiman *et al*. (2008), the structure and the composition of riparian communities are determined and influenced by the river channel slope and the flow of water. Riparian vegetation communities are dynamic, and their composition is determined by the ambient conditions along the channel that exhibit favorable conditions for them to germinate and establish themselves.

2.3. Biogeography of Riparian Vegetation

The type of vegetation found in a riparian zone is an indication of the conditions observed in the area. Naiman *et al.* (2005) state that riparian vegetation is dependent on the regional climate, the variety of species, hydrological, and geomorphological processes and disturbances that are characteristic to the area. The most dominant form of riparian vegetation is categorized by structure and is woody plants. Woody plants entail shrubland, woodland, and forest vegetation (Richardson *et al*. 2007).

Different environments cater to different types of riparian vegetation. Areas that have high latitude and longitude values are unfavourable for woody species; herbaceous riparian species thrive due to the unfavourable climate, hydro-geomorphology, and disturbances. Herbaceous vegetation also thrives in conditions where there is an excess of water, which results in waterlogging or in areas that are prone to veld fires where the growth of woody plants does not persist. On the other hand, in areas that are characteristic of seasonal droughts and where aridity is persistent, woody species are dominant (Richardson *et al*. 2007).

Gregory *et al.* (1991) observe that disturbance events are both natural and anthropogenic. Natural disturbances such as floods, avalanches, fire, wind and glacial activity, and anthropogenic disturbances range from channelization, agriculture, and urban developments. Natural disturbances in a riparian zone promote positive changes as habitat heterogeneity increases. However, exceptions are made in extremely large disturbance events such as floods, which destroy riparian zones by destabilizing the soil and cause erosion. Hupp and Osterkamp (1985) note that plant species vary in their susceptibility to flooding disturbance and therefore the varying severity of flooding within the riparian zone serves to influence the spatial pattern of species composition. Therefore, it is evident that natural disturbance events can alter the composition, structure, and cover of riparian vegetation. It is with this notion that riparian vegetation monitoring must take note of the natural disturbances as an integral component of the system.

2.4. Functions of Riparian Vegetation

2.4.1. Riparian vegetation as a sediment sink

Vigiak *et al*. (2016) observe that riparian vegetation contributes to the reduction of sediment fluxes in freshwater outputs by two main processes. The first process is the ability of riparian vegetation to trap and buffer incoming sediment from flowing into the stream network. This process eminently depends on the width of the riparian zone in relation to hillslope areas and the characteristics of the incoming sediment (Vigiak *et al*. 2016). A study conducted by Poeppl *et al*. (2012) shows that there are linkages between sediment sources, sediment sinks, and riparian vegetation. A distinct decrease of diffuse lateral sediment connectivity in forested riparian zones was noted. Furthermore, they act as strong dis-connectors between the catchment area and river channel. Secondly, riparian vegetation increases cohesion given by root systems and significantly assists in channel stabilization, thus reduced bank erosion. Riparian zones are classified as natural bio-filters and prevent excessive sedimentation (Karssies & Prosser, 1999). This has mostly been identified near settlements and areas where land-use practices are prominently resulting in soil aggregates being destabilized (Sheridan *et al*. 1999). Destabilized soil is easy to transport by fluvial processes down hillslopes and by hydrological processes downstream. Apart from the availability of riparian vegetation, sediment accumulation is also determined by the type of climatic conditions observed in an area, namely, whether an area is humid, arid, or semi-arid.

Puigdefábregas (2005), affirms that when there is considerable vegetation cover, the accumulation of sediment yield is reduced. This was determined by a study conducted by Line *et al*. (2000), where riparian vegetation reduced stream suspended sediment by between 40% and 80%. This was associated with the decreased stream bank erosion and the reduced sediment in streams meant that water quality was improved. Furthermore, a study that documented the pre-and post-riparian management conditions was conducted by McKergow *et al*. (2001). The study was carried out between 1991 and 2001 and the stream reach was fenced after 1996. Suspended sediment concentration decreased dramatically following riparian management from 254 mg/λ to 15.8 mg/λ on average. As a result, sediment delivery from the catchment reduced noticeably following riparian management employing fencing, mainly due to reduced stream bank erosion (McKergow *et al*. 2001).

Due to the link between sediment sources and sediment sinks noted by Poeppl *et al* (2012), gullies and rills are identified as such sources and are determined as sediment feeders. Poesen *et al.* (2003) depict that gullies can attribute up to 94% of total stream sediment load which has implications for stream bank processes. Excess sediment derived from gullies induces channel widening perpetuating increased transport and increased erosional rates. Poesen *et al.* (2003) further reiterate that gullies are major sediment pathways that increase sediment connectivity. Due to the lack of riparian vegetation, the eroded pathways transport the sediment down the slope, and it collects into stream channels at the foot slope as colluvium which is observed in this present study. The stability of the colluvium highly depends on the streamflow and the density of riparian vegetation. The areas in which the sediment collects are called sediment accumulation zones. The sediment accumulation areas pose consequent effects on river habitats and streambank processes.

2.4.2. Riparian vegetation as biological corridors

Biological corridors primarily facilitate pathways for organisms, energy, and matter to move efficiently between micro and macro habitats (Foreman, 1995). When objects move along a biological corridor, it is said that it is acting as a conduit. According to FISRWG (1998), a conduit is essential for the preservation of stream habitat, as the movement has direct impacts on the hydrology, habitat, and structure of the stream. The conduit functions of corridors facilitate the colonization of new areas or the recolonization of areas that have suffered losses in species (Nicholls & Margules 1991). The conduit function of riparian vegetation modifies heat and energy from sunlight and regulates extremes in temperatures.

The use of riparian corridors by species was investigated by Hilty and Merenlender (2004), in Northern California. A total of 21 riparian corridors were categorized as denuded, narrow or wide. Remotely triggered cameras were used to monitor the predator species. The results showed that mammalian detection rates were 11-fold higher in riparian corridors compared to anthropogenic corridors (vineyards). The number and activity level of native predators was higher in vineyards adjacent to core habitat than in vineyards farther away, where the number, and activity level of non-native predators was higher. This indicated that the mammal preferred natural, wider and well-vegetated riparian corridors rather than anthropogenic ones (Hilty & Merenlender, 2004).

2.4.3. Implications of riparian vegetation for fluvial processes

According to Tabacchi *et al*. (2000), vegetation has a strong influence on fluvial processes. Darby (1999) states that riparian vegetation particularly is likely to assume control over surface and subsurface water flow. Surface water flow mainly manifests in runoff. Puigdefábregas (2005) observes that an increased volume of riparian vegetation reduces overland flow and sediment yields. Riparian vegetation intercepts precipitation, which leads to the reduction of the raindrop impact (Tabacchi *et al*. 2000). Peng Li *et al*. (2004) note that under the cover of vegetation, the accumulation of organic matter and the moderation of soil microclimate favour microbial activity and the creation of water-stable soil aggregates. The soil structure thus enhanced results in improved infiltration. Increasing cover by ground-story plants, on the one hand, particularly grasses play an important role in reducing runoff. Perennial plants on the other were found to be generally more effective than annual or ephemeral plants. These vegetation forms modify water flows and sediment dynamics, consequently controlling fluvial processes (Peng Li *et al*. 2004).

In a study conducted by Guillemette *et al*. (2005) in the Montmorency forest, Quebec City, water flow was monitored in different drainage basins after vegetation clearing. Results showed that the removal of more than 50% of the basin vegetation resulted in flooding and erosion. There was a significant increase in overland flow, which affected the stream morphology greatly. In another study that focused on the delineation of hydrological implications for the removal of riparian zones was carried out in South Africa by Scott and Lesch (1996). The authors noted that the removal of riparian vegetation resulted in an increase in streamflow by 9% in the first year. The study was carried out into the second year where regrowth was allowed. A 19% decrease in streamflow was recorded.

Burt and Pinay (2005) also observe that riparian zones play an important role in controlling water exchanges between surrounding land and stream patterns. Minshall *et al*. (1985) make a similar observation that riparian plant communities play a significant role in the river continuum particularly that of intercepting the flow of water as it moves from hillslopes and floodplains to main channels. Bertoldi *et al.* (2011) also note that riparian vegetation alters meander migration rates and has a significant impact on braiding patterns.

Naiman *et al*. (2005) state that riparian vegetation is related to soil characteristics. Consequently, when analysing the hydrological implications of the removal of riparian vegetation, it is important to account for soil characteristics. Riparian zone soils consist of high moisture content compared to terrestrial ones because they are situated close to surface freshwater bodies. Furthermore, the moist soils are related to the high-water tables that are a feature of riparian zones. This may explain the greater species diversity in the zones compared to upland vegetation that only receives water during precipitation (Naiman *et al*. 2005). The greater and longer periods of water availability in the riparian areas explain their ability to support more plants. Thus, agricultural practices indigenous to arid regions pride themselves in practicing farming along riparian zones.

In a study conducted in the Gilgel Gibe catchment area of the Jimma Zone, Ethiopia, Alemu *et al*. (2017) investigated the effect on water quality of land use in the form of agriculture within the riparian zone of highland streams. Satellite imagery and aerial photographs were used to delineate the streams and to quantify the land use in the area. The first and third-order streams were used for classification by Rosgen (1985). The land-use categories classified were forest, eucalyptus plantation, and agriculture. Parameters used to determine water quality included concentrations of orthophosphate, turbidity, and suspended solids. The results indicated that these parameters were significantly higher in agricultural streams than the naturally occurring riparian streams (Alemu *et al*. 2017). Furthermore, the preserved riparian zones indicated better riparian conditions and water quality. Therefore, from a hydrology standpoint, functioning riparian areas are defined by their ability to store and move water and sediment. The greater water storage capacity of riparian areas and their proximity to water bodies result in greater soil moisture content and drives distinct plant communities as compared to adjacent terrestrial uplands.

Catchments in South Africa, particularly in large parts of the Eastern Cape Province are largely characterized by invasive species. The invaders modify the physical characteristics of riparian zones in the affected catchments. Rowntree (1991) investigated the invasion of the riparian zones by alien vegetation. The study noted that alien vegetation encroachment will change the physical structure of the riparian zone. Furthermore, woody species induced channel modification and their removal showed the potential for comprehensive channel instability and mobilisation of sediment. Mehl (2015), conducted a study in the Nuwejaars Catchment, where the distribution of alien vegetation was mapped for 2003, 2005, and 2014. Results indicated that the distribution of alien vegetation decreased due to a comprehensive clearing programme. Areas that were characterised by woody alien vegetation were associated with lower channel width-depth ratios than the areas without. It was concluded that the removal of woody alien vegetation had considerable effects on channel morphology.

2.5. Effect of land use on riparian vegetation

The impact of anthropogenic activities on riparian vegetation is still poorly understood. Studies by several authors demonstrate how the spatial patterns and structure of riparian vegetation are affected by adjacent land use types (Inoue and Nakagoshi, 2001; Ferreira *et al*. 2005; Burton *et al*. 2005b; Gordon and Meentemeyer, 2006; Fernandes *et al*. 2011). The introduction of any form of land use near riparian zones results in the fragmentation of the riparian zone, which leaves it exposed to external factors such as rain and wind (Saunders *et al*. 1999). These external factors exacerbate the reduction of species richness and abundance that in turn imposes changes on the vegetation structure and ecosystem function (Dunning *et al*. 1992). A study carried out by Burton *et al*. (2005b) assessed the changes of riparian diversity and structure in response to urbanization. GIS tools were used to discern different land cover types namely, rural agriculture, mixed forests, evergreen forests-pine plantations, developing-suburban, and an urbanized area. The study indicated that fragmentation of native riparian vegetation due to urbanization resulted in a surge of invasions that interfered with the productivity and stability of riparian communities. Furthermore, a significant decrease in forest cover along the urban gradient was recorded due to the dominance of invasive species.

Méndez-Toribio *et al*. (2014) conducted a similar study in the Duero river watershed in Mexico. The influence of the adjacent land use on riparian structure and diversity in four hydrographic regions that made up the watershed was investigated. The study revealed that the average number of stems and individual woody plants was higher in forested areas compared to agricultural and urban land. Forested areas further indicated a higher alpha and beta diversity and higher species richness compared to urbanized and agricultural areas. Both these studies demonstrate a fundamental point that anthropogenic activities degrade native riparian communities, altering the structure and spatial patterns.

In the South African context, the degradation of riparian degradation by land use has been impacted by historical factors and the failure to implement environmental protection laws. Agricultural activities such as grazing, and crop farming have been at the forefront and one of the primary causes of riparian zone degradation in South Africa (Dube *et al*. 2017). Gauteng province recorded a 21% expansion of the agricultural activities in 2009, due to the removal of native riparian vegetation, which has increased the susceptibility of bank erosion along the rivers (Dube *et al*. 2017). Areas that have been intensively studied include the Jukskei River and the Berg River. The Jukskei River was reported as a degraded system as early as the 1970s (Wittmann & Förstner, 1976). This is greatly attributed to the riparian vegetation fragmentation due to the construction of both formal and informal settlements. Due to the adversity of the degradation, the area is prone to flash floods and has resulted in detrimental effects in the area. In the Berg River Catchment, Nyemba (2013) identifies a reduction in the spatial extent of the riparian zones by 23% between 1955 and 2012. This was attributed to persistent riparian degradation, poor governance, and management in South Africa.

2.6. Streambank erosion

Bank erosion is an important component of catchment sediment budgets (Kronvang *et al*. 2013). Quantifying it is essential for understanding the patterns of sediment and water transport processes in catchments (Prosser *et al*. 2001). Bank erosion refers to the removal of bank material due to sheet, rill, and gully erosion by the overland flow on bank surfaces resulting mainly from the removal of riparian vegetation (Duan, 2001). Trimble (1997), observes that streambanks erode as a result of changing conditions on the banks such as channel widening resulting from increased runoff, exacerbated by land-use change. In a study conducted by Thapa (2015), streambank erosion was investigated in the Kodku River. The removal of riparian vegetation was noted to lead to excessive streambank erosion and contributed significantly to bank failure problems in the river. Furthermore, high-velocity overbank flow, which accelerated bank instability was recorded. Streambank failures in small agricultural catchments in Eastern Norway were documented as a result of the bank toe undercutting and human activity associated with the use of heavy machinery close to streambanks that destabilized the stream channels (Krzeminska *et al*. 2019).

The common form of land degradation that is attributed to stream bank erosion resulting in even higher sediment outputs is manifest in gullies. Streambank erosion can contribute up to 80-90% of the total sediment found in the stream (Simon *et al*. 1996; Kronvang *et al*. 1997). This is supported by studies documented in Minnesota (Sekely *et al*. 2002). It is estimated that the bank erosion in a watershed contributed up to 30-45% of the total sediment found in streams (Kronvang *et al*. 2013). Higher estimations of 45-50% were documented by Schilling and Wolter (2000). Schumm (1999) observes that gullies also form as a result of poor land practices that result in reduced riparian vegetation. A similar observation is made by Stocking (1996) that gullies are not only formed in the aforementioned instances but by other mechanisms. Gullies are symptomatic of a degraded catchment, more so in the bad-land category, which is highly evident in the upper catchment of the current study area.

An investigation on the anthropogenic influences on sediment connectivity in the Upper Mzimvubu River was conducted by Van der Waal & Rowntree (2017). It was discovered that crucial pathways that increased connectivity and induced stream bank processes were natural drainage lines, connected and disconnected gullies, and cross-slope linkages which encompassed roads and livestock tracks. Connected gullies and disconnected gullies contributed 10% each to the drainage density. Consequently, the gullies contributed heavily to hillslope-channel connectivity. Due to the removal of vegetation that previously acted as buffers, the increased drainage density and altered other natural drainage features have led to the increased transportation of water and sediment which is further enhanced by the gully channels.

Furthermore, continuous gullies and stream channels result in a phenomenon known as coupling. According to Harvey (2001), coupling is described as the systemic linking of the upslope sediment sources to the fluvial system (Figure 2.1). Coupling systems in a catchment involve the up-system transmission of the effects induced by changes on the base level upstream and the down-system coupling involves the propagation of sediment through the system from the hillslope and headwater sources (Harvey, 2002). Therefore, coupling in catchments increases erosion downstream as the sediment eroding from the gullies is transported into channels which increases erosional rates. This further exerts negative impacts on stream bank processes such as more channel scouring and channel widening, which will lead to clogged stream beds. In a study conducted by Gutiérrez *et al.* (2011), continuous gullies resulted in flow contamination and reduced channel capacity, with an increased potential for flood risk. This added to stream bank erosion, as the bank slope was reduced due to excessive sedimentation.

When assessing bank erosion, it is important to note the scale before the formulation of management solutions. According to Lawler (1995), research has indicated that there tends to be a scale dependence of bank erosion processes in catchments, namely, high, mid, and lower reaches of catchments that represent different bank heights and stream power. He elaborates, that in the lower reaches, mass-failure mechanisms are the most distinct. It could be rather more effective to install bank stabilizing structures to prevent mass failure by channel scouring to reduce sediment yield by a large margin (Lawler, 1995).

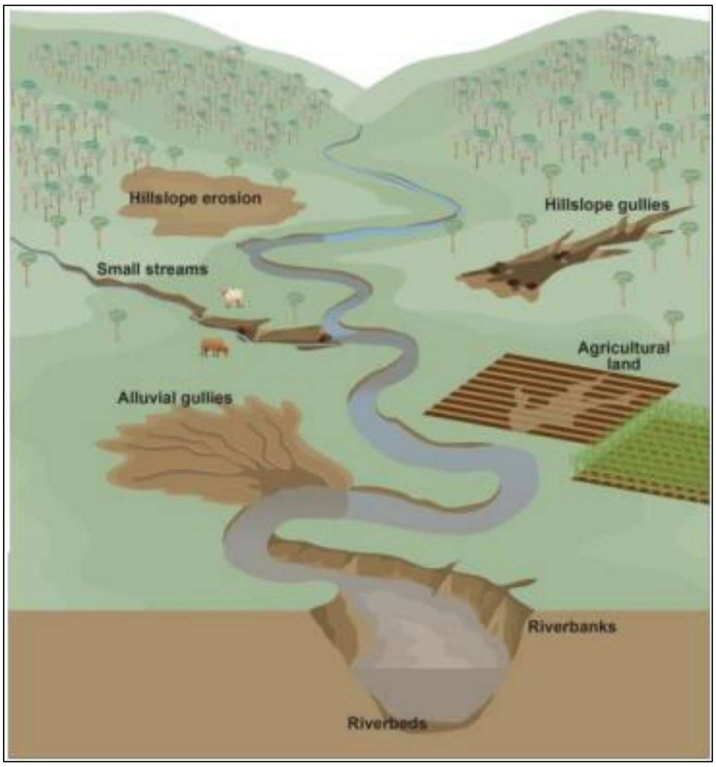


Figure 2.1. Gullies connecting into streams exacerbating erosion and sediment output (Image by Prosser, 2018).

2.7. Notable factors influencing stream bank erosion

Streambank erosion is induced by a variety of factors such as bank geometry, channel morphology, vegetation, the composition of the bank material, the magnitude of discharge (Janes *et al*. 2017), and subsurface conditions (Knighton, 1998).

2.7.1. Bank Geometry

Micheli and Kirchner (2002), evaluated the effect of bank geometry on stream bank erosion on dry and wet meadows by the use of a linear model to calculate coefficients that would demonstrate the susceptibility of bank erodibility, which will eventually lead to stream bank erosion. Results showed that the average stream migration rates recorded on wet meadows were lower compared to dry meadows. By implication, banks without wet meadow riparian vegetation are more susceptible to erosion. Furthermore, bank heights that exceeded 1 m were dominated by dry meadows and the availability of water was low, thus channel incision may reduce bank stability by increasing bank height and by converting banks from wet meadows to dry meadows vegetation (Micheli & Kirchner, 2002). In another study conducted by Laubel *et* *al*. (2003) in rural catchments of Denmark, the bank erosion rate was monitored over 2 years. Distinct spatial variations were observed such that bank erosion rates were significantly higher at the 50 cm bank section averaging at 20 mm $year^{-1}$ than the upper bank section which averaged at 6 mm $year^{-1}$ (Laubel *et al*. 2003).

2.7.2. Factors that influence channel morphology and geometry

Channel geometry comprehensively captures the geographical attributes and essence of factors that affect the morphology of a channel (Julien and Wargadalam, 1995). These characteristics encompass the depth, width or confinement, slope, and channel bed morphology (Montgomery and Buffington, 1997). Advances that occur in channel geometry are regulated by changes relating to water discharge (Hu *et al*. 2017). Changes that occur along the sides of banks alter bank properties such as riparian vegetation diminution and sediment load (Easson, 2002). Pitlick and Cress (2002), observe that discharge coupled with vegetation incorporate pivotal changes such as grain size, sediment processes, downstream fining and bank erosion. Park (1997) points out approaches undertaken in the study of channel geometry. The morphometric analysis approach underpins the channel size, shape and geometry employing a downstream direction as a reference. This analysis rigorously determines the channel depth as a three-dimension component. The hydraulic geometry approach breaks down all aspects relating to the discharge of water and the transportation of sediments (Park, 1997).

2.7.3. Influence of Vegetation

Vegetation influences channel morphology; this depends on its contribution to bank strength and resistance. In instances where the vegetation density is comprehensively high, this increases the critical shear stress for fluvial entrainment of bank sediments (Thorne & Osman, 1988). Thorn and Osman's assertions are supported by a recent study. In a study conducted by Valyrakis *et al*. (2021), bed shear stress at a main channel generally increased with increasing riparian vegetation density. It further increases critical height, which simultaneously induces a decrease in the channel width (Thorne & Osman, 1988; Thorne, 1990). Riverbank erosion has geomorphological importance that involves inducing modifications in the river channel course and the reconstruction and development of the flood plain (Hooke, 1979). Streambank erosion can be induced by changes in vegetation cover that are induced by deforestation or cattle grazing (Schumm, 1999). Vegetation consists of relative root systems that reinforce bank material which reduces susceptibility to erosion (Knighton, 1998).

Factors that influence streambank erosion work in tandem, particularly vegetation and channel geometry. The relationship between vegetation and channel morphology is demonstrated through, studies by Thorne (1990) and Rowntree and Dollar (1999). The benefits of a high vegetation density are investigated, and results indicate that the stabilization of banks and channel width which also exerts an effect on channel roughness is apparent. The stabilizing effects of vegetation on channels only apply to a certain degree as an interplay of vegetation type and vegetation structure is considered. This depends on the spatial and temporal variability in the density, type and composition of riparian vegetation (Montgomery, 1997; McBride *et al.,* 2008), channel scale, bank material and the location of the catchment, which can influence the degree to which vegetation can exert the stability on channel form (Thorne, 1990; Dunaway *et al*., 1994; Friedman *et al*, 1996).

According to Merchant (2007), the relationship between vegetation situated in the riparian zone and stream geomorphology is important. Furthermore, the type of vegetation found along the banks plays a crucial role in bank stability. The hydrologic regime and sediment yield crucially depend on the type of vegetation that inhabits a certain area because it is through this that variation across a channel is determined (Nanson and Beach, 1977). This is supported by Arnold and Toran (2018) that this is due to vegetation having the ability to provide structural support through root development. This significantly reduces sediment transport by increasing soil cohesion through the supply organic material, which further influences the soil moisture. Gurnell (2014) experimented the effect of vegetation on erosion and found a 20,000-fold increase in erosional resistance with an 18% increase in the volume of root mat in silty bank materials. Observations made by Zimmerman *et al* (1967), that comprehensive streams that inhabited the sod were empirically narrow and the channel depth was much more pronounced are still relevant and are substantiated by recent studies. The ratio of rooting to channel depth is pertinent, as it determines the erodibility of bank sediments (Richardson *et al*. 2007). The same study showed that streams under forest cover showed variance in terms of channel width, which is attributed to constant disturbances occurring. Vegetation induces significant effects on overall channel systems, attributed to channel morphology, the intensity, and velocity of the flow of water, and of sediment transportation downstream (Nanson and Beach, 1977). Nanson and Beach (1977), observe that the intensity of vegetation tends affect overbank sedimentation rates.

It is important to note that to a certain degree, vegetation is driven by climate. In humid areas, forest biomes are aggressively observed, and they happen to occur densely. This will maintain reduced levels of bank erosion and will promote adequate sediment trapping. Stream hydrology will improve, as there will be increased incision and flow interception. Arid areas are mostly inhabited by shrubs which tend to have spaces in between shrubs. In relation to physiography, particularly slope angle and gradient, the degree of these two factors will enhance runoff where wide inter-shrub spaces exist. In such instances, the flow of water will not be controlled adequately. So would the transportation of sediment. This will result in considerable bank erosion and significant changes to the channel will be observed. The geology of an area can also be incorporated because it determines the type of soil that is found in that specific area. Extensive land use namely, deforestation or overgrazing, will also influence riverbank stability, particularly due to processes like trampling.

The role of riparian vegetation is comprehensively illustrated in literature with its effect on the stability of stream channels being the most investigated phenomenon. Thorne (1990) points out that it reduces bank erosion through its ability to maintain soil reinforcement, adequate bank drainage, and curtails near-bank flow velocities flow. Increased riparian diminution results in increased streambank erosion. In studies conducted in watersheds in Iowa, USA, it was noted that streambank erosion from riparian zones that consisted of crop fields and further extensively grazed pastures, contributed 17 times more phosphorus than in forested riparian zones (Zaimes *et al*., 2004). This study also indicated that riparian forests can be used as buffers to reduce sediment sources derived from bank erosion into streams by 81%, compared to those characterised by intense land-use practices (Zaimes *et al*., 2004).

2.7.4. Composition of bank material

Debnath *et al*. (2007) state that prior knowledge of the influence of the erosion rate on flow and bank material characteristics is required to quantify and predict bank erosion. Grain size is the most fundamental property of sediment particles, which affects their entrainment, transport and deposition (Blott & Pye, 2001). This implies that the transportability of sediment depends on grain size. Alluvial fans are made up of cohesive materials such as silt and clay-sized particles and are particularly known for their resistance to entrainment (ASCE Task Committee, 1998). These are formed at ephemeral streams originating from a steep terrain into lowlands. These sediments rapidly decrease in grain size and have the ability to coalesce (Church and Jones, 1982; Hoey, 1992). These particles aggregate as a result of an amalgamation of single grains and large flocs containing millions of grains. The aggregation is enhanced by an increase in clay-sized particles which are known to have cohesive properties (McAnally and Mehta, 2002). In a study conducted by Bhowmik *et al*. (2018) in North-East India, bank material with a high sand percentage (90 %) and a lower silt and clay percentage showed a high erodibility potential. This was the basis of the conclusion that bank material was the main driver of bank erosion.

2.8. Implications of soil properties for streambank erosion

According to Mazumdar and Talukdar (2018), the physical soil properties of bank soil play a role in inducing and preventing bank erosion. Manjoro *et al*. (2012) observe that soil properties that are prevalent in initiating erosion are soil texture, bulk density, organic matter and particle size distribution. Soil properties, such as bulk density, organic matter content and soil particle component, exert first-order control over the ability of a soil to store and transport water (Jacobs *et al*. 2004; Hu *et al*. 2010; Biswas and Si, 2011).

According to Li *et al*. (2018), soil texture is determined by the distribution of various particle size fractions and it represents the fundamental characteristics of soil that have a profound influence on the physical, chemical and biological processes. These fractions influence the movement of water through soil by utilizing pore spaces of soil surface. Schaetzl & Anderson (2005) point out that soil with a coarse texture has larger pore spaces and a reduced surface area. This consequently results in a lower water retention capacity and lower nutrient retention capabilities. These factors pose an effect on soil quality that influences erodibility, as illustrated by the Hjulström curve (Figure 2.2.) (Kakembo, *et al*. 2007). Particle-size distribution holds a significant role in soil physical properties as it reflects hydraulic properties such as water retention (Campbell and Shiozawa, 1992).

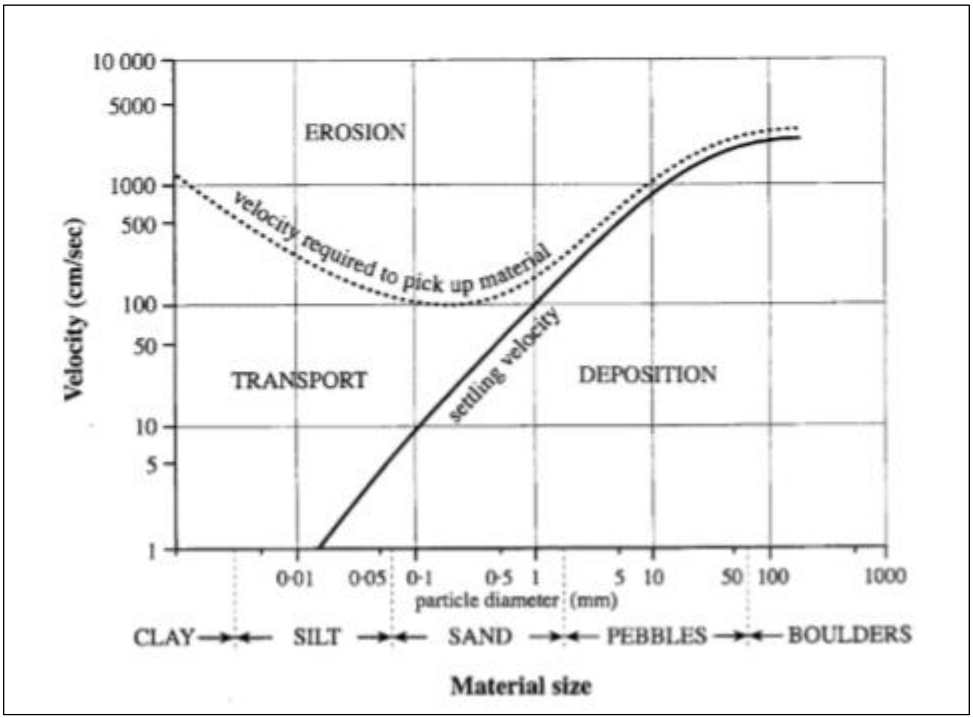


Figure 2.2. An adaptation of the Hjulström curve (Hjulström, 1939).

Assouline (2011), points out bulk density as one of the fundamental physical properties of soil. It is thus an important factor for soil nutrient retention and can indicate soil compaction and root limitation growth (Dexter, 2004). Bulk density is related to other fundamental soil parameters such as soil organic matter, soil texture and soil structure. Fuentes *et al.* (2004) and Horn and Smucker (2005) state that an increased bulk density implies low macro pores and high meso-and micro pores that have a significant impact on hydraulic conductivity. Furthermore, Dec *et al.* (2008) observe that an increased bulk density does not only exert changes to pore spaces but it affects the ability of the soil to shrink and to conduct water in the soil. In a study conducted by Tanveera et al (2016), it was determined that sand showed a positive correlation with bulk density whilst clay content and porosity were negatively correlated with bulk density.

Organic matter acts as a binding agent to produce stable aggregates thus it reduces the soil's susceptibility to erosion if found in considerate concentrations. It further enhances the ability of the soil to stabilize soil structure and provides formidable protection against raindrop impact (Van Zijl, 2010; Valentin *et al*. 2015). It is due to this that aggregate stability and organic matter as a unit are used as an indicator of the soils susceptibly to erosion. Studies conducted by Fenton *et al*. (2008) support the aforementioned observations. According to Trimble (1990), soil with an organic matter percentage less than 3.5% unstable aggregates, which induces erosion. This is supported by Loveland & Webb (2003), who found that soil with an organic matter threshold of less than 3.4% is susceptible to erosion. This is supported by the results of a study conducted by Fenton *et al*. (2008) on agricultural soils of parts of the USA, where organic matter ranges between 3% and 6%.

2.9. Distribution of riparian vegetation in drylands and humid regions

The distribution and the composition of riparian vegetation are linked to hydro-geomorphic factors *viz;* flood frequency and severity (Stromberg *et al*. 1993a), depth to the water table, channel, and valley form (Birkeland, 1996) and substrate particle size (Craig & Malanson, 1993). Hupp and Bornette (2003) observe that vegetation organization and composition along a river or stream is directly dependant on the nature of disturbances occurring in the area and the biological characteristics of the plants which persist and resist competition and disturbance.

Drylands are typified by arid and semi-arid climatic conditions (D'Odorico & Porporato, 2006). Precipitation predominantly becomes overland flow and reaches the stream relatively quicker and ephemeral streams are a key characteristic (Zaimes, 2010). Furthermore, the streamflow contributes to groundwater (Zaimes, 2010). According to Malanson (1993), the most distinct aspect of semi-arid regions is that a regular arrangement of landforms in the channels is absent. Sandercock *et al*. (2007) also observes that channels in arid regions regularly show marked variations in riparian vegetation at various scales. Studies conducted by Planty-Tabacchi *et al.* (1996) show that semi-arid rivers present irregular patterns of species richness, related to inconsistent water availability. In Arizona, there were distinct linkages between the distribution of phreatophytes and groundwater discharge in arid and semi-arid areas (Nicholas, 1994).

Humid regions are characterized by a more organized structure in the riparian zone, with vivid longitudinal and transverse trends (Sandercock *et al*. 2007). Abundant precipitation leads to increased streamflow and soil moisture. Thus, riparian vegetation in these regions appear lush, as it is sustained by the regular water supply. Due to the high precipitation and high riparian vegetation density, infiltration and subsurface flow rates are also high. Consequently, the groundwater contributes to streamflow; while the opposite is true for dry regions (Zaimes, 2021). The regular flow regime influences the channel environment as channels exhibit well-defined in-channel micro-landforms, *viz*; bars, floodplains, terraces (Sandercock *et al*. 2007). In a study conducted by Hupp and Osterkamp (1996), vegetation species distribution patterns were largely controlled by frequency, duration and the intensity of floods. Riparian zones in humid regions show strong downstream trends in morphology and regularity in the distribution of vegetation across the valley floor. The general effect of vegetation in these channels appears to be to enhance the processes of sedimentation and increase resistance to erosion.

2.10. Remote sensing as a tool to monitor vegetation condition

The application of remote sensing as a tool to study and monitor the environment has progressively changed through the years (Mutanga *et al*. 2016). Due to the discovery of satellite data, significant advances have been made, particularly in vegetation monitoring. According to Lawley *et al*. (2016), vegetation monitoring does not only help determine the degree of vegetation damage but influences crucial environmental decision making, which has a significant effect on vegetation management. Remotely sensed imagery is used to analyse vegetation conditions by utilizing vegetation indices and spectral classification (Lawley *et al*. 2016). According to Cruden *et al*. (2012) and Bin Abdul Rahim *et al.* (2016), the application of remote sensing in vegetation monitoring is fundamentally based on spectra derived from specific wavelengths. These include the ultraviolet region (10-380 nm), the visible spectra which consist of the blue (450-495 nm), green (495-570 nm), and red (620-750 nm) wavelength regions, the near and mid-infrared bands (850-1700 nm).

A variety of vegetation indices has been designed to produce various outputs of vegetation conditions. However, the scope of the present study will zero in on the Normalized Difference Vegetation Index (NDVI).

The NDVI is one of the frequently used vegetation indices to distinguish between vegetated surfaces and to document various vegetation density patterns (Bellone *et al*. 2009). It distinguishes growing vegetation from background features (Hansen *et al*. 2000; Southworth *et al*. 2004). Whereas the Vegetation Index (VI) is one of the most used indices to quickly identify vegetated areas with the use of multispectral data (Pirottia, *et al.* 2014), the NDVI has a higher sensitivity corresponding with crown density change than the VI. The NDVI can be derived from Landsat 8 OLI using the red and near infra-red band using the formula:

$$\text{NDVI} = \left(\frac{NIR-RED}{NIR+RED}\right)$$

Where: RED = Spectral reflectance measurements obtained from the red (visible) band

NIR = near-infrared band.

The NDVI range falls between -1 and 1. According to Jayakumar *et al.* (2018), an increased vegetation density on a patch of land appears green and is reflected by a higher NDVI number, usually closer to 1.

Singh *et al*. (2015) used NDVI data that was derived from a multi-temporal Landsat 5 imagery to investigate vegetated and bare areas that contributed to soil erosion. The results showed that areas that observed a poor vegetation distribution which observed low NDVI numbers were the most susceptible to erosion and perpetuated further land degradation (Singh *et al*. 2015). Ndou (2013) used NDVI to relate the vegetation trends to grazing management systems. The study showed that vegetation condition was severely degraded in close proximity to villages.

Similarly, a study by Fox (2003), conducted in Namaqualand identified NDVI as a vegetation index that could be used as a tool to measure the phenology and growth of vegetation. It could further be used in climate models and desertification prediction, due to its correlations with mean annual NDVI, precipitation and potential evapotranspiration.

This chapter gave a detailed description of the implications of riparian vegetation density variations and aspects that influence its distribution. The relationships between the NDVI and variations in riparian vegetation are reviewed. A triangulation of the review made in this chapter is used as a basis for data collection, analysis and discussion in this project.

CHAPTER 3

CHARACTERIZATION OF THE STUDY AREA

3.1. Introduction

This chapter provides an overview of the physical characteristics of the catchment and land tenure units that give a background to the degradation and riparian vegetation variations observed in the study catchment. An overview of land-use changes, geologic, climatic, and edaphic setting of the study area is also provided.

Land tenure systems have defined the land-use history of the study area. The study area consists of traditional villages, betterment areas, and former commercial farms that were owned by white farmers. Land use practices in these tenure units have had varying impacts on the quality of land both in space and time (Kakembo, 1997).

3.2. Locational settings

The Mgwalana catchment is situated in the former homeland of Ciskei in the Eastern Cape, Province of South Africa. The catchment has been extensively researched in recent times particularly it's upland area due to the invasive species characteristic in the area and various land-use practices that have propelled severe erosion over the years (Kakembo, 2004; Kakembo *et al*. 2009; Manjoro *et al*. 2012). The study site is located at -33°16’08.76” S, 27°07’37.45” E (Figure. 3.1.). The catchment boasts a surface area of 178.2km ^{2} and it is situated east of the Bira catchment and west of the Mtati catchment. It shares a boundary with the Great Fish River which is at an elevation of 327 above sea level.

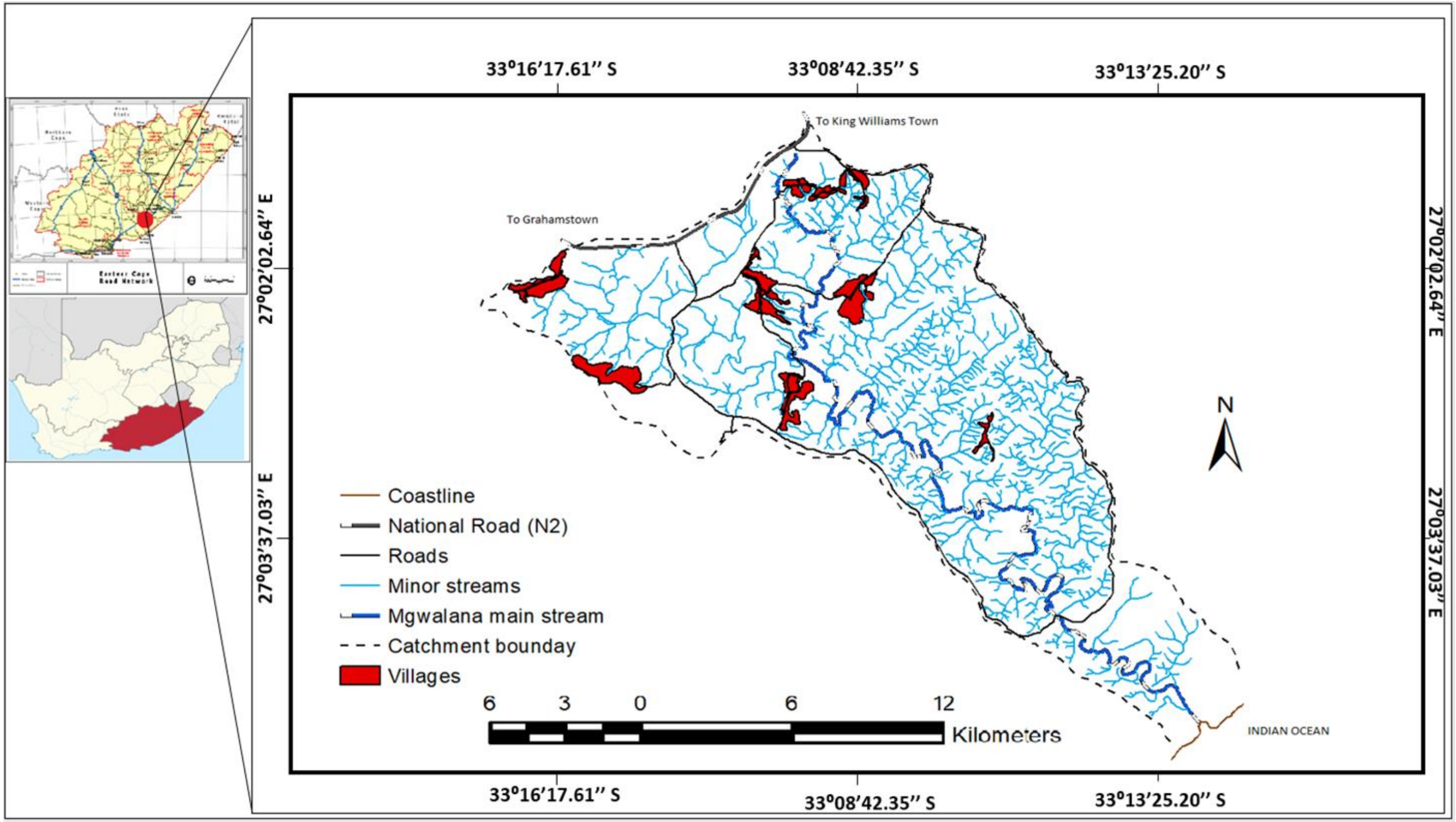


Figure 3.1. Map of the study area, Mgwalana catchment.

3.3. Vegetation

Overutilization of land over the years has resulted in drastic modifications of natural vegetation. Acocks (1975), classified veld types in South Africa and the current study area as the Thornveld, which is characteristic of the *Acacia karoo Hayne.* Due to land tenure-related land-use changes, the natural vegetation has extensively been modified. This modification is reflected by the spatial differences in vegetation cover among the land tenure systems, particularly in form of the limited nature of palatable vegetation species in the traditional and betterment villages of the study area. The indigenous grass species are the *Themeda triandra* and *Digitaria eriantha* (De Jager, 2015). These species have now almost been diminished by overgrazing, giving way to the patchy invasive shrub, *Pteronia incana*, which has encroached upon most hillslopes of the upper part of the catchment.

P. incana is indigenous to the Karoo and listed as one of the problematic plants in South Africa, which falls under the *Asteraceae* family (Kakembo, 2003). It has strong unmatched competitive characteristics, as it survives on minimal rainfall (Wells *et al*. 1986). It creates resource zones that prohibit nutrients cycling and confines all the nutrients within such zones. This resource confinement causes a depletion of resources in the inter-patch areas (Kakembo, 2004). The inter-patch spaces promote increased runoff connectivity, erosion, and high sediment output (Kakembo, 2003). The invader shrub is most dominant in the upper parts of the catchment, comprising communal villages. Most formerly cultivated fields, identifiable as severely eroded abandoned lands are currently colonized by the invader shrub on a blanket basis.

The lower parts of the catchment towards the sea comprise the former white commercial farms. Pockets of woodland vegetation still persist here, despite increasing encroachment by communal farmers and utilization of sections of them for pineapple cultivation (Kakembo, 1997). Limited pockets of *P incana* invasion are noticeable in a few disturbed sections of the lower catchment parts.

Recently, the Agricultural Research Council (ARC) has generated a new set of data and has provided alternative names for the vegetation groups of the study area, as illustrated by Figure 3.2. It is noticeable that the dominant indigenous vegetation type in the catchment of study is supposedly the Great Fish thicket and the Albany coastal belt in the upper and lower parts of the catchment respectively (see Figure 3.2). However, a remarkable deviation from such cover is evident on the ground, particularly in the upper catchment parts.

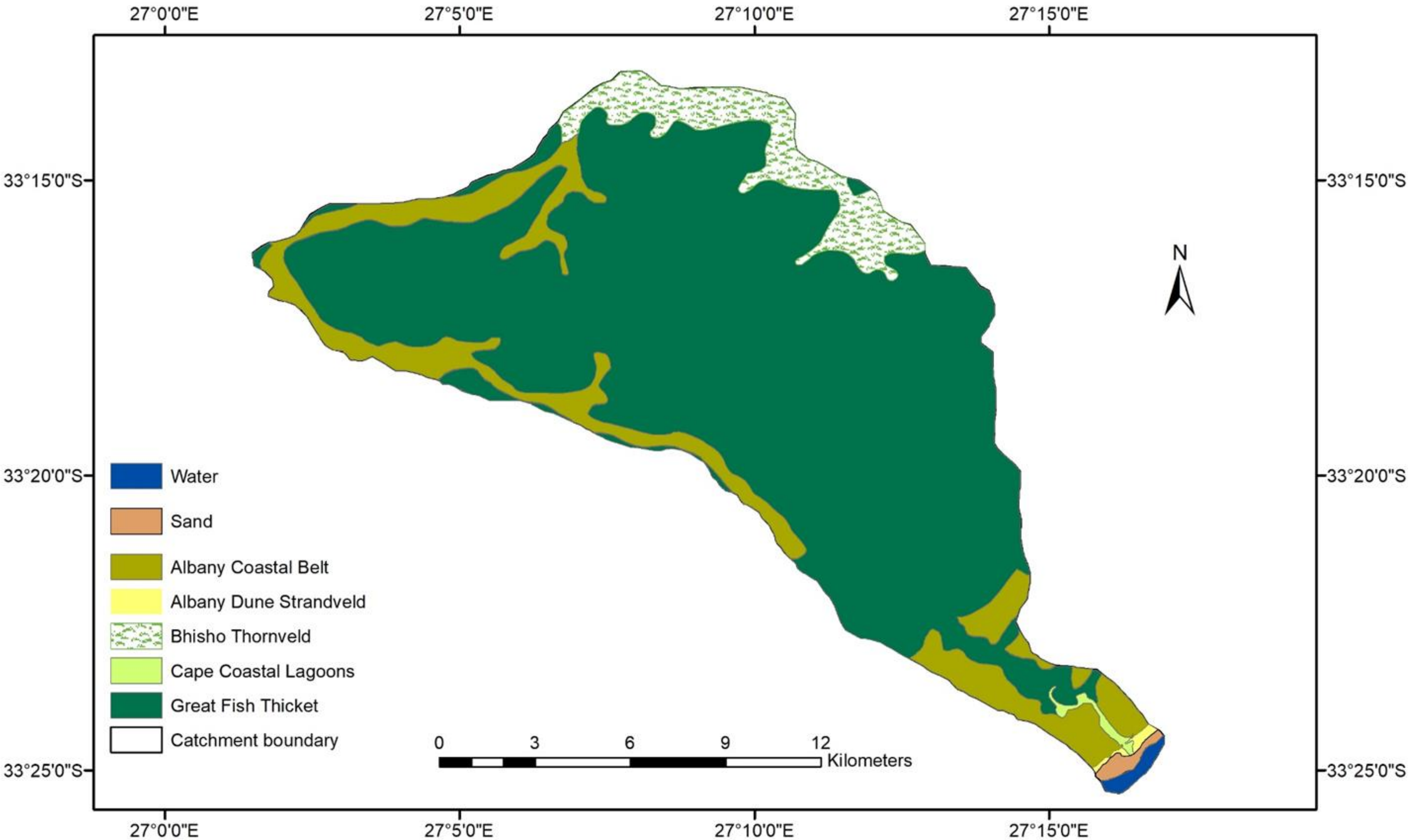


Figure 3.2. Vegetation map of the study area (ARC, 2017)

3.4. Land use/cover history

The study catchment has a unique history of land use and cover changes. Evidence obtained from aerial photographs indicates that during the 1930s, the area had already been separated into two land tenure units i.e. African traditional villages and white commercial farmlands. Parts of the traditional villages were forcefully converted to betterment settlements by the apartheid government. Such villages were supposedly organized settlements with gridiron street patterns, which would permit the consolidation of fragmented subsistence farmlands. Resistance to betterment villages in part explains the abandonment of cultivation.

The controversial betterment program carried out in the area in the 1960s entailed the comprehensive relocation of scattered homesteads. Previously cultivated fields were abandoned mainly because many of them were situated at quite a distance away from the betterment villages.

The figure below (Figure 3.3), shows the distribution of land use/land cover as mapped by the ARC during 2017.

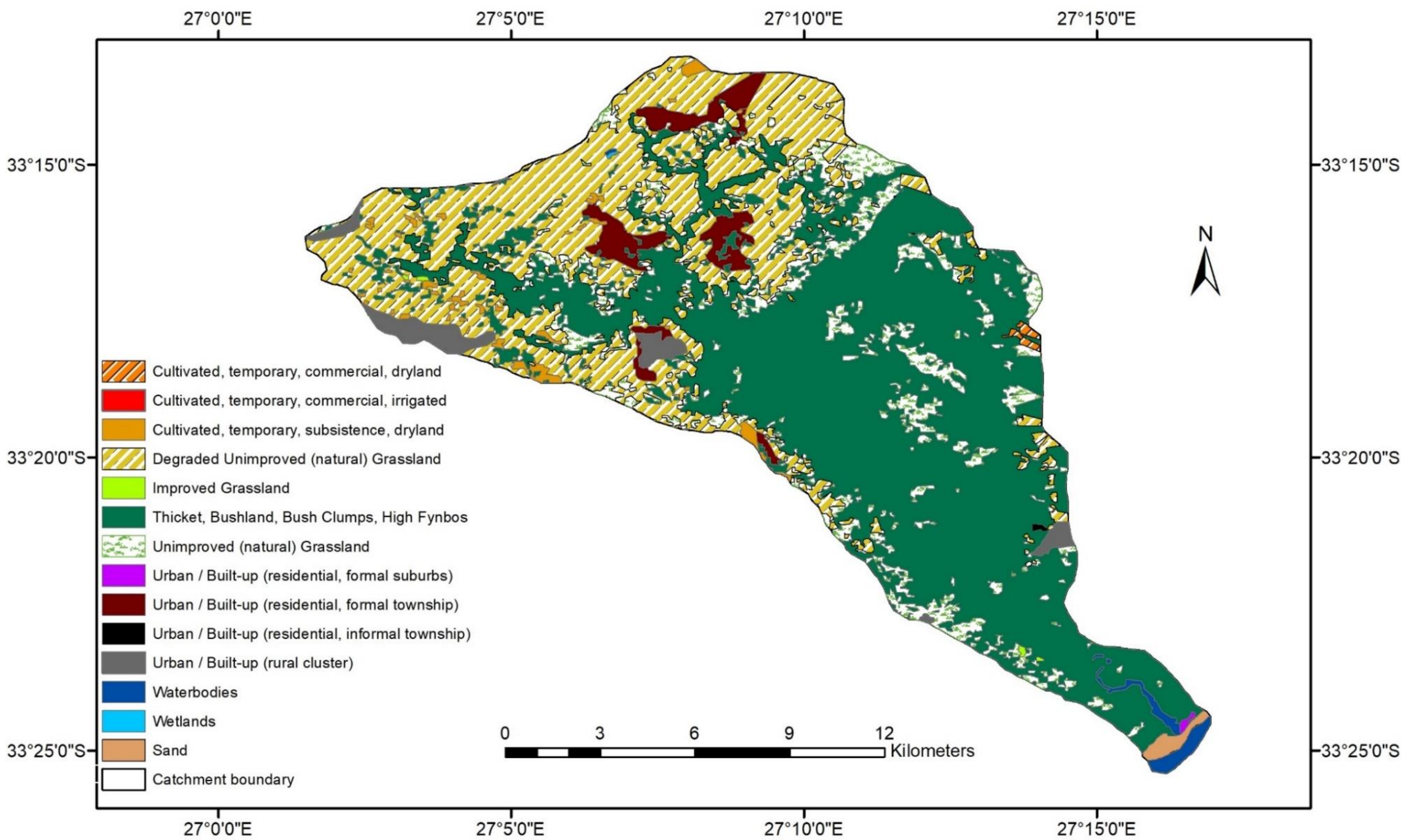


Figure 3.3. Land use/land cover map of the Mgwalana catchment (ARC, 2017).

3.5. Climate

Rainfall

The study area lies in a semi-arid region and falls within the summer rainfall region of the Eastern Cape. The annual rainfall received in this area is approximately 491 mm per year (Figure. 3.4), which is erratic and irregularly distributed (Kakembo, 2003; Manjoro *et al*. 2012). According to the ARC map (Figure 3.4), lower precipitation is recorded along the coast compared to inland.

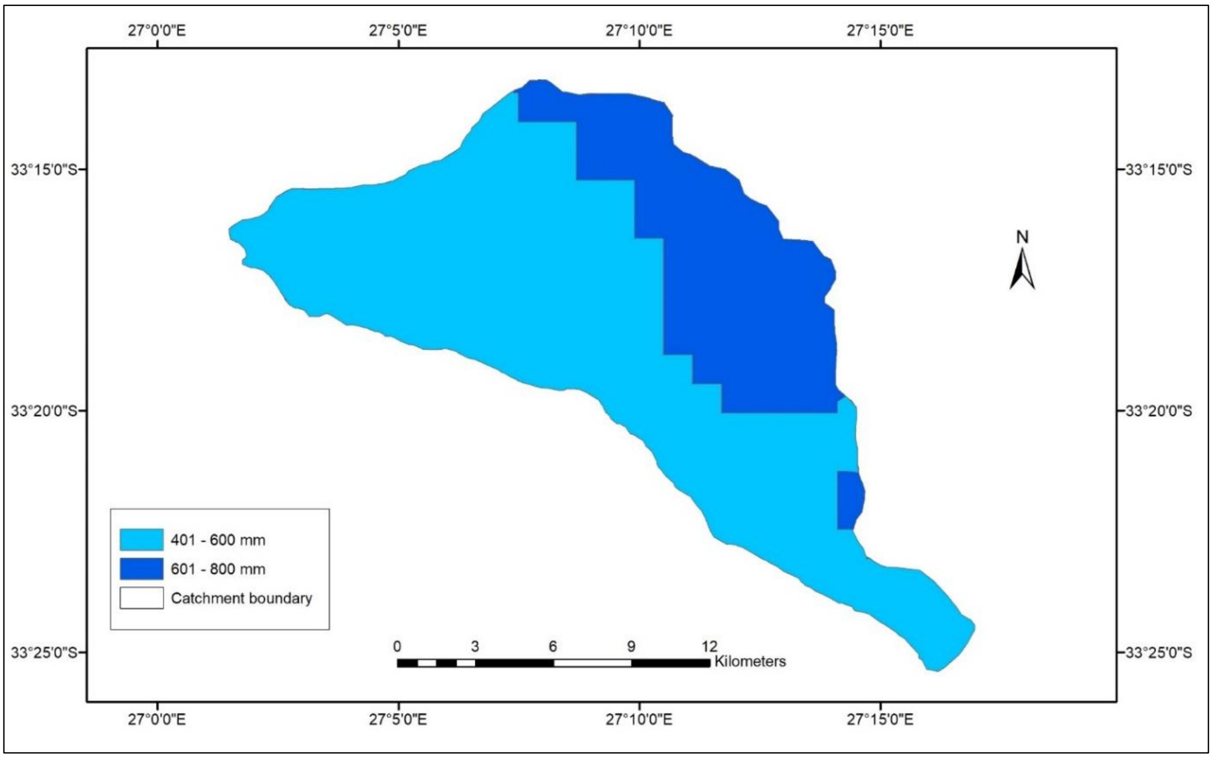


Figure 3.4. Map showing rainfall patterns in of the study area (ARC, 2017)

Temperature

The highest temperatures recorded fall between 29°C and 31°C and the lowest between 7°C and 9°C in summer and winter respectively. The variations derive from the catchment's close proximity to the ocean, where there is an onshore flow of cold air brought in by the passage of cold fronts and the Atlantic pressure systems working simultaneously with Berg winds resulting in abrupt warming. Furthermore, the seasonal variations experienced in certain parts of the catchments are attributed to slope direction (Kakembo, 1997). The south-facing slopes are colder than their north-facing counterparts.

3.6. Topographical setting

Most slopes facing the stream channels within the catchment of study characteristically rise steeply (10^0 and above) before they even out into gentle and extensive interfluves (Kakembo, 2003). It is these steeply rising slopes that are hotspots for *P. incana* invasion, particularly in the communal land section of the catchment. Hillslopes with lower slope angles display a significant degree of concavity while hillslopes found in the upper parts of the catchment show a high degree of convexity. The general topographic trends of the study area are such that the south-facing slopes have a greater frequency than the rest of the slope directions.

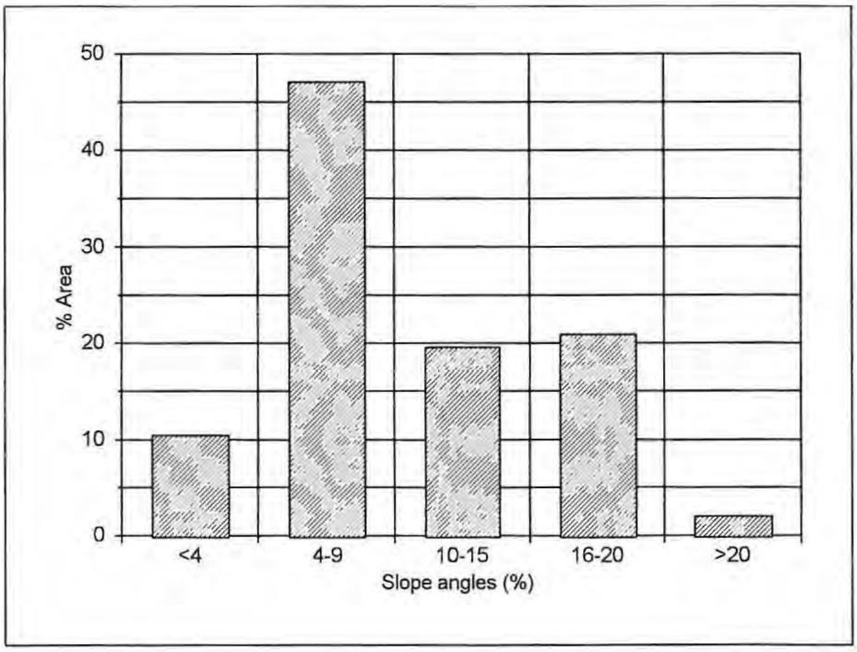


Figure 3.5. An illustration of the slope frequency of the study area (extracted from Kakembo, 1997).

The hillslope profile for the Mgwalana catchment is shown from a Digital Elevation Model (DEM), using ArcGIS (Figure 3.6).

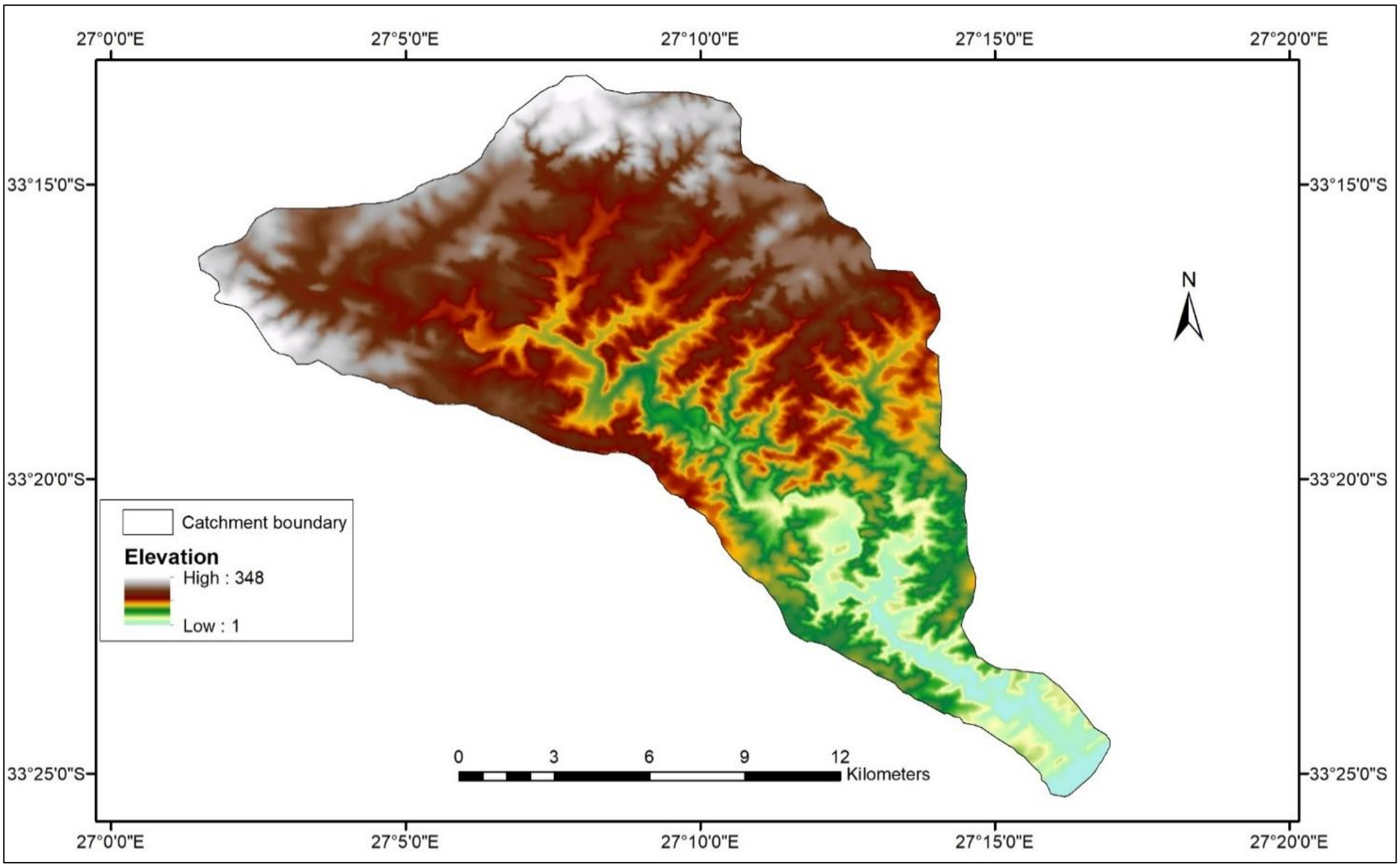


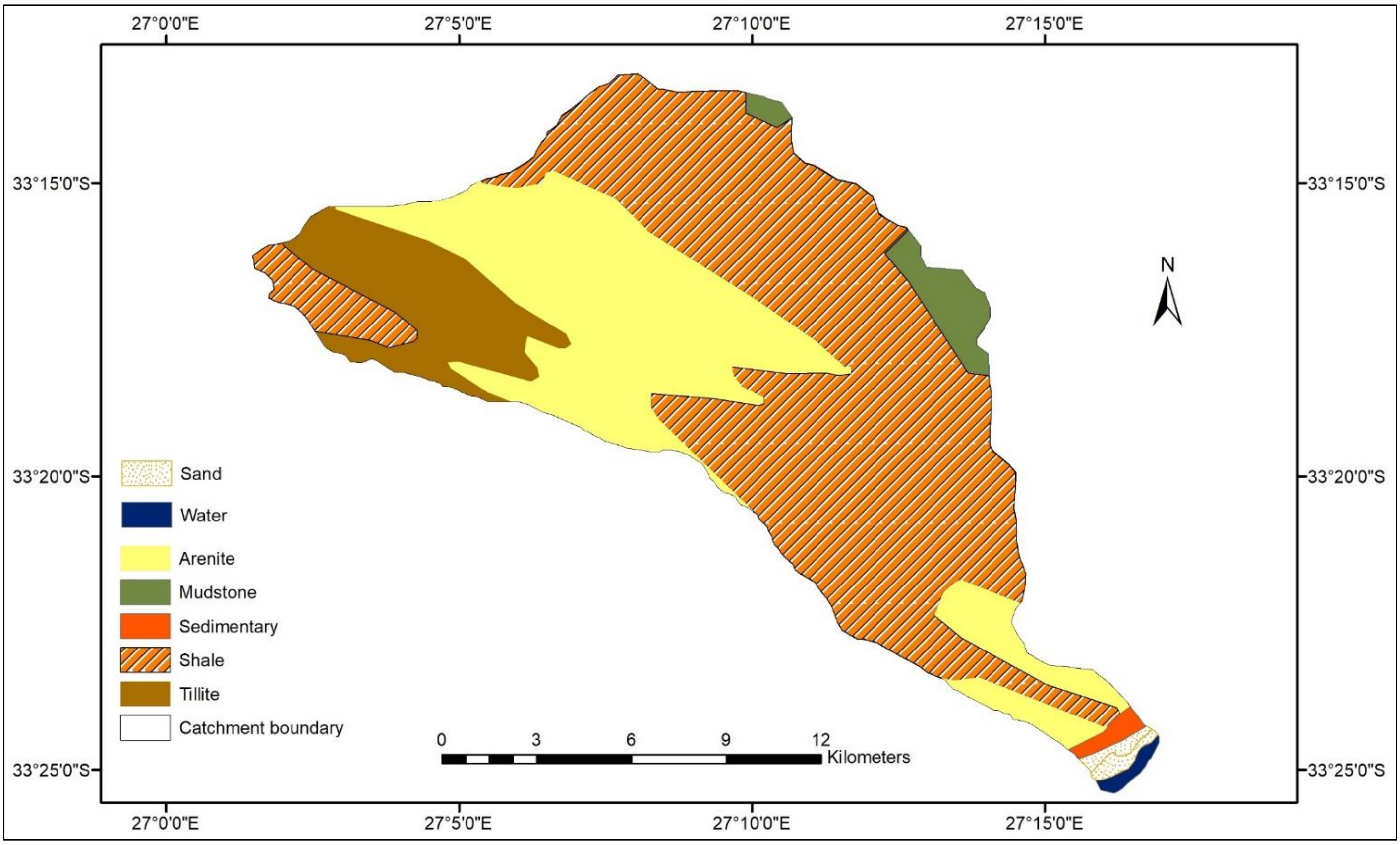
Figure 3.6. Digital elevation model (DEM) showing the hillslope profile and elevation.

3.7. Geology

The catchment is predominantly made up of the sandstones and shales, which belong to the Ecca group and red mudstones which belong to the Karoo Supergroup (Manjoro, 2012). Sandstones characteristic of the Ecca group are dominated by feldpathitic greywackes and minor quartz wackes. (De Jagers, 2015).

Figure 3.7. Shales of the Ecca group characteristic in the study area.

Due to natural processes such as weathering, the shallow soils deriving from the sandstones and shales consist of rocky phases from the weathered material (Kakembo *et al*. 2009). There are small concentrations of limestones and calcareous sandstones scattered around the catchment. Kakembo *et al.* (2007) note that soils deriving from the Ecca group are highly dispersive in nature, resulting in inherent susceptibility to erosion.



3.8. Geology of the study area (ARC, 2017).

3.8. Soils

The type of soil found in this area is largely derived from the weathering of fissile shales and red mudstones. The study area is dominated by juvenile shallow soils which make up much of the African land surface (Watkeys, 1999). The soils that are derived from the Ecca group are litholic soils that form the Mispah group. This form is characterized by stony and rocky phases. Soils in this area have the ability to swell and predominantly consist of clay (Kakembo, 2003). The swelling clayey soils are made up of the hydrous micas which have a structure similar to montmorillonite (Kakembo *et al*., 2007).

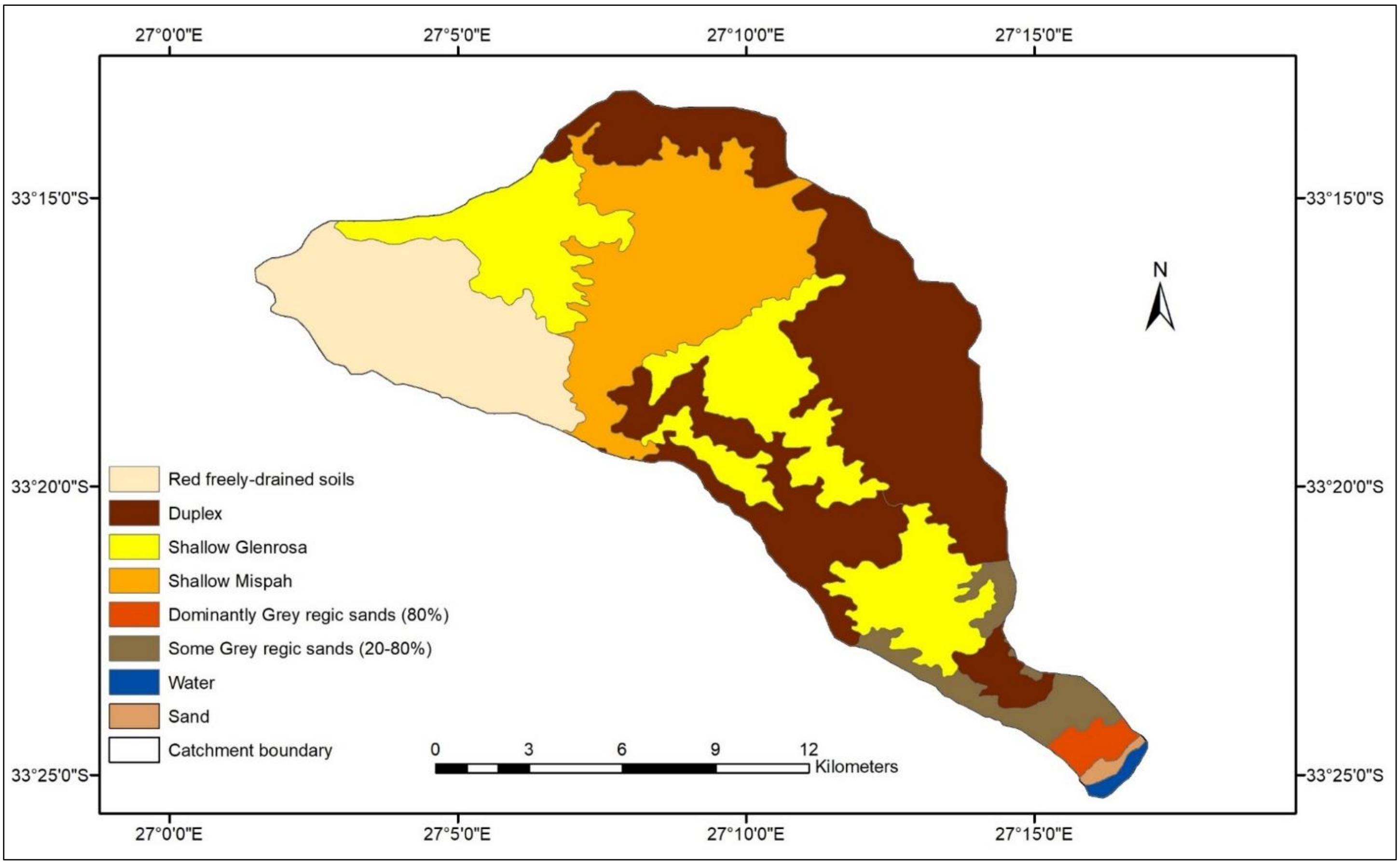


Figure 3.9. Distribution of soil of the study area (data provided by the ARC).

Soils derived from the Glenrosa forms are also found in the area (Kakembo, 1997). They make up less than 25% of the study and are directly underlain by their parent bedrock. It is also important to note that lithic soils typify the convex slopes of the catchment, due to processes that enable the transport of water and sediment from these slopes (Fey, 2010b). The methods used to achieve the objectives of this study are presented in the subsequent chapter.

CHAPTER 4

METHODS AND MATERIALS

4.1. Introduction

This section of the thesis presents the methods and materials employed in this study. The methods employed to acquire data were determined by the aim and objectives of the present study. A three-pronged approach was pursued. The first approach involved the use of Geographic Information Systems (GIS) and remote sensing techniques to capture and map spatial variations of riparian vegetation density, sediment accumulation zones and the relationship between riparian vegetation, bank erosion and land tenure.

Field surveys were undertaken to assess the present streambank conditions and the salient characteristics of selected stream reaches in terms of riparian vegetation density variations. This entailed soil sampling and field measurements. The measurements were taken at sites that showed contrasts in riparian vegetation density and stream bank conditions.

The third section involved laboratory analyses, where various sediment analysis procedures were undertaken to determine the physical soil characteristics that would have implications for streambank erosion and riparian vegetation density.

4.2. GIS and Remote sensing methods

Geographic information systems and remote sensing methods were used to capture, analyze and present variations in riparian vegetation density, as described in the sub-sections below.

4.2.1. The spatial assessment of riparian vegetation density and delineation of land tenure systems

Vegetation coverage is deemed important to assess ecosystem balance and land conditions (Zaitumah *et al*. 2018). It is thus crucial to assess the degree of the fragmentation of vegetation to monitor whether a system has a thriving ecosystem or not. In the present study, riparian vegetation density was analysed and related with processes like streambank erosion and excess sediment delivery.

ArcMap 10.3 was used to map riparian vegetation variations within the catchment by creating shape files through digitizing. The mapped shape files included settlements, dense and sparse riparian vegetation, roads, a coastline and the catchment boundary. The shape files were projected into UTM (Universal Transverse Mercator), for compatibility with Landsat 8 satellite image. The riparian vegetation buffering zone was estimated at 30 m from the stream channels.

The study area has a long history of land-use. Land use is expected to be directly linked with vegetation patterns that occur in this area. Polygons that represented the different shape files were digitized on Google Earth Pro and saved as kml files. The kml files were converted to layers and then to shape files on ArcGIS. This was carried out to map features as how they occurred in 2018, which demonstrated present conditions. The spatial patterns between land tenure systems and riparian vegetation density were demonstrated using ArcGIS.

Distinct boundaries of land-use were identified and mapped. The boundaries show the land tenure systems unique to this area. The land use categories that were mapped in ArcGIS include four classes namely abandoned cultivation, cultivated land, grazing land and bare or eroded land. The classes were mapped in relation to riparian vegetation to demonstrate the spatial relationship between land use and riparian vegetation density.

The land tenure systems which were notably the traditional villages/betterment areas and former commercial farms were mapped on Google Earth Pro as polygons and converted into layers and shape files on ArcGIS. These two land tenure layers were overlaid on the already mapped land use types and riparian vegetation maps to create a clear depiction of the relation between them. A clear pattern was presented between the two land tenure types, namely former commercial farms and the traditional villages/betterment areas.

4.2.2. Riparian density determination using image classification and vegetation index

Image classification was carried out using IDRISI Selva. The classes included scanty and dense riparian vegetation, water bodies, *Pteronia incana*, and bare land. The 2018 satellite imagery was used, as it mirrored the current conditions surveyed in the field. The image classification method used was informed by riparian vegetation patterns.

4.2.2.1. Image acquisition

The satellite image utilized for the present study was acquired through GIS and remotely sensed methods. The data required to carry out this study included Landsat-8 imagery, which was retrieved from the United States Geological Survey (USGS) online portal (http://earthexplorer.usgs.gov/) to analyse the variations in riparian vegetation. The selected Landsat image was of November 2018 for representation of the recent conditions. The imagery had a medium spatial resolution of 30 meters and clear for the distinction of specific land use/cover types for the purposes of this study. Satellite imagery from this period was deliberately chosen as vegetation is at its vigour during this time. Furthermore, when assessing vegetation, it is crucial to analyse it during the growing season to capture it at its peak (Kakembo, 2003).

4.2.2.2. Pre-processing

According to Sonka *et al*. (1993), the sole aim of pre-processing is the improvement of data in order to enhance image features. In the same vein, Krig (2014) points out that image-processing provides positive benefits, such as adding quality to the feature extraction and results of image analysis. The data were downloaded in GeoTIFF format and had to be imported into IDRISI Selva and then converted into raster, as GeoTIFF files are not compatible with IDRISI Selva software. The conversion was carried out on all bands of the imagery. Band 4, 5, and 6 were used to create a composite as these bands show vegetation characteristics clearly. Training sites digitized were classified into five classes for classification. The six classes included sparse and dense riparian vegetation, *Pteronia incana*, catchment boundary, bare land and water.

Satellite imagery obtained from the United States Geological Survey (USGS) website did not require geometric correction as there was no cloud cover distinguishable in the image. The windowing, distinguishing line outs and image rectification tools was utilized. This was carried out to extract the area of interest. In addition, the clip tool was used on ArcMap to delineate the catchment of interest using the Peddie catchments shape file obtained from the Agricultural Research Council (ARC).

4.2.2.3. Image rectification

The projection and standard coordinate system used was the Universal Transverse Mercator (UTM), Southern Hemisphere, World Geodetic System 1984 (WGS84) Datum.

4.2.2.4. Classification

The classification was carried out on classes listed in Table 4.1 below to show the spatial variations in riparian vegetation in the catchment using IDRISI Selva. A supervised classification technique using a maximum likelihood algorithm was applied due to its ability to group pixels according to their homogeneous spectral properties and its proven credibility (Lu and Weng, 2007; Reis, 2008; Conrad *et al.*, 2015). This classifier evaluates the probability that a given pixel will belong to a category and classifies the pixel to the category with the highest probability of membership (Richards, 2013).

Table 4.1. Land use/cover (LULC) type's classes' description

ID Number	Land use/cover type	Land use/cover type description
1	Scanty riparian vegetation	A sparse riparian vegetation density
2	Dense riparian vegetation	A dense riparian vegetation density
3	Water bodies	Includes rivers, dams and the sea
4	*Pteronia incana*	Invasive plant species
5	Bare land	Land that is eroded, exposed and lacks vegetation

4.2.2.4. Accuracy assessment

The process of accuracy assessment is undertaken to assess the reliability of the classified images. The classified images were exported from Idrisi Selva to GeoTIFF files and opened on

ArcMap 10.3 for a further overlay with the Ground Control Points (GCP's) generated from Google Earth Pro. This was carried out in order to open the Ground Control Points (GCP's) digitized in Google Earth Pro as layers in ArcMap 10.3. GCP's were created in Google Earth Pro satellite image. The sample GCP points taken from the field were overlaid on the vector layers in ArcMap and the accuracy assessment was determined.

4.2.2.5. Vegetation Index derivation as a surrogate for riparian vegetation density

Vegetation density and differentiating vegetation surfaces using vegetation indices through remote sensing is common (Payero *et al*. 2004). The Normalized Difference Vegetation Index (NDVI) is one of the frequently used vegetation indices to distinguish between vegetated surfaces and to document various vegetation density patterns.

For this study, Landsat 8 TM was used to determine the NDVI values for the different vegetation densities on the different parts of the catchment and land tenure systems. Through image analysis, the NDVI was calculated. The NDVI value is calculated as follows:

NDVI= (NIR-RED) / (NIR+RED) (Tarpley *et al*. 1984).

- NIR – reflection in the near-infrared spectrum
- RED – reflection in the red range of the spectrum

4.3. Assessment of coupling between sediment sinks (accumulation zones) and riparian vegetation conditions

The catchment was divided into an upper and lower catchment areas which represented the two land tenure units. Sections from each catchment were assessed and a catchment boundary was digitized. The sediment sink zones were identified using Google Earth Pro and their coordinates were noted. The kml files represented the sediment sources were converted into shape files and mapped out in ArcGIS using the Global Positioning systems (GPS) coordinates captured in the field. The sediment sources in the form of gullies were mapped and it was therefore possible to discern the spatial relationship and coupling between sediment sources, sediment accumulation zones and riparian vegetation patterns.

4.4. Assessing implications of riparian vegetation density on stream bank erosion

In the present study, spatial maps were constructed to illustrate the upper and lower parts of the catchments that show a pattern in the distribution of riparian vegetation density. Shape files were digitized in ArcMap after loading a base map that showed the desired features. The shape files included sparse and dense riparian vegetation and areas that demonstrated streambank erosion.

4.4.1. Field methods

Fieldwork was carried out in the catchment to observe spatial patterns of riparian vegetation and stream channel conditions. The fieldwork consisted of a two-part process that included soil sampling and field observations in two separate land tenure units namely; the former commercial farms and traditional villages, where variations in riparian vegetation density were apparent.

The effect of riparian vegetation on streambank processes has been documented by Webb and Erskine (2003), Zlotina and Berkovich (2012) and Rowntree and Dollar (1996). This analysis was carried out to determine the salient characteristics of the impact of the removal of riparian vegetation and to document the implications of riparian vegetation density spatial variations for stream bank erosion. The riparian vegetation variations along the streams were either scanty or densely vegetated. Riparian vegetation exerts a significant influence on bank stability, as it either increases it or reduces it. This however depends heavily on the vegetation type, bank material and physical soil characteristics (Stott, 1997). This view is also supported by Wynn *et al*. (2004).

An investigation was carried out between two types of channel reaches namely; densely and scantily vegetated. Five reaches were assessed on either reach categories of the catchment (Figure 4.1 and Figure 4.2). Figure 4.1 and 4.2 demonstrate the exact sampled points on both land tenure systems.

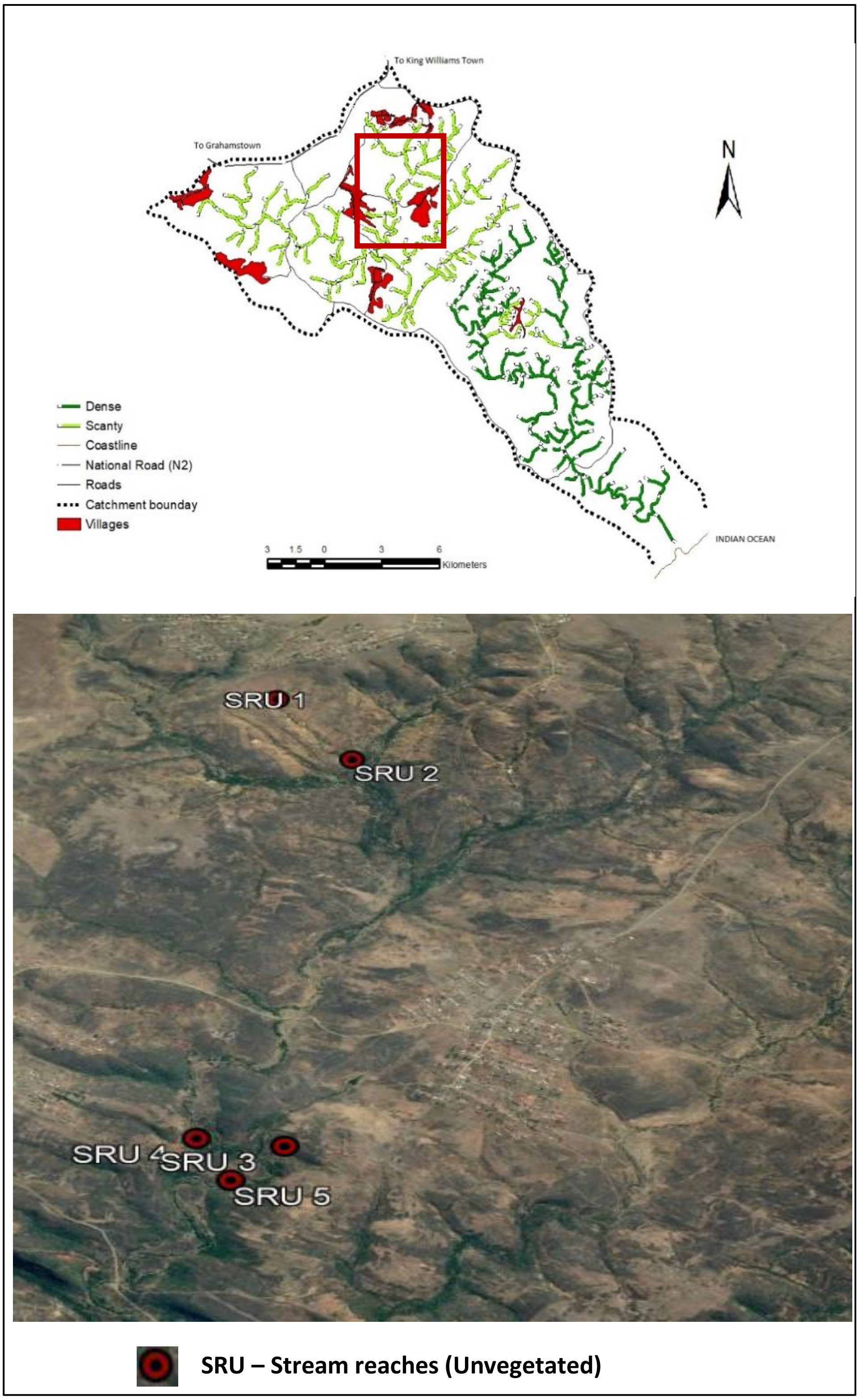


Figure 4.1. Sampled stream reach points on the upper catchment area with a scanty riparian vegetation distribution.

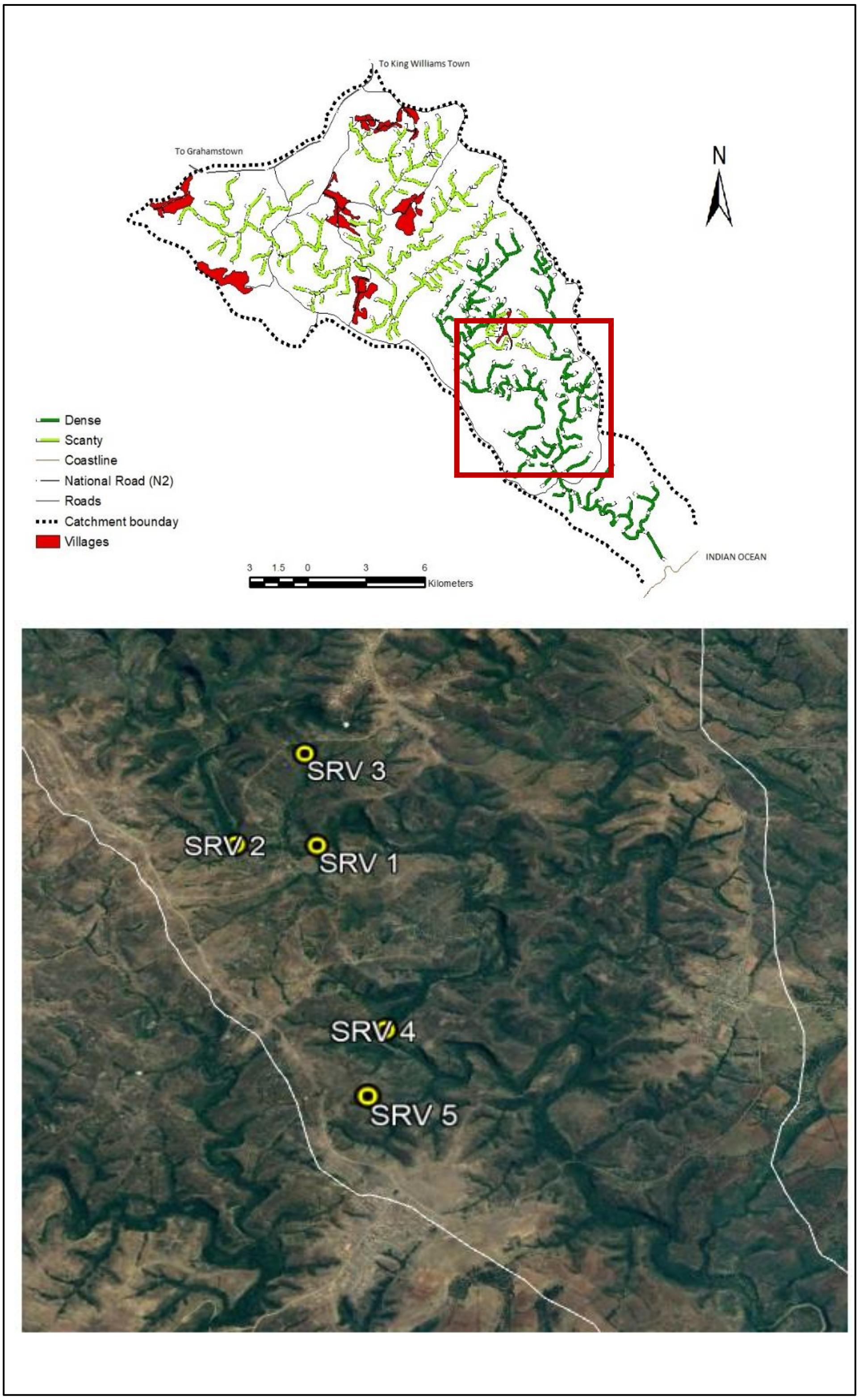


Figure 4.2. Sampled stream reach points on the lower catchment area with a dense riparian vegetation distribution.

4.4.1.1. Sediment accumulation zones

The upper part of the catchment consists of the betterment area and traditional villages land tenure. Visible sediment sink (accumulation) zones were unique to this part of the catchment, due to the diminution of riparian vegetation and pronounced erosion near formerly cultivated lands. Sediment accumulation zones were identified on Google Earth Pro and GPS coordinates were recorded. The coordinates of the sediment accumulation zones were determined and their exact location in the field was identified using a mobile GPS. Sediment sinks were apparent in a series of stream channel reaches adjacent to gully sites. It is noteworthy that observations made in the field represent a fraction of the sediment zones, as some of them were inaccessible. Five sediment accumulation zones were identified and assessed and are seen on in the table below (Table 4.2)

Table 4.2 Sediment accumulation zones that were assessed

Sediment accumulation zone	Coordinates
1	33°14'35.14"S; 27° 7'23.93"E
2	33°14'29.99"S; 27° 7'35.32"E
3	33°16'11.31"S; 27° 8'2.35"E
4	33°16'16.56"S; 27° 7'57.83"E
5	33°16'30.55"S; 27° 7'54.03"E

A total of twenty soil samples were taken using an auger in all five sediment accumulation zones. An additional ten soil samples were taken in areas that appeared devoid of active sediment deposition and these were control samples for comparison purposes. Furthermore, an Abney level was used to determine the elevation in both the sediment accumulation zones and control areas. This was carried out to prove variations in elevation between active sediment deposition zones and control areas devoid of deposition. This was also used to highlight the impacts of riparian vegetation degradation.

4.4.1.2. Stream reach surveys

Five stream reaches were identified on both scantily and densely vegetated streams on two land tenure systems. On each reach, channel morphology was assessed on the basis of variables namely channel width, channel depth, and the channel condition. The selection of stream reaches was determined by accessibility. Channel width and depth were determined using a measuring tape across the channel. The assessment of channel conditions involved observations of the stream reaches by way of determining whether the stream reach was aggrading or actively eroding.

Soil texture and bulk density influence soil erosion and soil properties differ in certain areas based on the type of vegetation and vegetation density characteristic of the area. Therefore, a total of twenty soil samples were taken using a hand-held auger on the channel walls and banks on both scantily and densely vegetated stream reaches to assess the physical soil properties to categorize whether the sediment is made up of cobbles, gravels, silt, sand or clay to acquire a clear picture of bank conditions. The samples were taken at a depth of 30cm. The soil samples were packaged in plastic bags and labelled accordingly. This was carried out to establish the influence of riparian vegetation density on bank erosion based on the physical soil properties and channel conditions.

4.4.2. Laboratory procedures of stream bank soil and sediments

Laboratory procedures involved sediment analysis by determining the particle size distribution, bulk density and soil texture. The first part of this analysis was carried out on the soil samples collected from the sediment sinks (sediment accumulation zones). The samples were poured into beakers. They were then dried overnight in an oven at 105°C (Figure 4.3) and were taken out to cool. Soil samples were inserted in a mortar and were separated using a pestle until they were not as intact. The second part of the analysis involved samples collected from the stream reaches and channel banks.

Figure 4.3. Soil samples in beakers

4.4.2.1. Particle size distribution

Sieving method is one of the most common methods for sediment analysis. For this analysis, the sieve sizes employed were 8mm, 4mm, 2mm, 1mm, 0.5mm, and 0.25mm. A total of 400g was weighed out using an electronic scale and inserted in the sieve stack. A mechanical shaker was used to agitate the sieve stack for 10 minutes. The sieve stack was dismantled, and the soil collected in each fraction were collected and weighed for each sample. The particle size distribution of sediment was analyzed in terms of the mean, median, skewness and kurtosis as sediment characteristics. Mean and median define the middle or central tendency of the distribution of the grains, the sorting and kurtosis distinctly are used to account for the non-normality of the distribution (shape of particle distribution). This was initially noted by Briggs (1977). He asserts that the sorting, kurtosis and skewness define the scatter and non-normality of the distribution. Kurtosis and skewness were adopted for this study. This method was also adopted by Xanga (2007). The particle distribution analysis was used to delineate the difference in the grain size distribution between actively eroding and areas devoid of erosion.

Table 4.3. Grain-size statistical parameters and indications for skewness (Folk, 1968).

	Skewness		
Values from	**To**	**Mathematically:**	**Graphically Skewed to the**
+1.00	+0.30	Strongly positive skewed	Very negative phi values, coarse
+0.30	+0.10	Positive skewed	Negative phi values
+0.10	-0.10	Near symmetrical	Symmetrical
-0.10	-0.30	Negatively skewed	Positive phi values
-0.30	-1.00	Strongly negative skewed	Very positive phi values, fine

Table 4.4 Grain-size statistical parameters and indications for kurtosis (Folk, 1968).

	Kurtosis	
Values from	**To**	**Equal**
0.41	0.67	Very platykurtic
0.67	0.90	Platykurtic
0.90	1.11	Mesokurtic
1.10	1.50	Leptokurtic
1.50	3.00	Very leptokurtic
3.00	-	Extremely leptokurtic

4.4.2.2. Bulk density

Soil bulk density is used as an indicator of the soil's degree of compaction, aggregate stability, and the infiltration rate. After the drying process, the soil samples were weighed using an electronic scale. The 'dry weight' was already obtained when the soil moisture content was determined. The volume of the auger was related to the total weight of the soil. Bulk density of the soils was determined using the equation:

$$Bulk\ Density\ (BD) = \frac{Weight\ of\ dry\ soil\ (g)}{Volume\ of\ dry\ soil\ (cm^3)}$$ (Starr and Geist, 1988)

4.4.2.3. Hydrometer method

Soil samples collected from the stream reaches required a further analysis on the finer bank material to give an indication of bank strength. The hydrometer method was used to determine the sand, silt and clay percentage (Bouyoucos, 1927). The sand, silt and clay percentages were calculated using the formula represented below:

$$\% \text{ Sand} = \left(\frac{W-R1}{W}\right) \text{ x } 100$$

$$\% \text{ Silt} = \left(\frac{R1-R2}{W}\right) \text{ x } 100$$

$$\% \text{ Clay} = \left(\frac{R2}{W}\right) \text{ x } 100$$

4.4.2.4. Aggregate stability

Soil aggregate distribution is a fixed measure that provides information on the changing conditions of soil overtime. It has to be repeated several times and the alternative to obtain a once off value is to account for the soil stability (CIMMYT, 2013). Wet sieving is a proposed method to determine soil aggregate stability against water erosion (Yoder 1936; Kemper 1966). Soil aggregate stability further serves as an indicator of the soil susceptibility to surface seal or crusting. A low aggregate stability indicates that the soil is highly susceptible to erosion and vice versa (Barthès & Roose, 2002; Ramos, Nacci, & Pla, 2003). This was carried out to show the physical soil characteristics between areas representing contrasts in vegetation density and implications on streambank erosion. The aggregate stability will give an indication of the soil's susceptibility erosion.

The most frequently used index is the Mean Weight Diameter (MWD), where $\mathbf{X}_i$ represents the mean diameter of each fraction and $\mathbf{W}_i$ represents the total weight of the sample (Nimmo and Perkins, 2002). This index was used for the current study. A total of 80g was weighed out from each soil sample taken from both sparsely and densely vegetated stream reaches. A total of two replicates were weighed out and inserted into beakers. A sieve stack with the diameters of 2mm, 1mm, 500µm, 250µm, 125µm and 63µm was arranged. The sieve stack was placed in a container and distilled water was poured unto it. It was left submerged for 15 minutes and it was moved a couple of times to maintain movement. This was carefully carried out so that soil was not lost during the process. After 15 minutes the sieve stack was dismantled carefully and the contents were inserted in beakers. The samples were then oven dried at 105°C. Once dried the samples were left to cool and then weighed.

The MWD index seen below was used:

$$\text{MWD} = \sum_{i=1}^{n} XiWi$$

4.5. Statistical analysis

All statistical analysis procedures were carried out on Microsoft Excel.

The results obtained using the methods and techniques explained in the above sections are presented in the subsequent chapter.

CHAPTER 5

RESULTS

5.1. Introduction

In this chapter, the results obtained using the methods described in Chapter 4 are presented. As aforementioned, the study involved a comparative analysis of the variations in riparian vegetation density in two distinct land tenures systems namely; traditional villages and former commercial farms. The implications of the variations for streambank erosion were analysed. The first section of the chapter addresses objective one 1, where an analysis of the spatial variations of riparian vegetation density along stream channels is presented. The second section presents findings of objective 2, where the coupling among hillslope gully erosion, sink (sediment accumulation) areas and riparian vegetation density is analysed by deriving spatial relationships. The third section responds to objective 3 where spatial relationships of land tenure systems, land use/cover and riparian vegetation diminution and the spatial relation of riparian vegetation density and land tenure systems are derived. Lastly, the fourth section addresses objective 4, where spatial illustrations of the implications of riparian vegetation density for stream bank erosion are presented. The physical attributes of channel bank material are also analysed. Streambank field surveys and measurements are also presented to support the spatial analyses.

5.2. Spatial variations of riparian vegetation density

5.2.1. Distinct riparian vegetation categories

Spatial variations of riparian vegetation density are illustrated in Figure 5.1. Two distinct categories namely scanty and dense riparian vegetation variations were mapped. It is discernible that scanty riparian vegetation is predominantly confined to the upper parts of the catchment, where traditional villages and betterment areas occur. Therefore, scanty riparian vegetation is associated with communal traditional villages. During fieldwork, it was also observed that the diminution of riparian vegetation is also associated with the encroachment by *P. incana* invasive shrub on hillslopes in the vicinity, which were formerly cultivated.

Conversely, the lower parts of the catchment observe relatively denser riparian vegetation. These areas are identified as former white commercial farms (Figure 5.1).

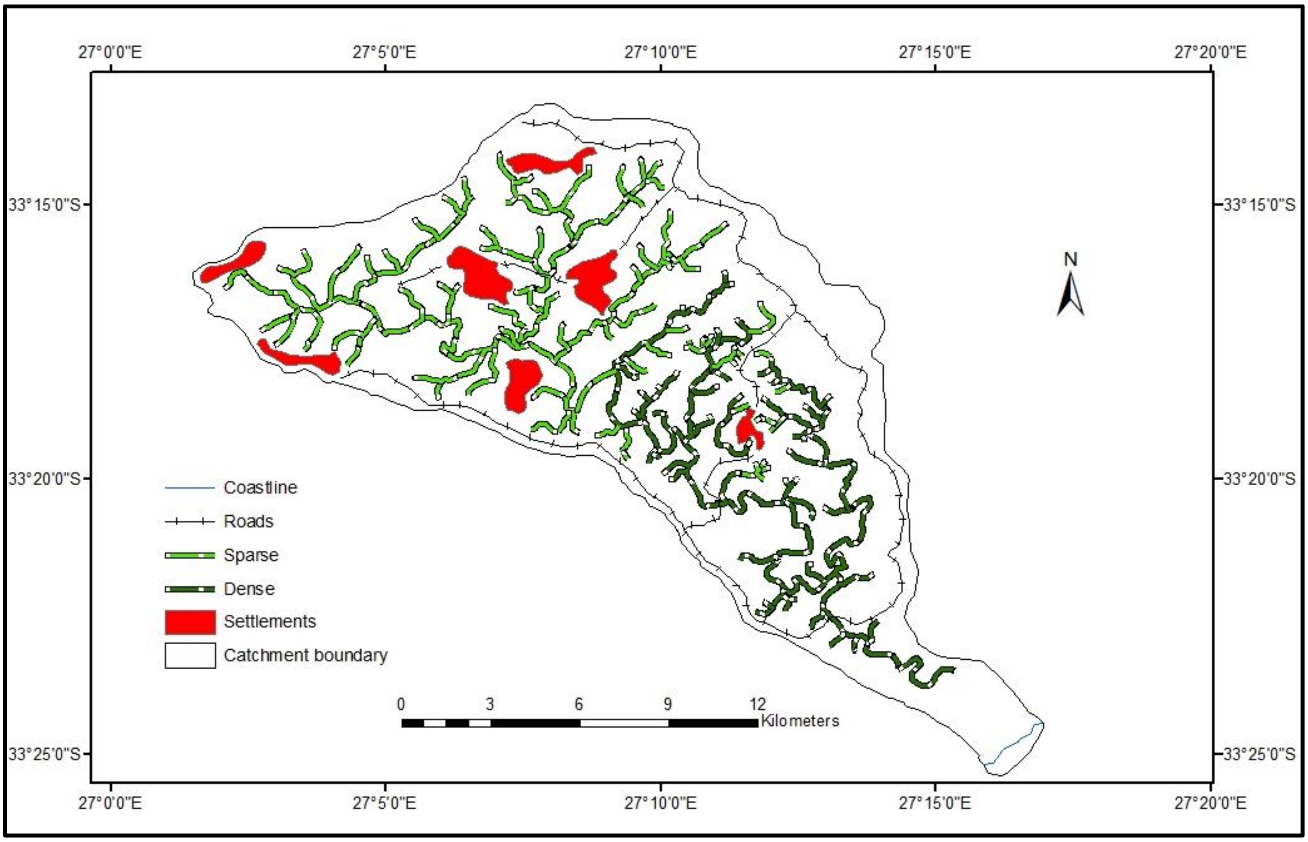


Figure 5.1. Variations of riparian vegetation density in the study area.

5.2.2. Land cover conditions in relation to riparian vegetation

Accuracy assessment was undertaken to provide the degree of reliability of the classified map (Figure 5.2) that represents the current land cover conditions observed in the Mgwalana catchment. The results are shown in Table 5.1, which yielded reliable classification accuracy results.

Table 5.1 Summary of accuracy results of the classified land use/cover map for 2018

Land use/cover types	**Producers**	**Users**
Bare land	84.12	91.27
Dense	95.00	97.54
Pteronia Incana	89.33	87.14
Sparse	86.33	95.32
Water	96.68	98.66
Overall Accuracy	**85.23 %**	
Kappa coefficient	**0.71**	

A reliable representation of land cover conditions on the hillslopes adjacent to stream channels is thus presented in Figure 5.2, which is based on 2018 image classification. It is quite evident that bare and eroded hillslopes, which were identified as abandoned lands are also associated with scanty riparian vegetation. Once again, such conditions are unique to the upper parts of the catchment, which are traditional and betterment villages. A distinct boundary in these conditions is noticeable, where hillslopes adjacent to dense riparian vegetation are not bare and eroded. Notwithstanding the sparse vegetation on the hillslopes adjacent to these areas, the riparian vegetation density is still reasonably dense. The sparse nature of vegetation on these hillslopes is explained by the recent encroachment by communal farmers from traditional and betterment villages and land use stewardship.

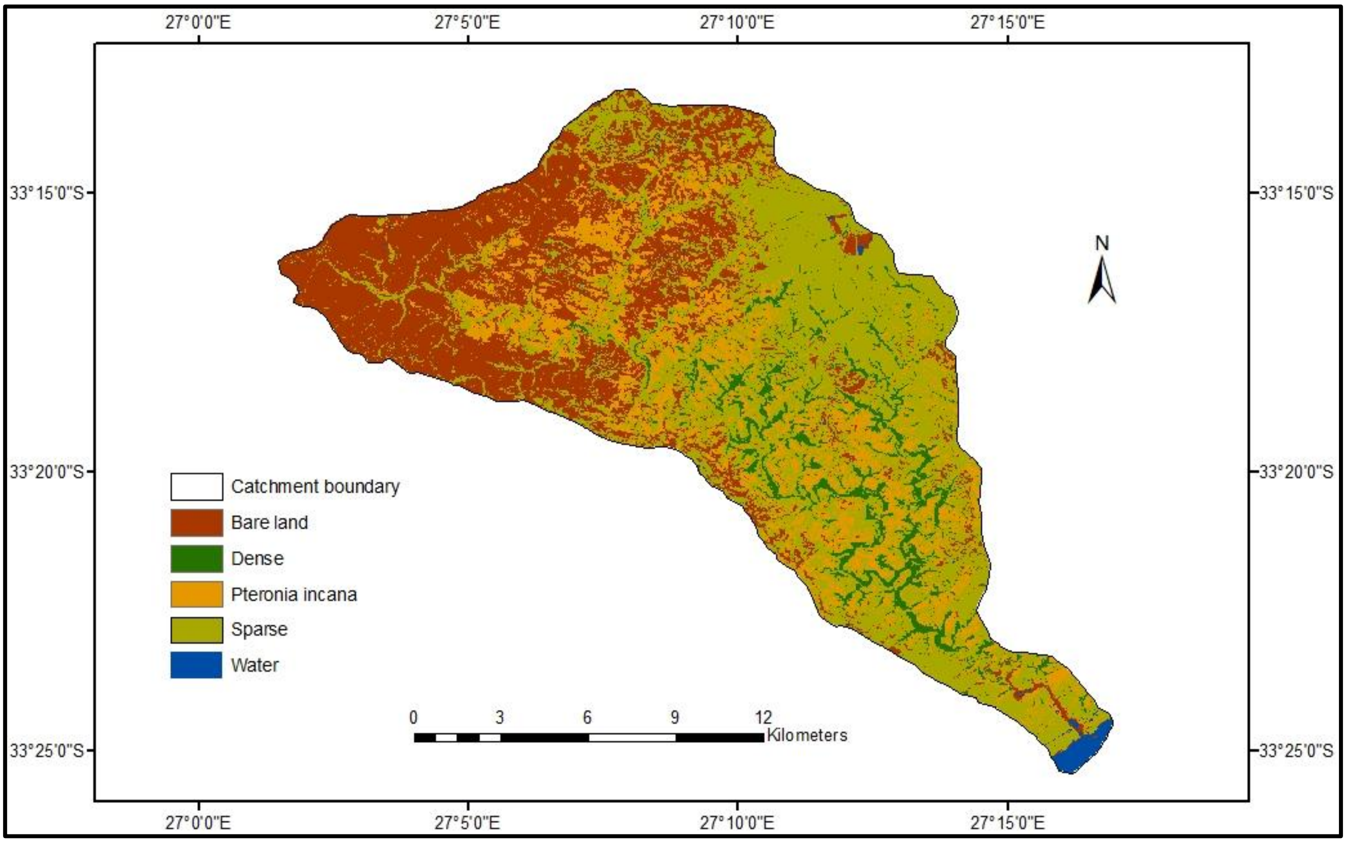


Figure 5.2. A classification of land cover conditions in relation to riparian vegetation,

5.2.3. Normalized Difference Vegetation Index (NDVI) analysis

The vegetation conditions based on the classification presented in sub-section 5.2.2 above are further depicted by means of the NDVI. Figure 5.3 shows NDVI values that bring out the variations in riparian vegetation densities. The standard NDVI number falls between -1, being the lowest vegetation cover or none and 1, which represents a highly vegetated surface. The NDVI values for the present study fall between -0.14 and 0.22 (Figure 5.3). The NDVI map depicts a distinct variation in riparian vegetation density condition along the riparian zone between the upper and lower parts of the catchment and reinforces the conditions that are observed in Figure 5.1. The same applies to vegetation cover on the adjacent hillslopes. The general trend of spatial variations of riparian vegetation is that the upper catchment area is associated with a scanty riparian vegetation and predominantly bare hillslopes. The converse is true for the lower part of the catchment, where dense riparian vegetation and reasonable vegetation cover on the hillslopes are noticeable.

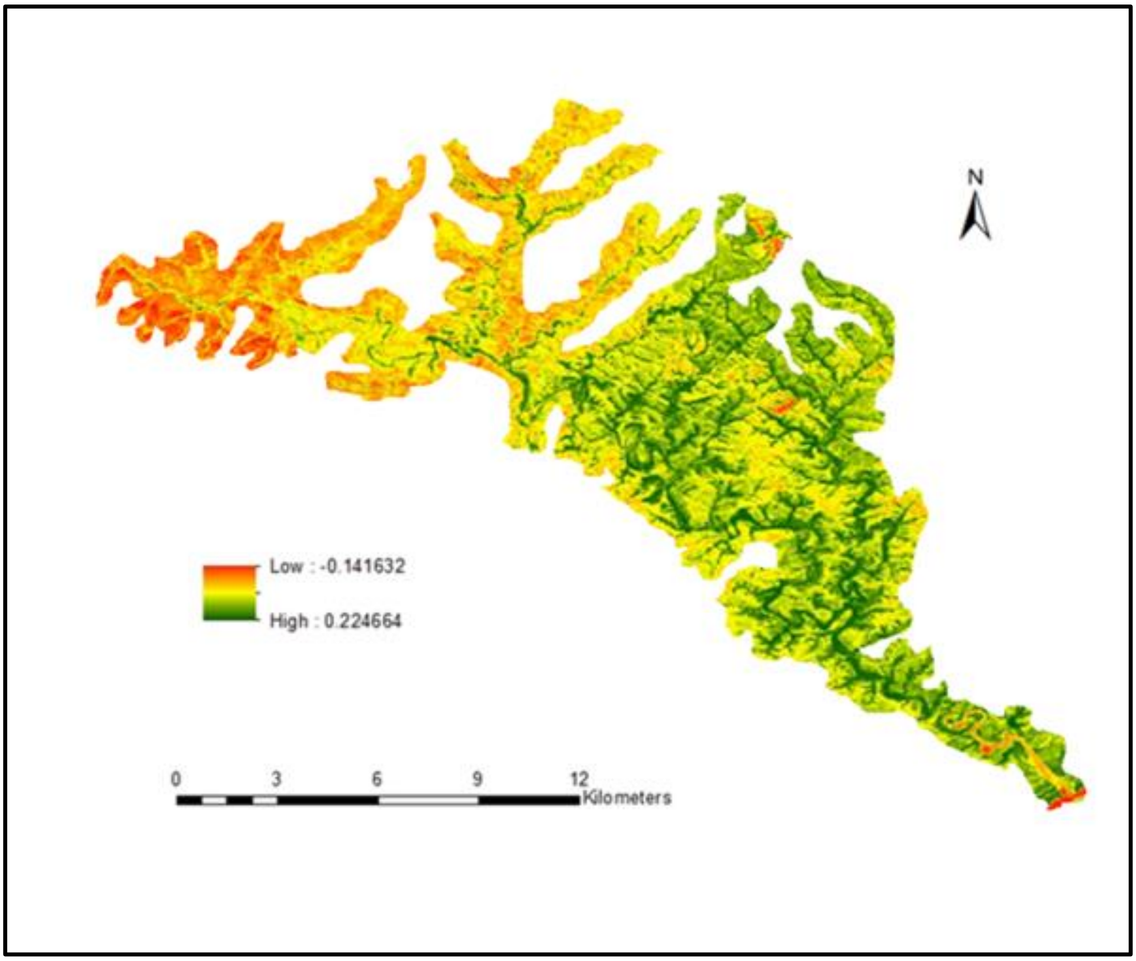


Figure 5.3. NDVI analysis of the study catchment illustrating the riparian zone

5.3. Sediment accumulation areas and riparian vegetation density

The sediment accumulation areas were discernible in the upper part of the catchment, which represent a land tenure system that consists of traditional villages and betterment areas (Figure. 5.4). The hillslopes in this part of the catchment are severely eroded due to poor land stewardship. They are also characterised by encroachment of the invasive shrub, *P. incana*. Furthermore, riparian vegetation density is scanty in this part of the catchment and associated with the occurrence of gullies and sediment accumulation areas as presented in Figure 5.4. It is discernible that the hillslope gully erosion is coupled with sediment accumulation zones. During fieldwork, it was observed that the degraded hillslopes have distinct erosional features such as gullies and rills. These gullies connect to the streams and are automatic sediment feeders, as the sediment transported downslope collects in the stream channels, in many cases coupled to the gullied hillslopes. A general trend noted is that gullied hillslopes are a common occurrence and are coupled with stream courses with the scanty riparian vegetation distribution and sediment sinks (sediment accumulation zones) (Figure 5.4).

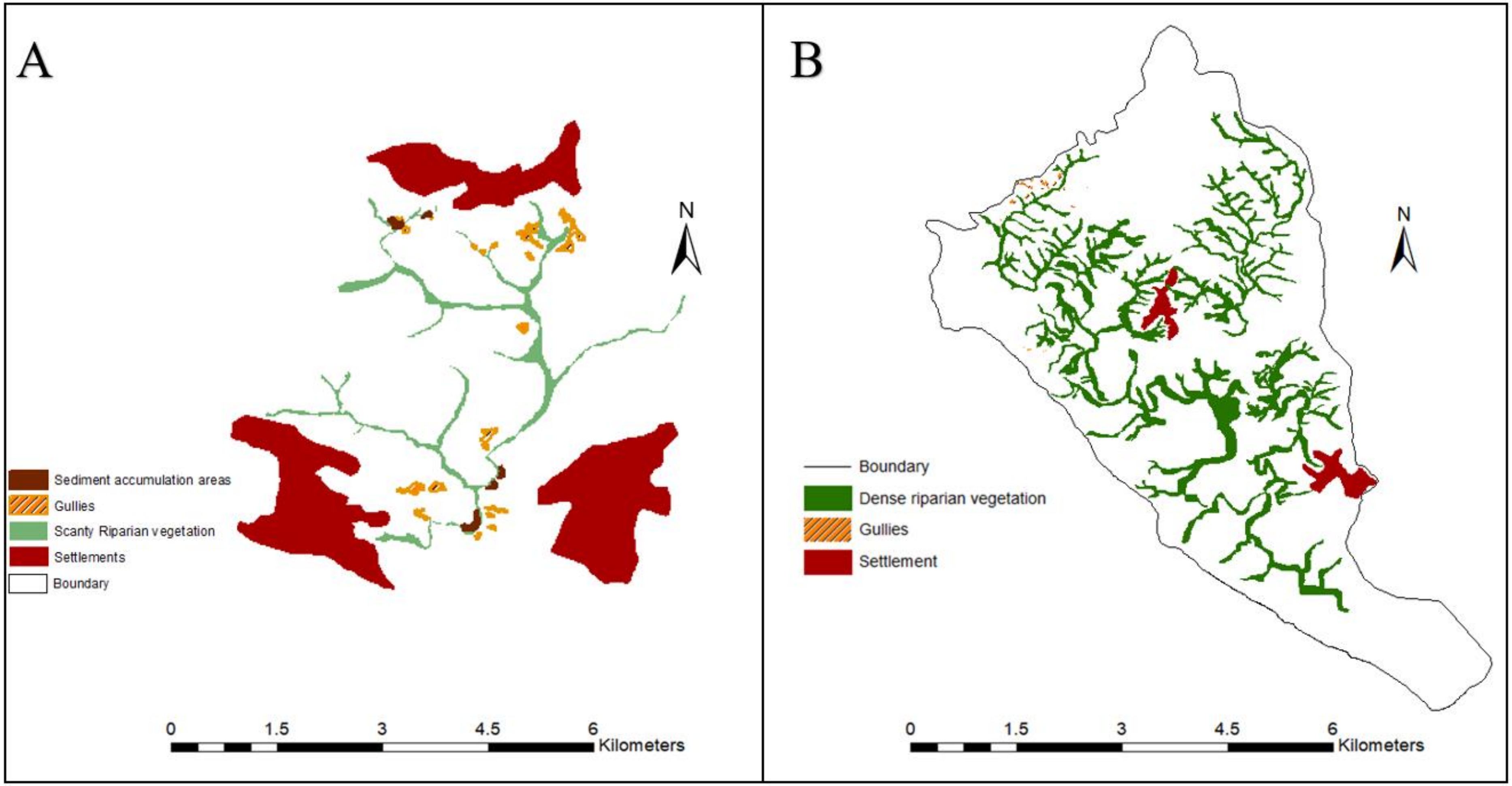


Figure 5.4. Sediment accumulation zones and variations in riparian density on the upper catchment area (A) and the lower catchment area (B).

The spatial relationship between the gullies on the hillslopes and sediment sink zones as shown in (Figure 5.4) is presented below (Figure 5.5). Sediment sink zones are identified as occurring directly adjacent and coupled with extensive gullied sites (Figure 5.6), many of which were gully fan remnants. This confirmed that gullies are the main source of sediment for the sink zones as also observed in Figure 5.5.

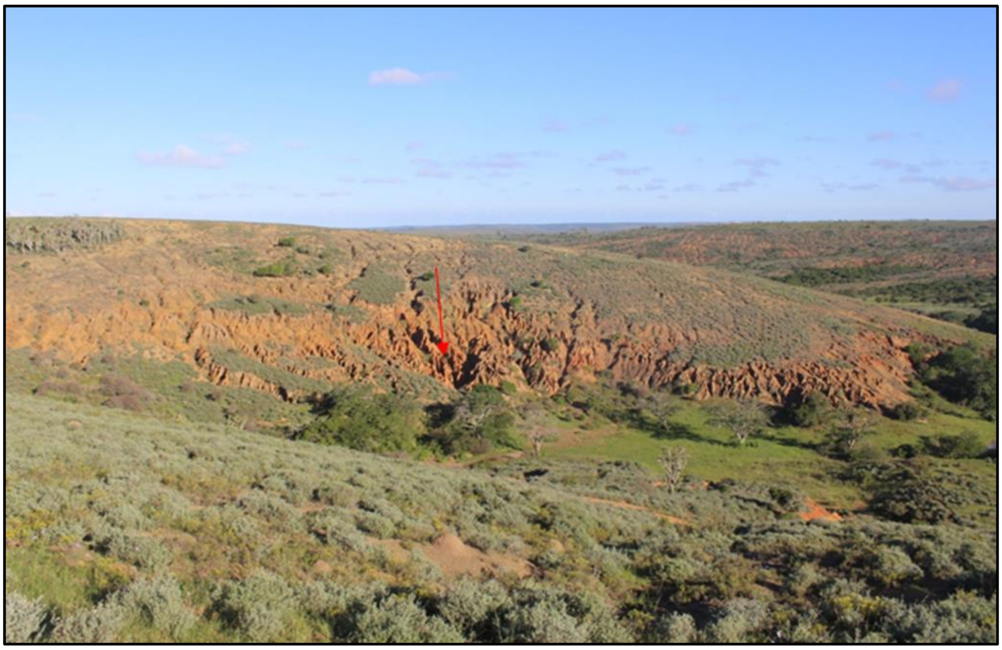


Figure 5.5. Gullied hillslopes that directly deliver sediment into channel

Figure 5.6. A gully that is directly connected to the stream channel in the Mgwalana catchment.

Sediment sinks (sediment accumulation zones) that were assessed in the present study are presented in Figure 5.7.

Figure 5.7. Sediment accumulation zones found in the upper catchment area (Images taken by Asakhile Maxama and Vusumzi Tsipa)

5.4. Relationship between land use practices and riparian vegetation diminution in relation to land tenure

The spatial relations of land use and riparian vegetation diminution mainly in the upper part of the catchment are presented in Figure 5.8. The most significant trend is that land-use is predominantly found in the upper catchment area. The abandoned lands are associated with eroded hillslopes. It is on these hillslopes that severe gully development is predominant. The gullies are coupled with stream courses and this is where the sediment accumulation areas stem from, as sediment movement downslope from gullies increases sediment connectivity. The bare or eroded land, abandoned cultivation, gullies and sediment accumulation areas are all spatially linked with a scanty riparian vegetation distribution (Figures 5.4. A).

Another important observation is that there were very few erosional features present in the lower part of the catchment and there was no coupling of gullied slopes and sediment sinks in this part of the catchment. This is subjected to areas that were assessed due to restrictions. Dense riparian vegetation characterizes this part of the catchment (Figure 5.8).

Furthermore, the relationship between scanty riparian vegetation, bare eroded lands and land tenure are presented in Figure 5.8. Cultivation is characteristic of the lower part of the catchment, as illustrated by Figure 5.8. Dense riparian vegetation is further illustrated as a feature of the lower catchment, where land tenure was in the form of former commercial farms (Figure 5.8). This pattern was illustrated earlier by the NDVI analysis (Figure 5.3).

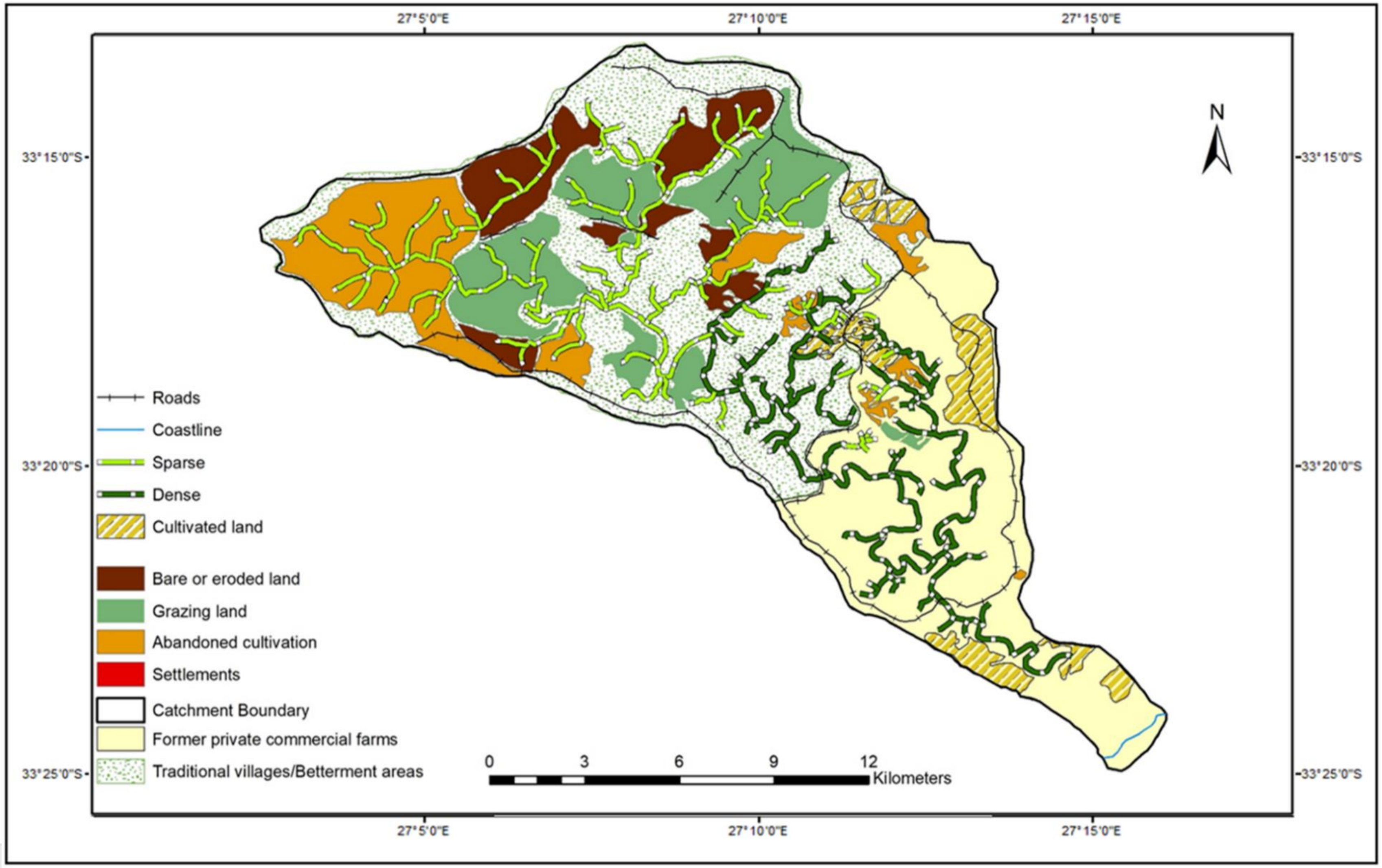


Figure 5.8. Spatial relationship between and land-use practices and riparian vegetation variations in relation to land tenure.

5.5. Implications of variations of riparian density on streambank erosion

The spatial variations between these reaches surveyed between the sparse and dense riparian vegetation distribution found in the two land tenure systems were quite distinct and are presented in Tables 5.2 and 5.3. The illustrated data (Table 5.2 and 5.3) is limited to areas that were accessible. The vegetation density along the channels vary with land tenure as represented in Figure 5.8. Distinct channel condition patterns in terms of width and depth variations on the densely and scantily vegetated stream reaches was identified. The scantily vegetated channel reaches showed that channel morphology is characterized by eroded banks along scantily vegetated stream courses. The channel width of reaches assessed along the un-vegetated reaches was significantly higher than that observed along vegetated stream reaches ($p=0.008$; $p<0.05$) (Table 5.3). There was no significant difference in terms of the depths observed along densely and scantily vegetated stream reaches ($p=0.31$; $p>0.05$). It is evident from Table 5.2 that the banks of most sections of the scantily vegetated reaches surveyed are actively eroding.

Table 5.2 Results of channel conditions of scantily vegetated stream reaches

Scantily vegetated channel reaches (Traditional villages)				
Reach	**Section**	**Channel morphology**		**Channel condition**
		Width (m)	**Max depth (m)**	
1	1	7	4.4	Eroding
	2	6	2.5	Eroding
	3	7.6	2.1	Eroding
2	1	9.5	1.6	Eroding
	2	7	2.2	Eroding
	3	6.5	3.1	Eroding
3	1	8	4.3	Eroding
	2	7.8	3.2	Eroding
	3	7.5	2.3	Eroding
4	1	6.6	2.2	Eroding
	2	Erosion on sidewalls		Eroding
	3	6.3	2.5	Minor aggradation
5	1	7.5	3.5	Eroding
	2	6.5	3	Eroding
	3	5.4	3.2	Eroding

Through observations in the field, it was discovered that reach 1 was actively eroding and had minor patches of protective vegetation in the form of grass (Figure 5.10). There were gullies and rills all round and a significant invasion by the *P. incana* invader shrub was located about 5 m from the channel reach. There was visible bank undercutting, with channel walls characterized by poorly sorted pebbles and cobbles embedded in channel walls.

Figure 5.9. Scantily vegetated reach one (1) found in the upper catchment area in the communal traditional villages.

Reaches 2 and 3 showed similar trends (Figure 5.10). They were also characterized by coupling of gullies with the stream channel. Incision and bedrock exposure (Figure 5.10) were also typical of these scantily vegetated banks.

Figure 5.10. Reach two (2) and three (3) found in the upper catchment area representing unvegetated channels in the traditional village land tenure.

A similar pattern is also illustrated by reaches 4 and 5 (Figure 5.11). Reach 4 shows a degree of bedrock exposure and evidence of significant active erosion. Reach 5 shows minor aggradation and stable channel condition even though the riparian vegetation distribution is scanty.

Figure 5.11. Reach four (4) and five (5) found in the upper catchment area representing unvegetated channels in the traditional village land tenure.

The densely vegetated channel reaches are situated in the lower part of the catchment, which as indicated earlier represents former commercial farmlands. The channel morphology of the densely vegetated reaches in terms of width was significantly lower ($p=0.008$; $p<0.05$) than that of the scantily vegetated ones. The reaches located in the former commercial farms are characteristically either aggrading or stable. Only two sites were identified as eroding, owing to the removal of riparian vegetation at the two sites.

Table 5.3. Results of channel conditions of densely vegetated stream reaches

Densely vegetated channel reaches (Former commercial farmlands)				
Reach	**Section**	**Channel Morphology**		**Channel condition**
		Width (m)	**Max depth (m)**	
1	1	3.6	1.9	Minor aggradation
	2	4.2	2.3	Stable
	3	4.1	1.1	Eroding
2	1	6.8	3.1	Eroding
	2	5.5	2.6	Stable
	3	5.7	1.9	Eroding
3	1	6.5	3.4	Stable but minor erosion
	2	5.1	3.9	Eroding
	3	5.9	3	Eroding
4	1	4.1	3.9	Eroding
	2	4.5	2.2	Eroding
	3	4.8	2.7	Eroding
5	1	2.3	3.7	Stable
	2	2.7	4.2	Stable
	3	2.5	3.2	Stable

In the lower section of the catchment, reaches 1 and 2 were noted as stable and showed no signs of erosion. Vegetation cover in the form of trees (*Umnga*), grass on berms and shrubs was observed (Figure 5.12). Berm development is a clear sign of bank aggradation.

Figure 5.12. Reach one (1) and two (2) found in found in the lower catchment area representing densely vegetated channels in the former commercial farms land tenure.

Reach 3 was the only one that showed signs of early stages of erosion, as channel walls were noted as actively eroding.

Figure 5.13. Reach three (3) found in found in the lower catchment area representing vegetated channels in the former commercial farms land tenure.

Reach 4 and 5 showed similar trends. Reach 4 showed clear aggradation and there was no sign of erosion, both channels were stable. They were densely vegetation which resulted in certain difficulties navigating through the surveying process. There were boulders at the bottom of the stream channel and minor water which is attributed to recent heavy rains.

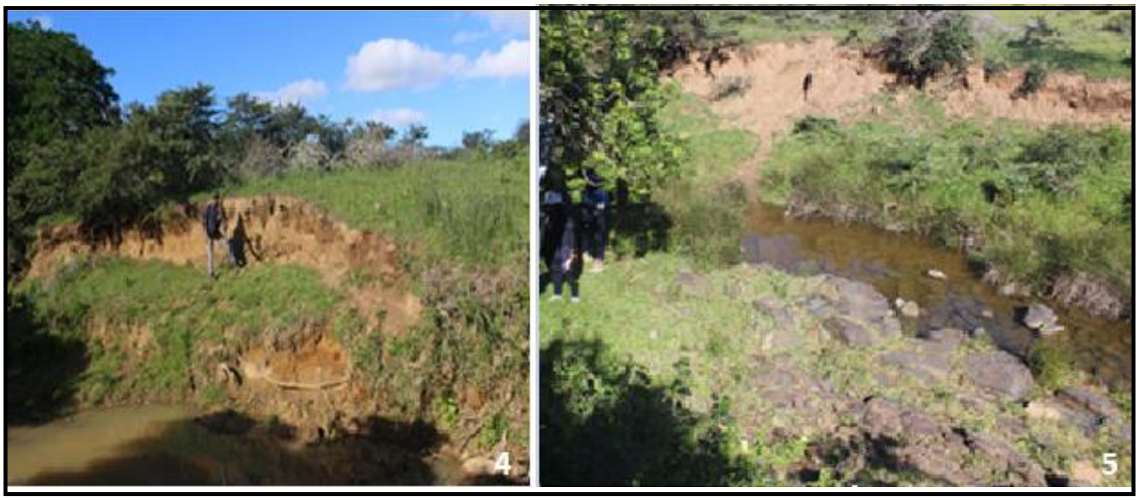


Figure 5.14. Reach four (4) and five (5) found in found in the lower catchment area representing vegetated channels in the former commercial farms land tenure.

5.6. Edaphic characteristics

This section presents results obtained from the analyses of soil physical characteristics. Soil samples were taken from the densely and scantily vegetated stream reaches in the study area.

5.6.1 Grain size distribution

The results of the particle size analysis between vegetated and unvegetated stream reaches are presented in the graphs below (Figure. 5.15- 5.19). The implications of these results are discussed in the next chapter. This was carried out for comparison purposes and to determine the physical characteristics of soils found in these spatially variant parts of the catchment. A table (Table 5.4), gives an indication of the standard grain sizes and phi values that were utilized in this study.

Noticeable trends from Figures 5.15 to 5.19 is that at most reaches, the scantily vegetated reaches have a greater percentage of coarser materials than the densely vegetated ones, as borne out by the curves in negative phi values zone. The trend also shows that the grain size distribution on both dense and scantily vegetated stream courses overlaps in terms of fineness of particles, between phi values 2 – 4. The grain distribution on densely vegetated stream reaches generally shows a less coarse component. The fine sediment component evidently dominates sediments collected from both the scantily and densely vegetated stream reaches.

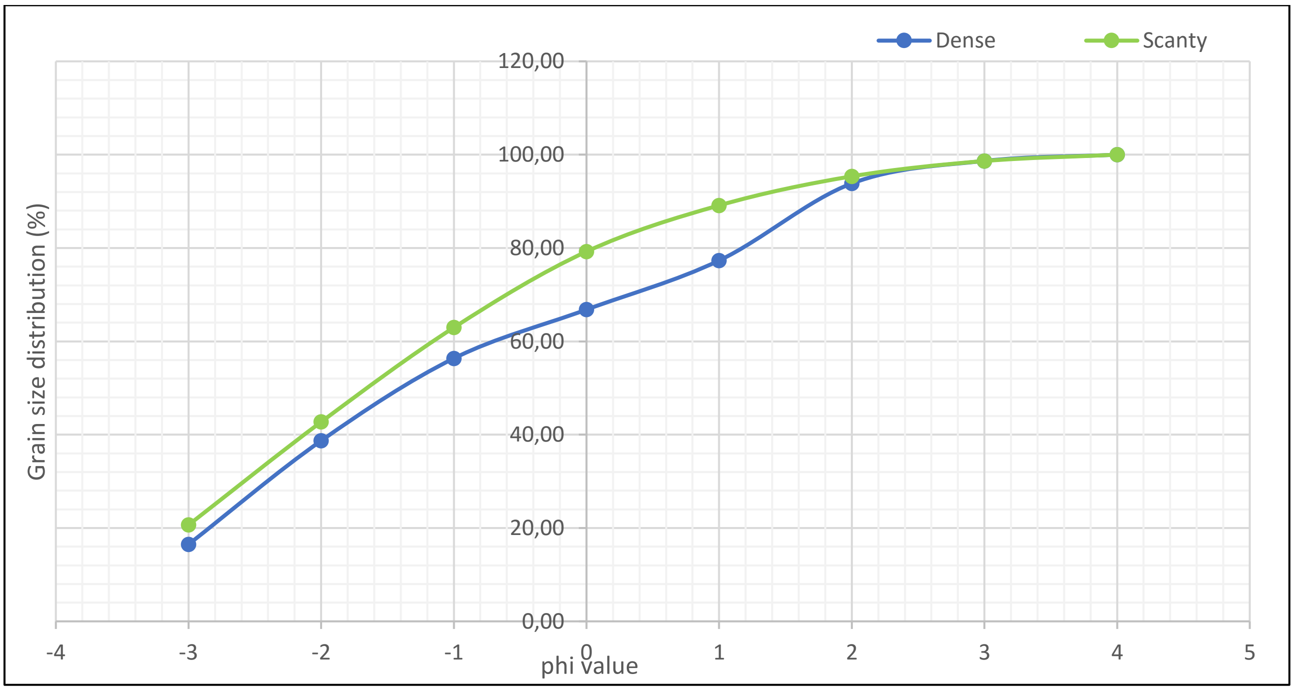


Figure 5.15. A comparison of grain size distribution curve between a densely and scantily vegetated stream reach one (1).

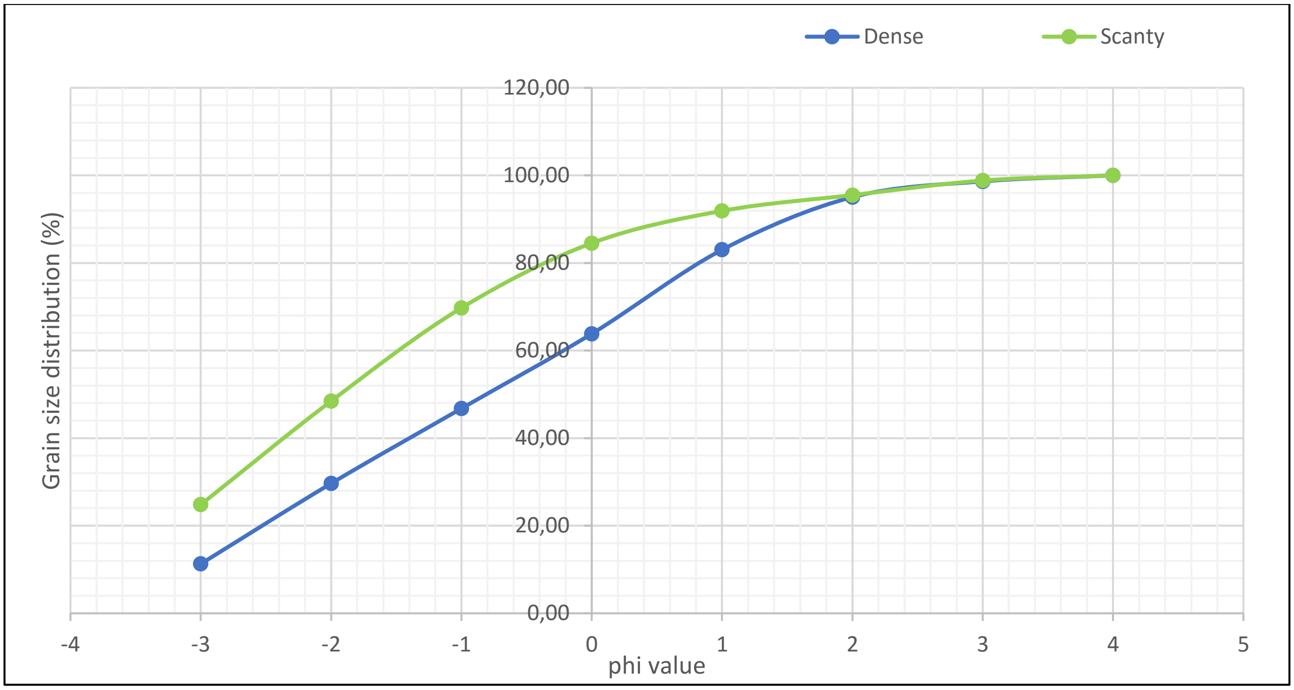


Figure 5.16. A comparison of grain size distribution curve between a densely and scantily vegetated stream reach two (2).

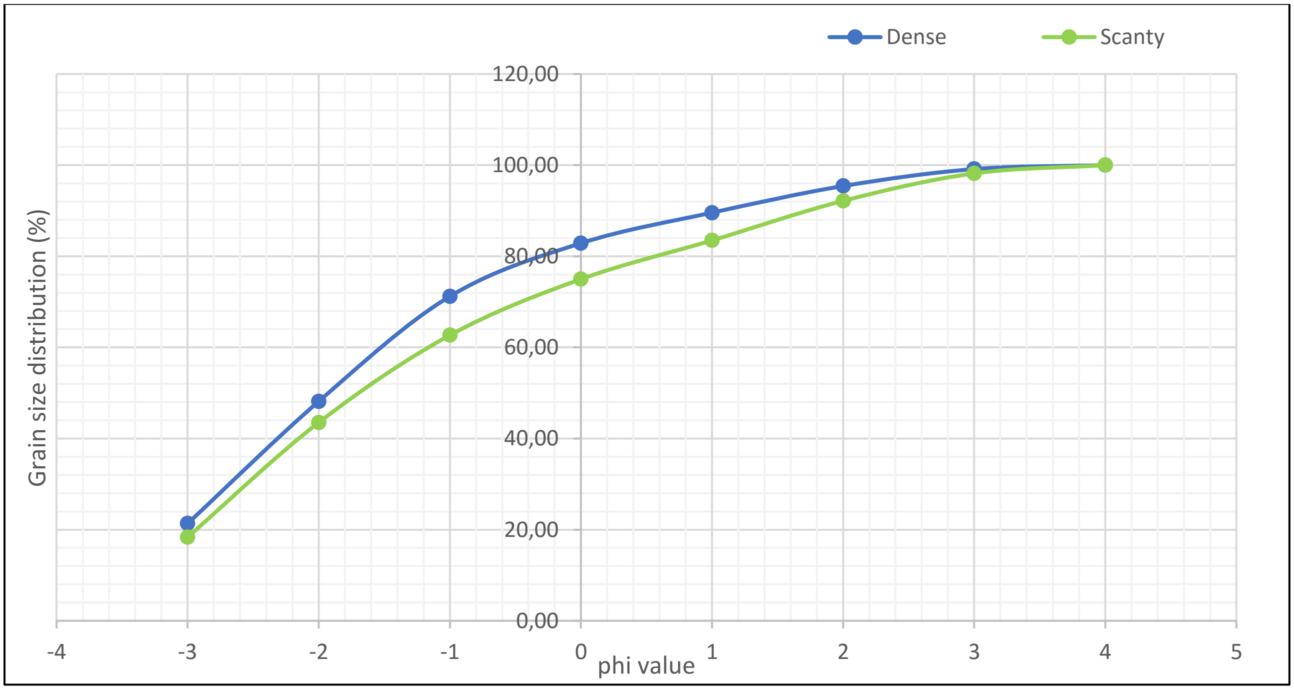


Figure 5.17. A comparison of grain size distribution curve between a densely and scantily vegetated stream reach three (3).

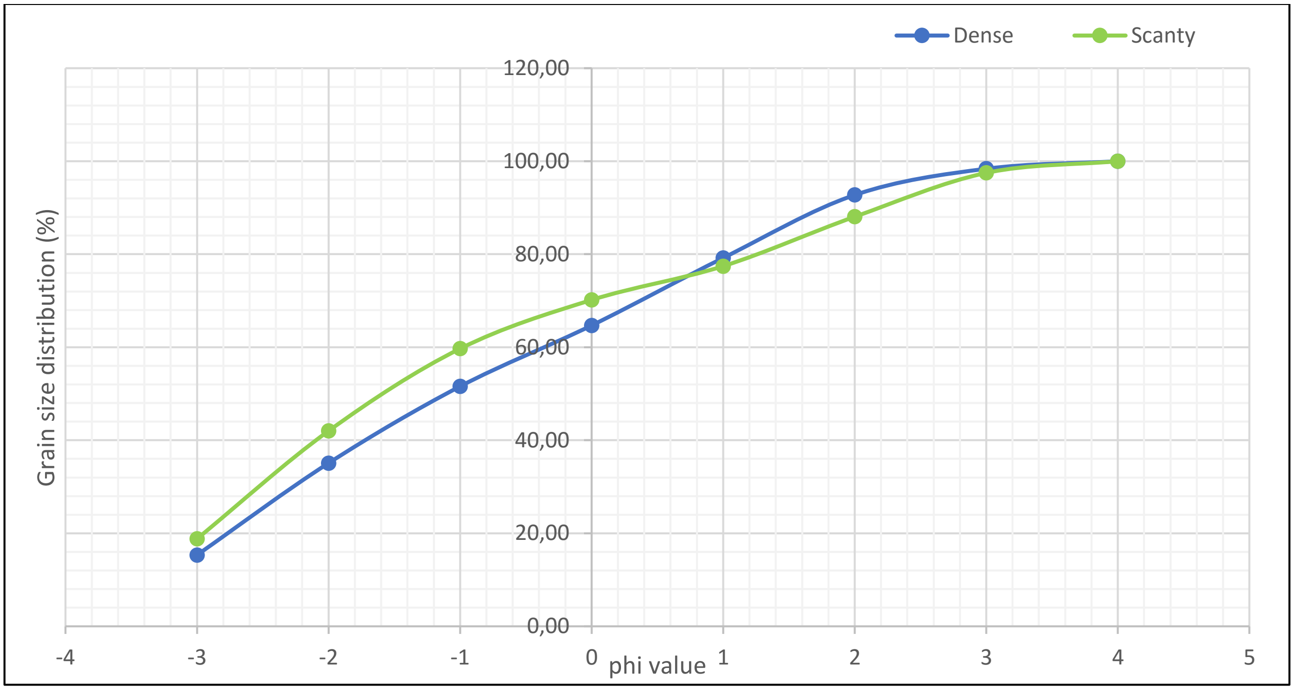


Figure 5.18. A comparison of grain size distribution curve between a densely and scantily stream reach four (4).

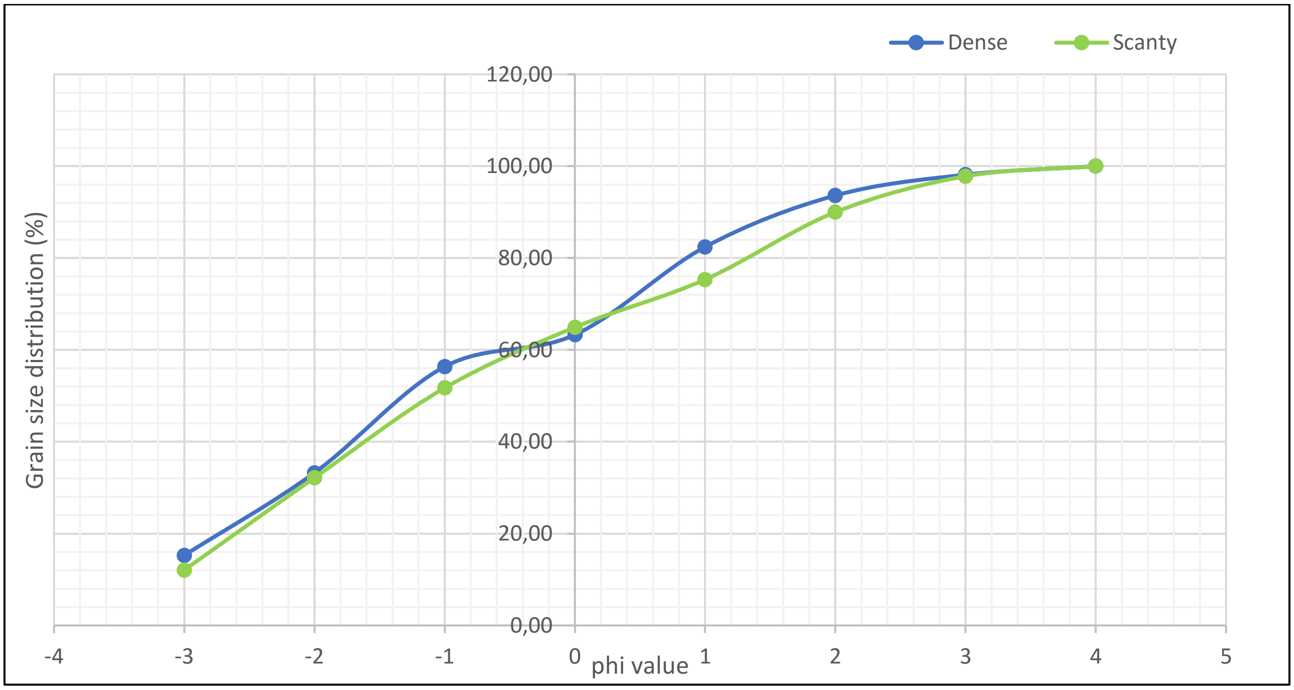


Figure 5.19. A comparison of grain size distribution curve between a densely and scantily stream reach five (5).

The results for particle size analysis detailing the skewness of the data are presented below (Figure 5.20). Samples along the scanty riparian vegetation distribution show a trend of being positively skewed as the values >1. However, there are two instances where particles show a much skewed distribution and an almost symmetrical particle size. On the other hand, samples on the dense riparian vegetation distribution show a pattern that varies from very negatively skewed to negatively skewed. One sample on reach 5 is skewed symmetrically.

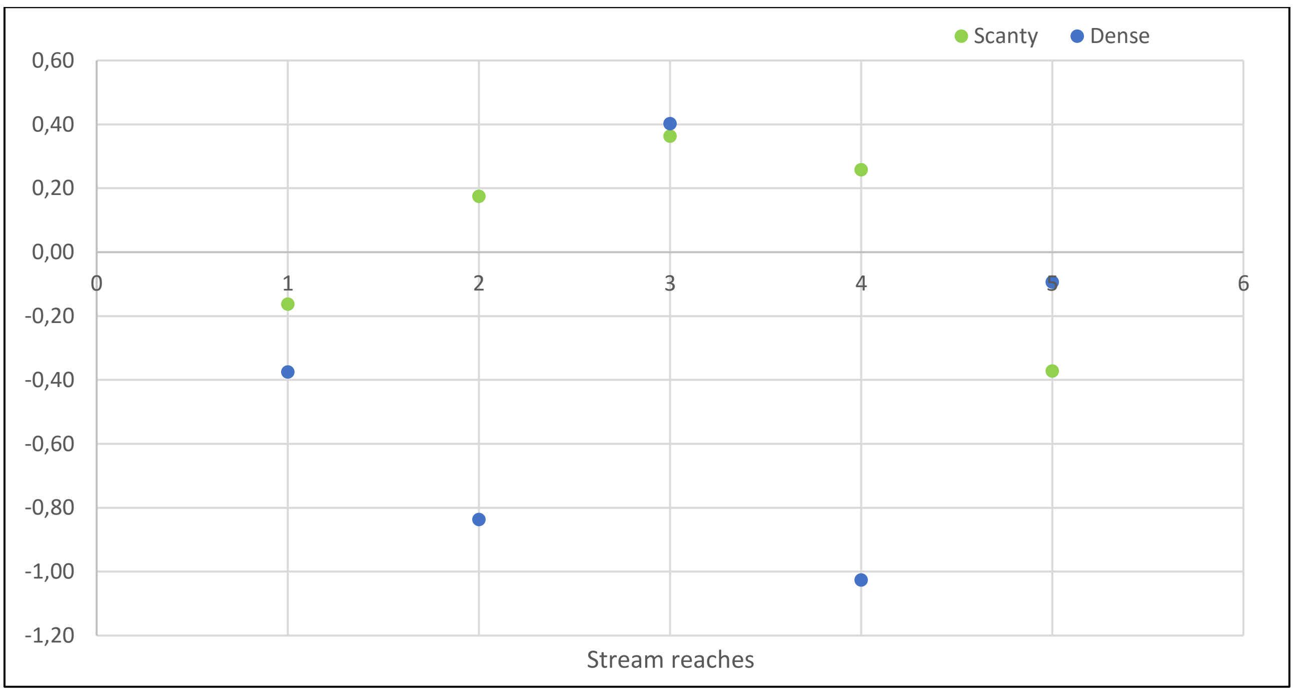


Figure 5.20. Characteristics of the particle size distribution in terms of skewness in scanty and densely vegetated reaches.

Results for kurtosis are presented below (Figure 5.21). A comparison was carried out between samples derived from scanty and dense riparian vegetation reaches. The general trend observed is that the particle size analysis for all samples is very platykurtic.

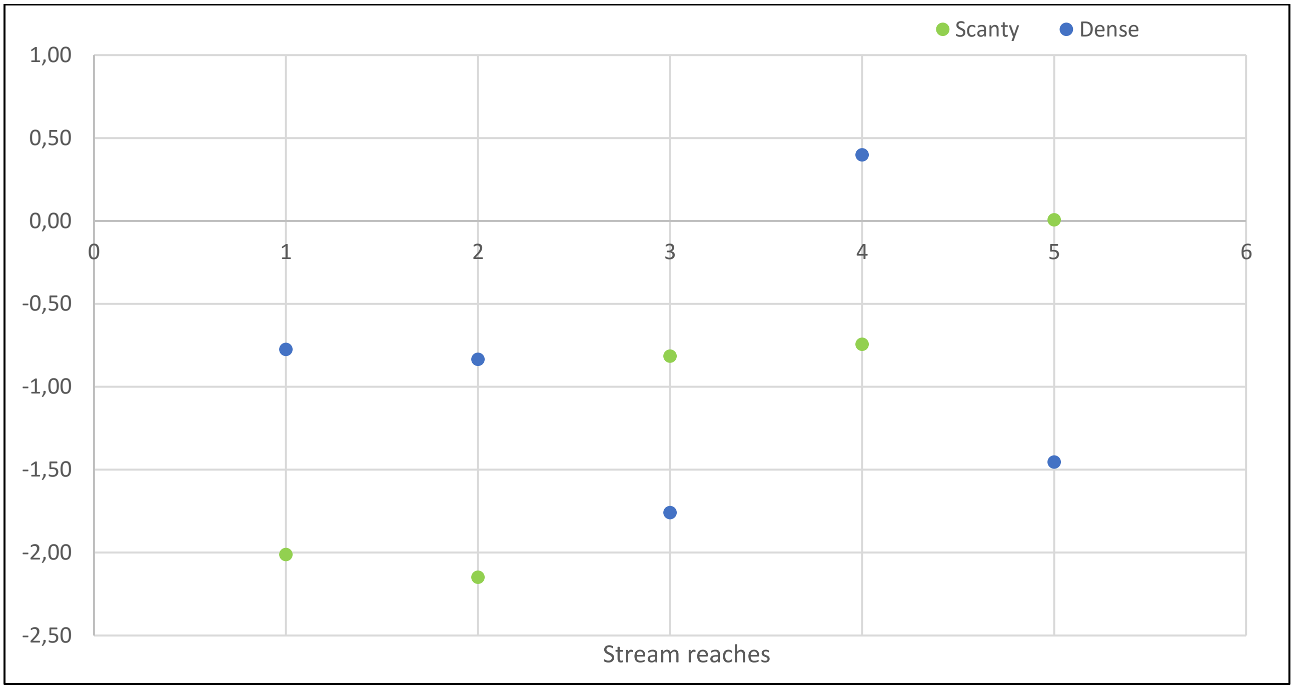


Figure 5.21. Characteristics of the particle size distribution in terms of kurtosis in scanty and densely vegetated reaches.

5.6.2 Soil texture

Soil texture influences the degree of infiltration of water and it controls the soils aggregate stability. Soil texture differs in certain areas as a result of vegetation or lack thereof (Yair & Lavee, 1974). The graph below (Figure 5.22) illustrates the grain size distribution results that were obtained. It is evident from Figure 5.22, that the most texture for both categories is sand. There was a significant difference between the sand component recorded for densely and scantily vegetated reaches ($p=0.01$; $p<0.05$), with the vegetated recording a higher sand component. There was also a discernible difference between the silt outputs. A significant difference in silt content was also recorded between the densely and scantily vegetated reaches, with the latter reaches displaying a higher silt content ($p=0.001$; $p<0.05$), whilst no significant difference was observed between both categories in the clay content ($p=0.79$; $p>0.05$). The general trend observed from the graph is that the percentage of sand for both the categories is greater than 70%.

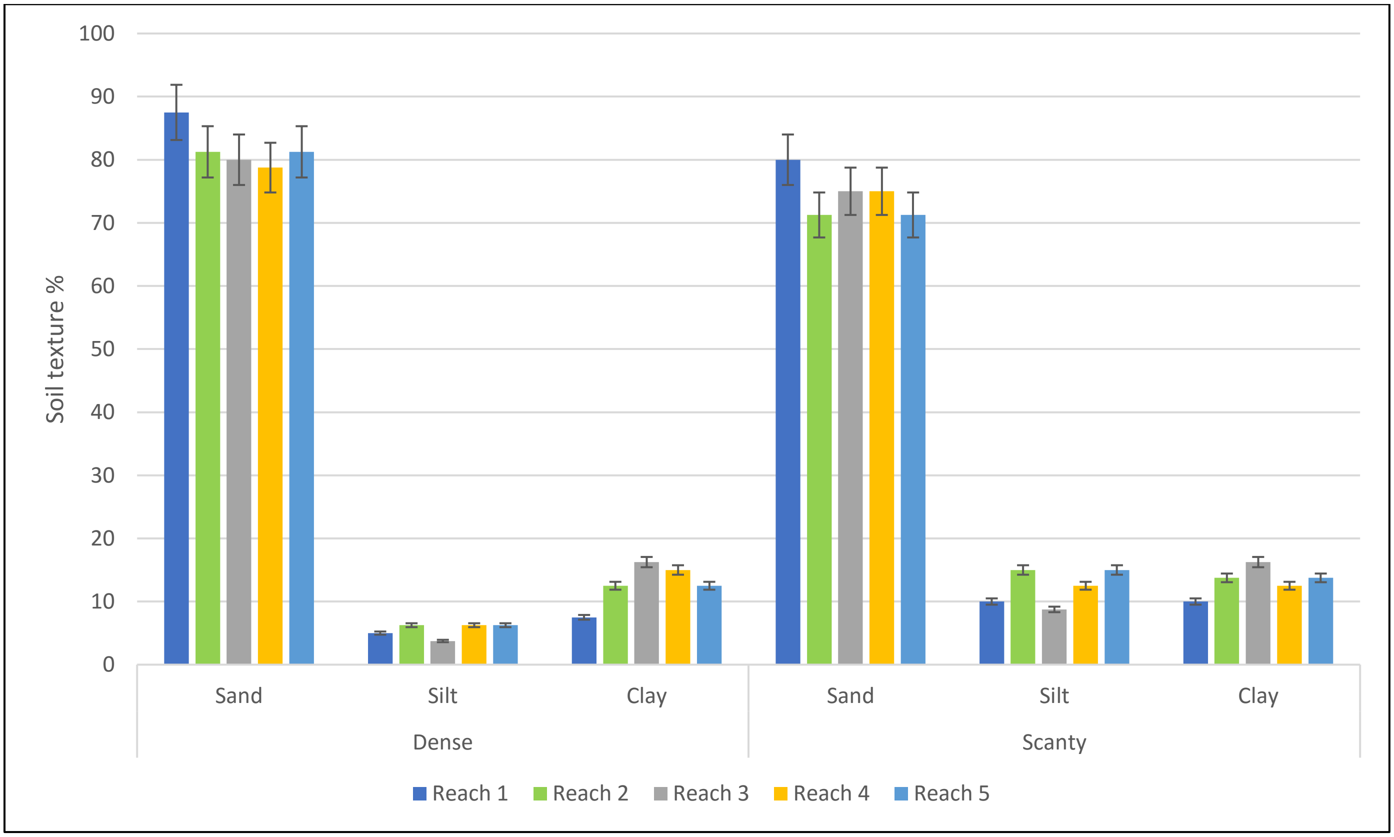


Figure 5.22. Soil texture for five scantily and densely vegetated stream reaches.

5.6.3 Aggregate stability

Aggregate stability is one of the most important factors to consider when studying the physical properties of soils, as it gives an indication of the soil's stability based on the way aggregates are bonded together. Le Bissonnais (1996) provided a classification of the soils aggregate stability and it potential to crust based on Mean Weight Diameter (MWD) (Table 5.4).

Table 5.4. Aggregate stability classification by Le Bissonnais (1996)

Class	MWD value/mm	Stability	Crustability
1	<0.4	Very Unstable	Systemic Crust Formation
2	0.4-0.8	Unstable	Crusting Frequent
3	0.8-1.3	Medium	Crusting Moderate
4	1.3-2.0	Stable	Crusting Rare
5	>2.0	Very Stable	No Crusting

The results of the average aggregate stability of soils at densely and scantily vegetated stream reaches are presented below using MWD (Figure 5.23). MWD values for scantily vegetated stream reaches lie below 0.5 on average. By implication, the soils have a poor aggregate stability, and are unstable, susceptible crusting and erosion. On the contrary, MWD values for all samples from the densely vegetated reaches lie above 1.3. Therefore, the soils are evidently stable, and crusting is rare. A significant difference was observed between the soil aggregate stability in unvegetated and vegetated stream as $p = 1.43 \times 10^{-6}$; $p < 0.05$.

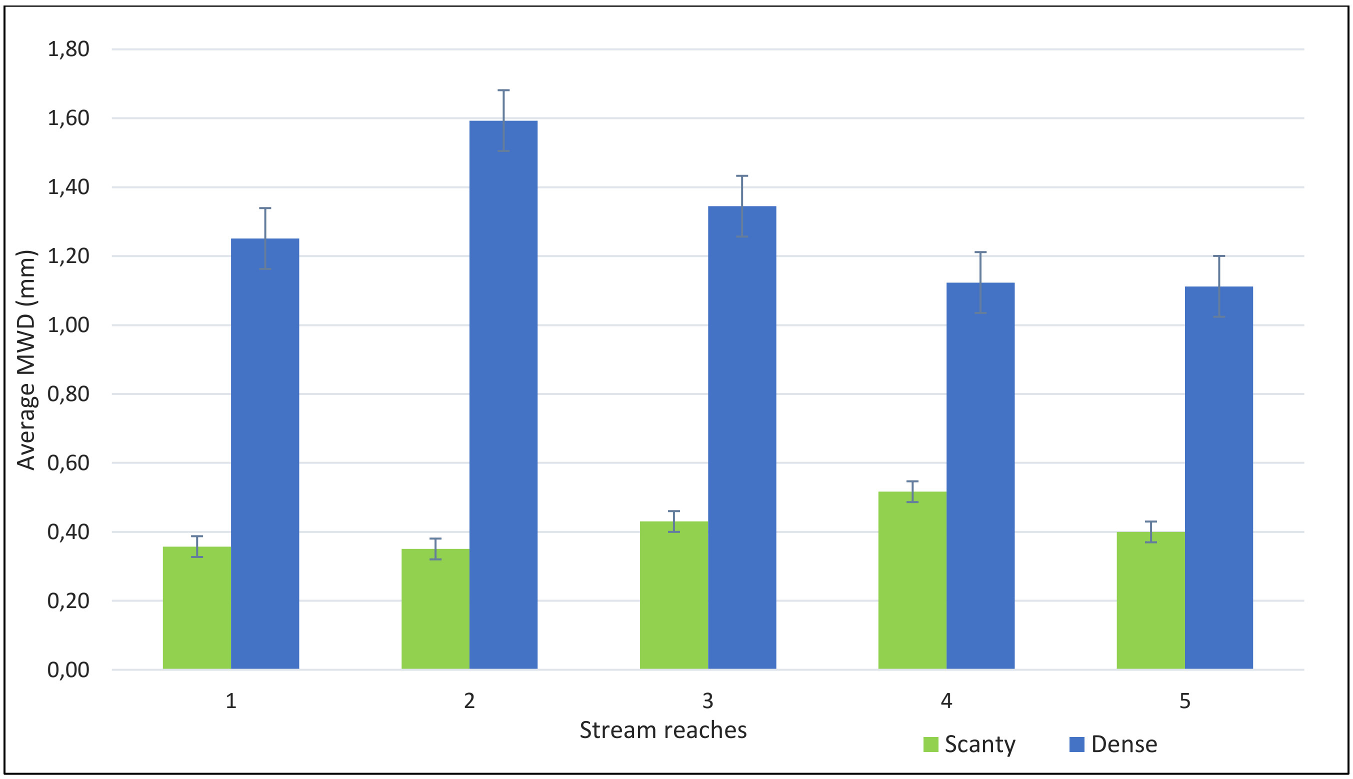


Figure 5.23. Average aggregate stability on vegetated and unvegetated stream reaches

5.6.4 Bulk density

Bulk density measurements form part of a requirement to predict soil stability. It is influenced by the amount of organic matter and texture (Chaudhari *et al*. 2013). It is also used as an indication of porosity and compaction (Costantini, 1995). The higher the bulk density, the lower the soil stability and less organic matter. The average bulk density of all stream reaches is presented in Figure 5.24. The trend is unmistakably that of significantly higher bulk densities for the scantily vegetated than densely stream reaches. ($p= 9.59393 \times 10^{0.8}$; $p>0.05$).

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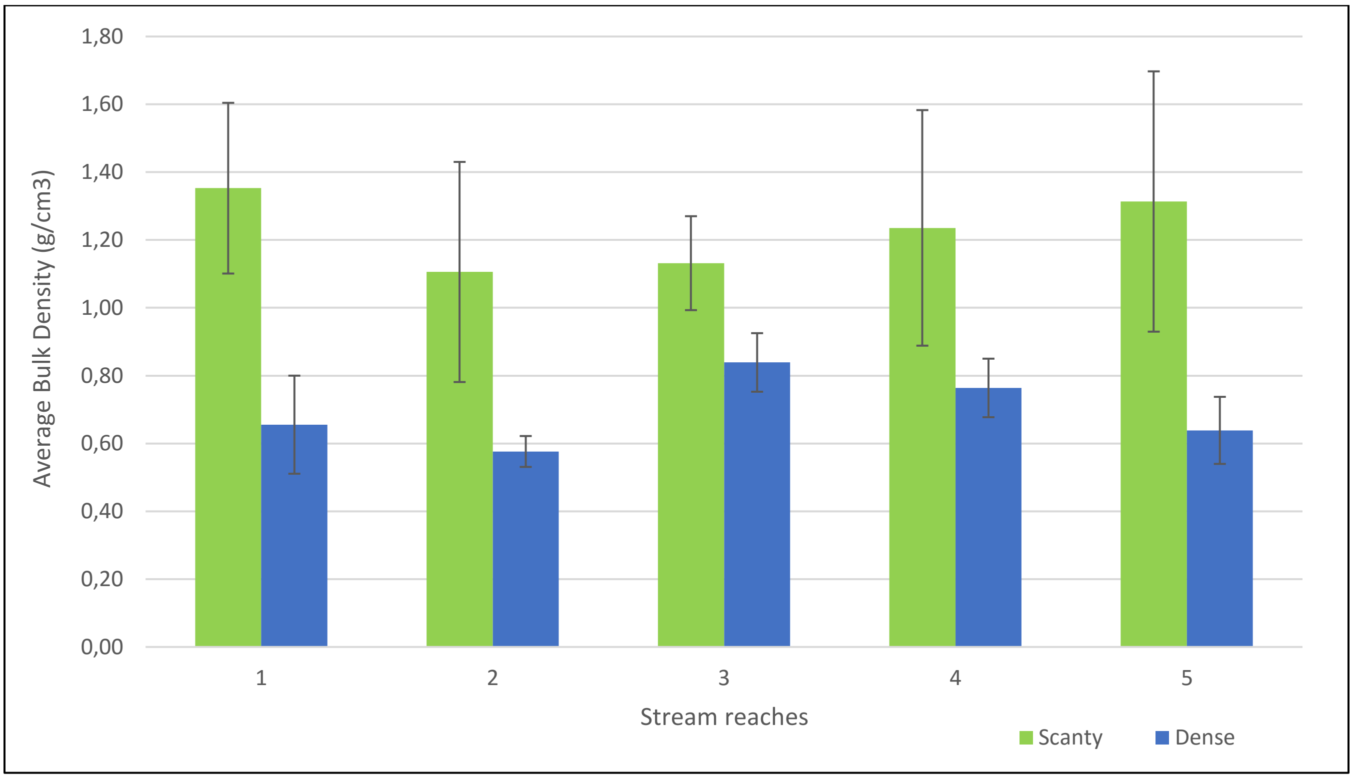

Figure 5.24. Average bulk density for densely and scantily vegetated stream reaches.

5.7. A spatial relation between variations of riparian vegetation and streambank erosion

Figure 5.25 represents a spatial map between a scanty riparian vegetation distribution, settlements, streambank erosion, gullies and sediment sinks (accumulation zones). The map shows the sections that were surveyed in the upper catchment area (A-D). All sections (A-D) shows that gully sites and stream bank erosion are in close proximity and consistent with scanty riparian vegetation. This demonstrates an important spatial link them. There are more gully sites in the upper catchment area consistent with the stream bank erosion.

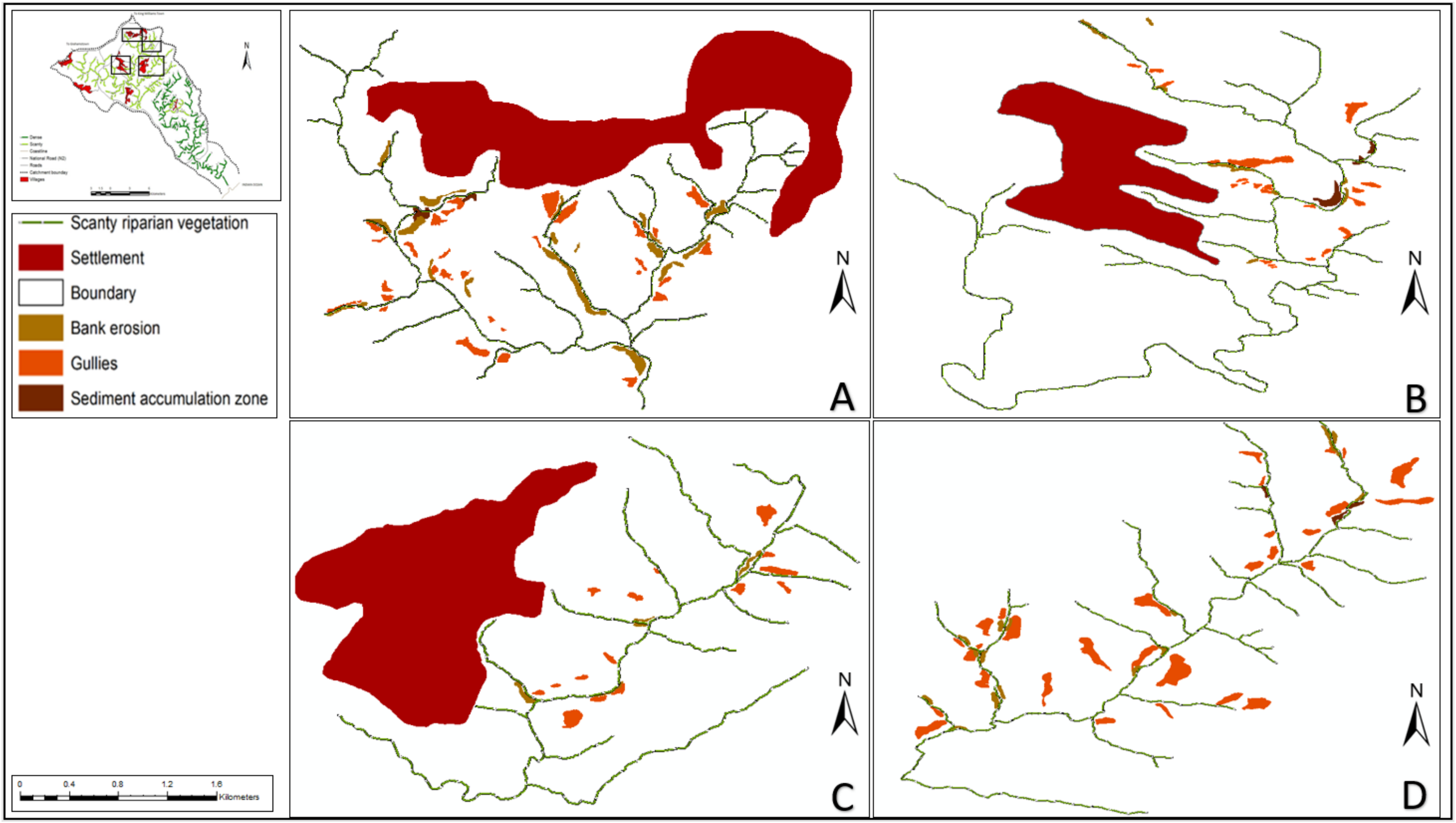

Figure 5.25. Sections of the upper catchment area illustrating the spatial relation between a sparse riparian vegetation distribution and streambank erosion

Figure 5.26 represents a spatial map between a dense riparian vegetation distribution and streambank erosion. It is discernible from the map that on the lower catchment area streambank erosion sites are reduced. The spatial relationship between gully and streambank erosion sites is apparent on area where vegetation patterns change from a scanty to a dense riparian distribution.

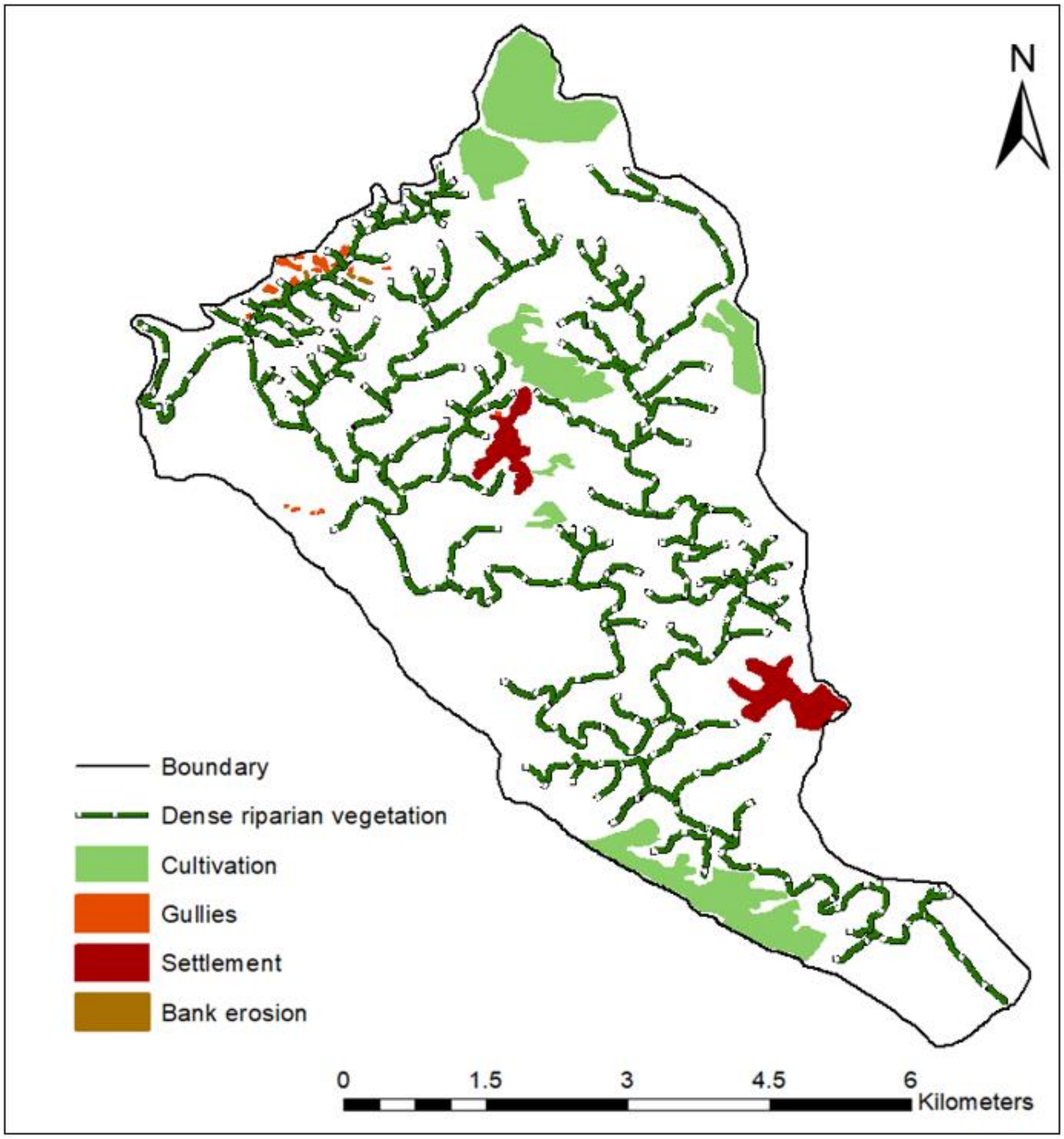

Figure 5.26. A section of the lower catchment area illustrating the spatial relation between a dense riparian vegetation distribution, gullies, and streambank erosion.

The implications of the findings presented in this chapter are explained in the next chapter.

CHAPTER 6

DISCUSSION AND SYNTHESIS

6.1. Introduction

This chapter will discuss the implications of results obtained in Chapter 5 using the methods and materials described in Chapter 4. The spatial variations of riparian density across two land tenure units are discussed. This chapter will elucidate the ramifications of the physical attributes of the channel bank material, spatial relations, and variations of riparian vegetation along channel reaches as determinants of channel bank stability and streambank erosion. Sink areas (sediment accumulation zones), as an important spatial feature situated in the upper part of the catchment, will also be put in context.

6.2. Spatial differences of riparian vegetation density

It is discernible from the results presented in Chapter 5 that the Mgwalana catchment exhibits two distinct riparian vegetation distributional patterns. There is a scanty riparian vegetation distribution in the upper catchment area where communal settlements are confined and dense riparian vegetation distribution in the lower parts of the catchment, which comprise predominantly former white commercial farms. These variations are explained by the pre-existing conditions of the catchment that are traced back to the early 1930s, linked to land tenure (Kakembo, 1997). It was observed during fieldwork that riparian vegetation in the upper catchment area was considerably removed and channel banks were riddled with gully, rill, and bank erosion. The NDVI map (Figure 5.3) corroborates the conditions reflected in the present study. The NDVI numbers recorded along the riparian zone in the upper catchment are negative (-0.14) due to degraded scanty riparian vegetation distribution interspersed by exposed and eroded banks. Low to negative NDVI values of the upper Mgwalana catchment were also quantified by Kakembo (2003), which he attributed to high reflectance in the Red band owing to exposed soil background. The NDVI numbers recorded for the lower part of the catchment are predominantly positive, depicting denser riparian vegetation density.

It is noteworthy, however, that the observed variations in riparian vegetation density cannot be explained by the current land-use practices and the rise in population. Kakembo (2001), identified a sharp rise in the density of the dwelling units in the communal areas in the Eastern Cape, in the Peddie district between 1955 and 1965. As pointed out earlier, riparian vegetation degradation was detected from the earliest set of aerial photographs in the 1930s. This is in conformity with the observation by Hoffman *et al*. (1991) that livelihoods in the communal areas do not currently involve levels of resource exploitation to match the apparent levels of land degradation in these areas. Therefore, the sharp rise of the population observed by Kakembo (2001) does not explain the manifested riparian vegetation degradation in the area. Turner and Ntshona (1999) observed that the establishment of betterment programs in the communal areas gradually disrupted established land-use practices and land management. The programs estranged the people from their conservation ethics, as they were forced to rely on subsistence farming and subsistent migrant labour. The ratio between the population and natural resources was disproportionate. This promoted their reliance on marginal resources and unsustainable land-use practices that led to perpetual land degradation.

As observed in the present study, variations in riparian vegetation density are unique to land tenure units. This robustly reflects the effects of differences in land management. It is noteworthy that along scantily vegetated stream courses, geomorphic impacts are manifest. Decimation of riparian vegetation has resulted in the reduction of bank stability and extensive channel erosion observed during field investigations. Furthermore, riparian vegetation removal has resulted in channel degradation, which has enhanced sediment transfer. This has resulted in valley fills and gullies incising the stream channels (Kakembo, 1997). It is important to note that abandoned cultivation and overgrazed land spatially correlate with scanty riparian vegetation in the upper catchment area. This spatial correlation explains the erosion conditions observed in the present study. This is in conformity with observations in Chile by Fierro *et al*. (2017), where anthropogenic land-use changes exacerbated riparian vegetation diminution and its overall quality.

Dense riparian vegetation on the other hand is consistent with the former commercial farms' land tenure system. It was noted during fieldwork that former commercial farms were located at a considerable distance from the communal villages and much of the riparian vegetation was still abundant. Furthermore, the most prevalent land use practice in this area is the chopping down of trees for firewood, given the abundant residual woody vegetation. It can be discerned from Figure 5.8 that a sparse riparian vegetation distribution can be seen in small parts of the former commercial farms land tenure system. This is attributed to recent encroachment by communal farmers. Therefore, the drastic differences in the vegetation cover along the riparian zones on these two land tenure units can be directly linked to different land management practices.

6.3. Implications of spatial variations of riparian vegetation density on stream bank erosion

6.3.1. Channel conditions in relation to riparian vegetation density

Channel geometry comprehensively captures the geographical attributes and factors that influence the morphology of a channel (Han *et al*. 2019). These attributes encompass the depth, width or confinement, slope, and channel bed morphology (Montgomery and Buffington, 1997). Tables 5.2 and 5.3 present the results of channel morphology in the present study, in terms of width and depth in the two land tenure systems. On average, channel width and depth in scantily vegetated channel reaches characteristic of the upper catchment area are greater than those of the densely vegetated reaches found in the lower catchment area, where the former commercial farms are located. Their eroding nature and poor channel condition (Figure 5.9- 5.11.) can be attributed to riparian vegetation removal in the communal areas. Nagle and Clifton (2003), observes that the changes induced on channel morphology are greatly influenced by the changes in grazing management. Changes observed on channels due to overgrazing are either manifest in streambank vegetation or on the adjacent channel which has exacerbated degradation along the stream bank and subsequently increasing widths of the upper catchment channels (Nagle and Clifton, 2003). In the present study, the channel morphology of the streams located in the communal betterment villages is a function of land use impacts and in-stream periodic processes (Kakembo, 1997). An increased concentration of livestock promotes overgrazing due to trampling and rubbing, propelling physical damage on stream banks and degradation, consequently inducing stream bank erosion (Kairis *et al*. 2015).

Continuous cultivation induces instabilities in stream channels (Johnson, 2006). This is due to substantial imbalances brought across by the state of the cultivated land that causes adjustments in channel capacity and hydraulic geometry. A study by Hayford and Gelhaus (2010) in the Mongolian Steppe streams showed that grazing can increase sediment concentrations due to bare land being exposed by constant grazing. Within the immediate channel and riparian environments, cattle grazing degrades stream banks (Figure 5.9), alters hydrologic and sediment processes, changes channel geometry by increasing width to depth ratios (Trimble and Mendel, 1995), and dramatically increases suspended sediment yields. All this is in keeping with the findings of the present study.

Anderson *et al*. (2004) investigated the width of streams in response to bank material and other factors. According to his findings, channels with thicker bank vegetation had narrower channel widths, as observed in the present study (Tables 5.2 and 5.3). It is also noticeable in Table 5.3 that the densely vegetated channel reaches situated in the former commercial farms exhibit lower channel widths. This is attributed to the higher riparian vegetation density, as vegetation controls resistance, bank strength, and bar sedimentation (Hickin, 1984).

Dollar and Rowntree (1995) investigated the spatial variability of channel form and found that riparian vegetation density, bed, and bank materials exerted controls on channel form. On the one hand, narrower and stable channels with fine bed material were associated with dense riparian vegetation, while wider and unstable channels were associated with low riparian density and a higher bed material on the other. These findings are consistent with those of the present study, as a greater percentage of coarse material (Figure 5.15-5.19), higher channels widths were recorded for scantily vegetated reaches, as opposed to the densely vegetated ones (Tables 5.2 and 5.3).

Channel width in response to vegetation density is also affected by cohesive bank conditions. According to Soar (2002), channels with a higher silt and clay content have narrower channel widths. However, when bank vegetation was factored in, channel widths were narrower, where a dense distribution of vegetation and a low silt/clay percentage were prevalent. A study conducted by Nanson and Beach (1997) identified narrowed channel depths associated with dense riparian vegetation. As noted in Table 5.3, the channel conditions in sections of the densely vegetated channel reaches, where vegetation has been removed exhibited some degree of erosion. This can be explained by later encroachment by communal farmers on streambanks when white commercial farmers expropriated this land.

According to Rowntree (1991), alien vegetation invasions in the riparian zone induced channel instability and excess sediment. Rowntree (1991) further observed that grasses and herbaceous vegetation consist of a shallow root system coupled with low biomass, but tend to have a greater surface cover, which enhances channel stability and minimizes scouring. In the present study, some reaches had a more considerable grass cover than herbaceous vegetation and exhibited good channel bank conditions (Figure 5.14). Woody vegetation contributes to stream channel stability by minimizing mass failure. The coupling of grassy with woody riparian vegetation explains the channel conditions observed in the lower catchment area, characterized by a dense riparian distribution (Figure 5.12-5.14).

Channel widening in the catchment can also be attributed to the increased sediment output being deposited in the channels (sink zones) due to the coupling of hillslopes gullies and stream channels. This is supported by Knighton (1989) and Harvey (1991), who related channel widening and the tendency to braid as a response to an increased sediment input. Furthermore, Dollar and Rowntree (1995) also note increased sediment input in catchments due to gully, sheet, and rill erosion resulting from poor veld management that led to channel instability. The increased influx of sediment due to the sparse riparian vegetation, injudicious land use, and the coupling of gullies with stream channels has changed the morphology of stream channels and induced stream bank erosion. The modified stream channels are generally characterized by valley fill (Kakembo, 1997), which has led to the destabilization of the stream channels even further.

6.3.2 Implications for bank stability

Due to the scanty riparian distribution associated with the communal betterment villages land tenure units of the upper catchment area, geomorphic effects on stream channels are exacerbated. The inability of scanty vegetation to intercept sediment from hillslopes and the absence of a strong root system results in high sediment yields moving freely downslope. Consequently, excessive sediment delivery, which takes the form of unconsolidated colluvium and alluvium material is evident on sections channel beds as sediment accumulation zones. This is attributed to the widespread channel degradation and coupling with hillslope gullies, observed during field investigations. The poor channel stability consistent with a sparse riparian vegetation density translates into streambank erosion. This is also underpinned by the inherently poor physical soil characteristics recorded for streambank material, which increases channel bank erodibility, as will be explained in the subsequent sections.

The close spatial relationship between scanty riparian vegetation distribution and streambank erosion (Figure 5.25), coupled with the spatial relationship between sediment accumulation zones, intricate gully sites (Figure 5.4 A), land use, and land tenure (Figure 5.8) collectively explains the implications for stream bank erosion. Sekely *et al*. (2002), found that up to 44% of suspended sediment contributed to streambank slumping. Even though a certain degree of these influences is due to intrinsic thresholds, for example bank material, the effect of extrinsic thresholds, for example land use play a considerable role in exacerbating stream bank instability.

The influence of dense riparian vegetation on bank stability is seen in the lower catchment parts (Figure 5.26), characteristic of former commercial farms. Most banks were noted as intact, which is attributed to riparian vegetation ability to maintain soil reinforcement, adequate bank drainage, and curtails near-bank flow velocities (Thorne, 1990). The quantification of effects of vegetation density on streambank stability remains difficult due to the complexity of the interactions occurring between riparian vegetation and processes of bank stability (Sidle *et al*., 2006; Pollen, 2007).

6.4.1. Sediment accumulation zones

Sediment accumulation zones were observed as unique to the upper part of the catchment, which represents a land tenure zone that comprises communal villages (Figure 5.4A). There is a close spatial relation between the sediment sink zones, gullies and a scanty riparian vegetation distribution (Figure 5.4A). The coupling of gullies, sediment sink zones and stream channels observed in Mgwalana catchment coincides with findings by Larsen *et al*. (2016) (Figure 5.5 and 5.6), who observed that a direct link between sediment delivery from gullied hillslopes to trunk streams represents a significant pathway of mass sediment transfer in the landscape, inducing sediment connectivity. Figure 5.4A illustrates that gullies are the main source of sediment. This is in keeping with Van de Waal (2014), whose study demonstrated that gullies were the main sediment source for a period of 100+ years. The augmentation in sediment accumulation closer to gullied hillslopes suggests sediment availability has increased, due to accelerated erosion and efficient sediment delivery as a result of increased hillslope-channel connectivity perpetuated by gullies (Van de Waal, 2014) and reduced riparian vegetation. In addition, Xanga (2006) observes that gullies in the Mgwalana catchment contributed excessively to sediment delivery into stream channels. He also observes that the close spatial correlation between gullies and sediment sinks (accumulation areas) in the form of adjacency is discernible, resulting from an increase in sediment connectivity. Similarly, Tsokeli (2005) states that the occurrence of sediment sources is likely to be localised in certain sections of the stream where gully erosion is dominant. This is in keeping with the conditions observed in the present study. This is also supported by a study investigated by Van de Waal and Rowntree (2017), where connected and disconnected gullies contributed 10% to increased hillslope-channel connectivity.

It has been established that scanty riparian vegetation conditions in the upper parts of the catchment, associated with traditional and betterment villages, are clearly spatially correlated with sediment accumulation zones. Connectivity between the hillslope gullies has developed at several sites. Beuselink *et al*. (2001) made observations that vegetation controls deposition at a higher slope gradient compared to a slope-controlled sediment deposition. It can be concluded that the coupling of gullies to stream channels resulting in a cascading sediment sink system could explain the increased sediment output resulting in stream channel degradation and sediment accumulation. The sparse hillslope vegetation cover and scanty riparian vegetation also play a part in enhancing connectivity, as lateral sediment connectivity increases with a decreased riparian vegetation zone (Poeppl *et al*. 2012). The gullies situated on the hillslopes have incised into the stream channels and increased sediment delivery in the catchment (Figure 5.5).

In a study conducted by Poesen *et al*. (2003), the prevalence of sediment accumulation zones was also attributed to land use practices persisting in the traditional village land tenure units. This is clearly illustrated in Figures 5.8. On the other hand, conditions observed in the lower catchment area are in sharp contrast. Gullied hillslopes, degraded channel banks sediment accumulation zones are non-existent. Incipient channel degradation can be seen in a few areas where communal farmers have started encroaching upon the riparian zone, removing riparian vegetation. Vigiak *et al*. (2016) showed that an increased presence of riparian vegetation promotes sediment retention. This corroborates observations made in the lower catchment area in the present study, where dense riparian vegetation distribution deterred streambank erosion and sediment accumulation zones (Figure 5.4B and Figure 5.26). According to Vanacker *et al*. (2007), vegetation cover employs a non-linear control on the production and the transfer of water and sediment. This means that if a small increase in vegetation concentration is discerned, it translates into a significant decrease in erosion, as observed in the present study. Vanacker *et al*. (2007) also note that the spatial distribution of vegetation is important as it exerts an influence on sediment sources and sinks within a catchment.

6.4.2. The influence of soil texture on bank condition

Soil texture influences the degree of infiltration of water through the soil, as it controls soil stability. There were no significant differences between clay percentages on densely and scantily vegetated stream reaches in the present study. However, clay percentages exceeded 10% in only some parts. Soils with clay content exceeding 10% are considered as problematic due to their expansive characteristics (Mugaga, Kakembo & Buyinza, 2011). However, it is documented by Nebo (2013), that clay-rich soils do not necessarily result in high erosion susceptibility.

Nonetheless, the greater channel widths of the upper catchment ephemeral streams can also be explained as being underpinned by perpetual erosion of the exposed banks owing to high clay composition. The exposed nature of the ephemeral stream banks facilitates bank material destabilization via processes such as desiccation, cracking, swelling, shrinking and expansion. In a study conducted Bhowmik *et al*. (2018) in North-East India, bank material showed a high erodibility potential due to non-cohesive material which consisted of a high sand percentage (90 %) and a lower silt and clay percentage. Based on the findings of the study, it was concluded that bank material coupled with scanty riparian vegetation contributed significantly to the apparent streambank erosion.

There was a significant difference in the silt percentage found in the two riparian vegetation patterns. Percentages over 10% were recorded for the scanty riparian vegetation distributions, whilst the dense riparian vegetation distribution recorded less. Soils with high silt and sand percentages have the greatest susceptibility of erosion (Nebo, 2013).

6.4.3. Aggregate stability as an indicator of susceptibility to stream bank erosion.

Channels located in the scantily vegetated stream reaches recorded poor aggregate stability (Figure 5.23). The distribution and the stability of soil aggregates are related to soil erosion resistance and one of the most effective indicators of erosion sensitivity (Guo *et al*, 2018). It is seen that soils from densely vegetated stream reaches recorded a higher average aggregate stability and is thus classified as stable with moderate crusting (Table 5.4). According to Le Bissonnais (1996) and Le Bissonnais and Arrouays (1997), these soils have a low propensity to erosion due to their bonding factor and possible higher soil organic carbon due to the presence of vegetation. This explains the reduced streambank erosion observed in densely vegetated channels in the present study.

6.4.4. The influence of bulk density on stream bank erosion.

An indication of the susceptibility of the soil to erosion is also determined by bulk density. Scantily vegetated channel reaches were noted to have a higher bulk density than densely vegetated reaches. Soil with poor aggregate stability indicated a poor soil structure thus, would not be able to efficiently sustain biological productivity through water movement (Dexter, 2004). In a study conducted by Jin *et al*. (2009), higher bulk densities were attributed to soil disturbances that were linked with land use and the removal of soil organic matter by erosion. This is consistent with the findings of the present study, where scantily vegetated reaches are associated with a high bulk density, which has increased stream bank susceptibility to erosion. The converse is true of the densely vegetated stream channel reaches, as observed during fieldwork. Low bulk density values were recorded, indicating greater soil stability, which, coupled with dense riparian vegetation enhances stream bank stability.

6.5. Recommendations

Recommendations based on the findings of this study point to incorporating robust catchment management strategies are reviewed below:

6.5.1. The establishment of riparian zone rehabilitation approaches

The current catchment of study lies in an area where degradation is widespread. Rehabilitating and restoring riparian zones can be the first step in creating an effective rehabilitation framework. Initiating rehabilitation, particularly, in the upper catchment area would be moving towards rebuilding riparian zones that have been destroyed by anthropogenic disturbances. For instance, mechanically reconfiguring eroded or demolished banks can result in substantial erosion retardation. As pointed out by Kakembo (1997), this can be achieved by re-establishing suitable riparian vegetation along the upper banks of stream channels. This will promote deposition of massive amounts of sediment from the abandoned cultivation fields, enhance bank accretion and colonisation of berms by volunteer species.

An alternative method would be naturalization. According to the NRC (2002), naturalization includes establishing self-sustaining geomorphic systems that involve diverse ecological communities that are categorically different from those that existed before. This method has been employed numerous times in agricultural settings that have resulted in severe streambank erosion and led to the complete modification of existing channels (Rhoads and Herricks, 1996)

The installation of riparian buffer zones directly kicks off the rehabilitation process and simultaneously mitigates riparian zone degradation. Riparian buffers are assemblages of plants that border streams and rivers. Riparian buffers have an array of functions and those pertinent to the present study include the prevention of sedimentation, the stabilization of streambanks and the mitigation of erosion. Castelle *et al*. (1994), notes the buffer roots reinforce banks and hold both the topsoil and the streambank weathered material, which in turn increases streambank cohesiveness, thus reducing erosion considerably. On the other hand, Daniels and Gilliam (1996), found that the installation of riparian buffers reduces sediment load flowing into stream channels by 60% to 90%.

6.5.2. Rejuvenating catchment ecological integrity through gully control

Land degradation in the form of gully erosion is one of the biggest environmental problems plaguing the catchment of study. The excess sediment delivery augments channel degradation and leads to streambank destabilization. Several studies have highlighted the detrimental effects of the gullied sites on the catchment (see Kakembo and Rowntree, 2003: Kakembo *et al*. 2009). Stabilization structures have already been installed in some parts of the catchment, but a catchment based holistic approach needs to be adopted to curb further gully expansion. Gullies have been confirmed as the main sources of sediment. Management approaches such as these will require intervention from government agencies to provide funding for rehabilitation efforts. This is also an opportunity to involve the community by creating employment and to educate them on the importance of reducing sediment connectivity as part of riparian zone rehabilitation.

CHAPTER 7

CONCLUSION

The main findings of this study are concluded in this chapter.

7.1. Conclusion

This investigation unravelled distinct variations of riparian vegetation density in the Mgwalana catchment. These variations were linked to two land tenure units namely, the communal traditional and betterment villages, and former commercial farms. On the one hand, scanty riparian vegetation distribution was confined to the upper catchment area, occupied by the communal traditional and betterment villages. On the other, dense riparian vegetation distribution was confined to the lower catchment area, occupied by the former commercial farms. This pattern is also corroborated by the NDVI map, where NDVI values demonstrate clear distinctions in the vegetation patterns.

Evidence obtained from previous studies confirms that riparian vegetation diminution was initiated in the 1930s. By implication, the sharp rise in population identified in the 1950s and1960s does not explain the degradation of riparian vegetation observed in the communal areas.

Gully sites and sediment sink zones (accumulation areas) typify the communal traditional villages and betterment areas. Gully sites situated on the catchment hillslopes were coupled with the sediment sink zones, which are associated with scanty riparian vegetation distribution. The coupling has enhanced sediment delivery into stream channels, resulting in the development of several sink zones.

Active erosion of channel banks with scanty riparian vegetation is widespread. This is coupled with greater channel widths, attributed to riparian vegetation degradation. Channel widening was related to the tendency to braid as a response to an increased sediment input. Poor aggregate stability and high bulk density of stream bank materials contributed to streambank erosion observed in the upper catchment area.

Riparian vegetation in the lower catchment, occupied by the former commercial farms is still relatively dense. This demonstrates clearly that the difference in land management explain the spatial variations in riparian vegetation and general land degradation. A few sections of the stream channels showed a certain degree of riparian vegetation removal and incipient bank erosion. This is attributed to the recent encroachment by communal farmers. The physical soil characteristics for this area, as identified in laboratory analyses corroborated the stable stream channel conditions and limited streambank erosion found in this part of the catchment.

Based on the findings of the study, where dense riparian distribution persisted, streambank erosion was non-existent. Physical soil characteristics associated with highly erodible soils were recorded for streambank erosion occurring in the upper catchment area, occupied by the communal traditional villages and betterment areas.

The present study has demonstrated distinguishable patterns and spatial links between variations of riparian vegetation density and its influence on streambank erosion in relation to land tenure. However, establishing the sole influence of vegetation density on streambank stability remains difficult due to the complexity of the interactions between intrinsic and extrinsic thresholds.

7.2. Directions for future research

During the course of this study, some areas were identified as needing further investigation. These include:

- Drawing more attention to catchment scale as research has shown that there tends to be a scale dependence of bank erosion processes in catchments.

- Incorporating in-situ testing of the erodibility was beyond the scope of this study. However, factoring it in can give a clear picture of the potential for erosion of the affected stream banks and provide a quantitative analysis of the effects of vegetation on streambank erosion, relative to other factors such as soil physical and chemical parameters.
- An integration of a model to quantify the enormous sediment yield in the catchment would give a quantitative analysis of the whole vegetation gradient to deepen the understanding of the influence of vegetation on stream bank erosion.
- The catchment is encroached by the invasive shrub, *P. incana*. It exerts its effects that exacerbate vegetation and soil degradation. Remote sensing plays an integral part in contemporary research, therefore, incorporating it to establishing the distribution of the invasive shrub encroachment and its spatial links to vegetation patterns and streambank erosion can be undertaken to generate a body of knowledge crucial to catchment rehabilitation.

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APPENDICES

Appendix 1. t-Test: Two-Sample Assuming Equal Variances for depths of scantily and densely vegetated reaches

	Scanty	*Dense*
Mean	2.571428571	2.942857
Variance	1.045274725	0.762637
Observations	14	14
Pooled Variance	0.903956044	
Hypothesized Mean Difference	0	
df	26	
t Stat	-1.033595647	
P(T<=t) one-tail	0.155422033	
t Critical one-tail	1.70561792	
P(T<=t) two-tail	0.310844066	
t Critical two-tail	2.055529439	

Appendix 2. t-Test: Two-Sample Assuming Equal Variances for widths of scantily and densely vegetated reaches

	Scanty	*Dense*
Mean	6.585714286	4.621429
Variance	4.61978022	2.032582
Observations	14	14
Pooled Variance	3.326181319	
Hypothesized Mean Difference	0	
df	26	
t Stat	2.849579109	
P(T<=t) one-tail	0.00422613	
t Critical one-tail	1.70561792	
P(T<=t) two-tail	0.008452261	
t Critical two-tail	2.055529439	

Appendix 3. Particle size analysis raw data for cumulative graphs on scantily vegetated reaches

Scantily vegetated reaches							
Reach 1							
mm	**phi value**	**sample 1**	**sample 2**	**Ave weight**	**Cumulative**	**Freq. %**	**Cum. Freq.%**
8	-3	65.39	85.41	75.4	75.4	20.65	20.65
4	-2	93.53	67.68	80.605	156.005	22.08	42.74
2	-1	89.66	57.98	73.82	229.825	20.22	62.96
1	0	62.39	56.44	59.415	289.24	16.28	79.23
0.5	1	29.91	42.38	36.145	325.385	9.90	89.14
0.25	2	12.92	32.55	22.735	348.12	6.23	95.36
0.125	3	7.17	16.81	11.99	360.11	3.28	98.65
0.063	4	4.63	5.24	4.935	365.045	1.35	100.00
Total				365.045			

Appendix 4. Particle size analysis raw data for cumulative graphs on densely vegetated reaches

Densely vegetated reaches							
Reach 1							
mm	**phi value**	**sample 1**	**sample 2**	**Ave weight**	**Cumulative**	**Freq. %**	**Cum. Freq.%**
8	-3	40,55	85,58	63,065	63,065	16,49	16,49
4	-2	57,63	112,23	84,93	147,995	22,21	38,70
2	-1	64,3	70,66	67,48	215,475	17,65	56,35
1	0	42,57	37,38	39,975	255,45	10,45	66,81
0,5	1	50,03	30,39	40,21	295,66	10,52	77,32
0,25	2	100,2	26,1	63,15	358,81	16,51	93,84
0,125	3	27,57	9,36	18,465	377,275	4,83	98,66
0,063	4	7,14	3,07	5,105	382,38	1,34	100,00
Total				382,38			

Appendix 5. Particle size analysis presenting skewness and kurtosis on scantily and densely vegetated reaches

Scanty reaches				**Dense reaches**		
Reach 1	**Ave weight (g)**	**Skewness**	**Kurtosis**	**Reach 1**	**Ave weight (g)**	**Skewness**
	75.4	-0.162655936	-2.01147		63.065	-0.3746585
	80.605				84.93	
	73.82				67.48	
	59.415				39.975	
	36.145				40.21	
	22.735				63.15	
	11.99				18.465	
	4.935				5.105	
Reach 2	76.555	0.175554953	-2.14851	**Reach 2**	44.455	-0.8362935
	72.94				72.32	
	65.66				67.45	
	45.645				67.185	
	22.735				75.57	
	11.125				47.395	
	10.225				14.1605	
	3.64				5.35	
Skewness				**Kurtosis**		
Reach	**Scanty**	**Dense**		**Reach**	**Scanty**	**Dense**
1	-0.16	-0.37		1	-2.01	-0.77
2	0.18	-0.84		2	-2.15	-0.83
3	0.36	0.40		3	-0.81	-1.76
4	0.26	-1.03		4	-0.74	0.40
5	-0.37	-0.09		5	0.01	-1.45

Appendix 6. t-Test: Two-Sample Assuming Equal Variances for the silt component

SILT		
	Scanty	*Dense*
Mean	5.5	12.25
Variance	1.25	8.125
Observations	5	5
Pooled Variance	4.6875	
Hypothesized Mean Difference	0	
df	8	
t Stat	-4.9295	
P(T<=t) one-tail	0.000575	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.00115	
t Critical two-tail	2.306004	

Appendix 7. t-Test: Two-Sample Assuming Equal Variances for the sand component

SAND		
	Scanty	*Dense*
Mean	81.75	74.5
Variance	11.40625	12.96875
Observations	5	5
Pooled Variance	12.1875	
Hypothesized Mean Difference	0	
df	8	
t Stat	3.283603399	
P(T<=t) one-tail	0.005563888	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.011127776	
t Critical two-tail	2.306004135	

Appendix 8. t-Test: Two-Sample Assuming Equal Variances for the clay component

CLAY		
	Scanty	*Dense*
Mean	12.75	13.25
Variance	11.25	5.15625
Observations	5	5
Pooled Variance	8.203125	
Hypothesized Mean Difference	0	
df	8	
t Stat	-0.27603	
P(T<=t) one-tail	0.394762	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.789524	
t Critical two-tail	2.306004	

Appendix 9. Wet aggregate stability

The mean weight diameter, using two samples as examples to demonstrate the calculations used

1mm	630um	250um	125 um	63um	sum	2000um	1000	630	250	125	63	MWD (um)	MWD (mm)	Mean MWD
	10.16	3.1		3.4	45.17	63.11711	0	22.4928	6.862962	0	7.52712	**357.2947**	**0.36**	0.3573675
	9.12	2.15		3.14	45.19	68.11241	0	20.18146	4.75769	0	6.94844	**357.4403**	**0.36**	
1mm	500um	250um	125 um	63um	sum	2000um	1000	500	250	125	63			
7.21	7.21	4.67		2.42	47.29	54.5147	15.24635	15.24635	9.875238	0	5.117361	**372.7283**	**0.4**	0.3504879
	10.69	5.12		3.23	41.18	53.76396	0	25.9592	12.43322	0	7.843613	**328.2475**	**0.3**	

*** Formula for MWD:

(((2mm*100/Σ diff) *2000) + ((630µm*100/ Σ diff.) *630)) + ((200µm*100/ Σ diff.) *200)) + ((63µm*100/ Σ diff.) *63))/100

Appendix 10. t-Test: Two-Sample Assuming Equal Variances for aggregate stability

	Scanty	*Dense*
Mean	0.41091918	1.284992358
Variance	0.004547213	0.038915365
Observations	5	5
Pooled Variance	0.021731289	
Hypothesized Mean Difference	0	
df	8	
t Stat	-9.37508156	
P(T<=t) one-tail	6.85629E-06	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	1.37126E-05	
t Critical two-tail	2.306004135	

Appendix 11. t-Test: Two-Sample Assuming Equal Variances for bulk density

	Scanty	*Dense*
Mean	6.585714286	4.621429
Variance	4.61978022	2.032582
Observations	14	14
Pooled Variance	3.326181319	
Hypothesized Mean Difference	0	
df	26	
t Stat	2.849579109	
P(T<=t) one-tail	0.00422613	
t Critical one-tail	1.70561792	
P(T<=t) two-tail	0.008452261	
t Critical two-tail	2.055529439	