AN INVESTIGATION OF THE SOIL PROPERTIES CONTROLLING GULLY EROSION IN A SUB-CATCHMENT IN MAPHUTSENG, LESOTHO

by

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Declaration

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ABSTRACT

Lesotho is a country with an international reputation for the severe degree of soil erosion in its landscape. Despite several national soil conservation projects, soil erosion continues at an astounding rate. One of the reasons for this is possibly that the interactions between soil properties and erosion in Lesotho are not understood. Soil erosion is a site specific, cyclic phenomenon, controlled by geomorphological thresholds. To control soil erosion, the processes and soil properties which influence soil erosion in the specific place must be understood.

In this study the soil properties of a highly eroded sub-catchment in Maphutseng, Lesotho was investigated. The gully extent in the sub-catchment, in 1957 and 2004 respectively, was mapped from aerial photos. These maps show where in the landscape gullies developed during this time. The gully maps were superimposed on maps of several soil erosion factors, to correlate the spatial distribution of the erosion factors with that of the gully distribution. A soil map was especially drawn for this.

The spatial analysis shows that gully development between 1957 and 2004 was primarily confined to the area where duplex soils occur. The rest of the sub-catchment underwent negligible differences in gully extent during this time. The initiation of the gullies on the duplex soil area is ascribed to tunnel erosion. The high dispersibility of the duplex soil samples, sink holes which occur in this area and previous observations by researchers in this area gave evidence to this hypothesis.

In the second part of the study the soil properties of seventeen soil profiles from across the study site were analysed. The difference in gully distribution between the duplex soils area and the rest of the catchment is ascribed to the high dispersibility of the duplex soils. No strong correlations could be found between the dispersion index and other determined soil properties. Segmented quantile regression was used to analyse the data further.

Soil samples with moderate levels of total carbon (1.17%), iron oxide (0.9%) and effective cation exchange capacity (13.7 cmolc/kg), have below average dispersibility. When none of these stabilising agents are present in moderate amounts, soils with even low exchangeable sodium percentage values (0.68%) are dispersive. Furthermore, soils which have developed in colluvial material from basaltic origin were found to be less dispersive, presumably because of the amorphous clay minerals present in the volcanic material.

The colour and increase in clay content between the A and B horizons of a soil can indicate the tunnel erosion potential of the soil. Dark coloured soils (values less than 4 and chromas less than 3) were found to have low dispersibility and free water can accumulate in the subsoils where the B horizon has much more clay than the A horizon. The accumulation of free water in the subsoil is necessary for tunnel formation. Thus soils with dark colours and/or a low clay accumulation index have low tunnel erosion potential.

OPSOMMING

Lesotho is ‘n land met ‘n internasionale reputasie vir die ernstige graad van gronderosie waaronder die landskap gebuk gaan. Ten spyte van verskeie nasionale grondbewaringsprojekte duur die erosie teen ‘n verstommende tempo voort. Een van die redes hiervoor is heel moontlik dat die interaksies tussen grondeienskappe en erosie in Lesotho nie verstaan word nie. Gronderosie is ‘n plekspesifieke, sikliese verskynsel, wat deur geomorfologiese drempelwaardes beheer word. Om gronderosie te bekamp moet die prosesse en grondeienskappe wat gronderosie in die spesifieke plek beïnvloed, geïdentifiseer en verstaan word.

In hierdie studie is die grondeienskappe van ‘n hoogs geërodeerde opvanggebied in Maphutseng, Lesotho ondersoek. Die dongaverspreiding in die opvanggebied, in 1957 en 2004 respektiewelik, is vanaf lugfoto’s gekarteer. Die kaarte wys waar in die landskap dongas gedurende hierdie tyd ontwikkel het. Die dongakaarte is op kaarte van verskeie gronderosie faktore gesuperponeer om die ruimtelike verspreiding van die erosie faktore met die donga verspreiding te korreleer. ‘n Grondkaart is spesiaal vir hierdie doel opgestel.

Hierdie analise het gewys dat donga-ontwikkeling tussen 1957 en 2004 hoofsaaklik op die area waar dupleks gronde voorkom plaasgevind het. Die res van die opvanggebied het weinig verskille in donga verspreiding in hierdie tyd ondergaan. Die ontstaan van die dongas in die dupleksgronde word toegeskryf aan tonnelerosie. Die hoë dispergeerbaarheid van die dupleks grondmonsters, sinkgate wat in die area voorkom en vorige waarnemings deur navorsers in die area verleen bewyse aan hierdie hipotese.

In die tweede deel van die studie is die grondeienskappe van sewentien grondprofiele van regoor die opvanggebied ontleed. Die verskil in donga verspreiding tussen die dupleksgrond area en die res van die opvanggebied is toeskryfbaar aan die hoë dispergeerbaarheid van die dupleks gronde. Geen sterk korrelasies is tussen die dispersiwiteits indeks en ander bepaalde grondeienskappe gevind nie. Gesegmenteerde kwantiel regressie is gebruik om die data verder te ontleed.

Hierdie ontleding het gewys dat grondmonsters met matige vlakke van totale koolstof (1.17%), ysteroksied (0.9%) en effektiewe katioonuitruilkapasiteit (13.7 cmolc/kg), ondergemiddelde dispergeerbaarheid toon. Waar nie een van hierdie stabiliserings agente in matige hoeveelhede voorkom nie, is selfs gronde met baie lae uitruilbare natriumpersentasie waardes (0.68%) dispersief. Daar is ook gevind dat gronde wat vanuit kolluviale basaltiese afsettings ontwikkel het, minder dispersief is.

Die kleur en verskil in klei persentasie tussen die A en B horison van ‘n grond kan as aanduiding dien van die grond se potensiaal vir tonnelerosie. Donker grondkleure (waarde laer as 4 en chroma laer as 3) wys op ‘n lae dispersiwiteit terwyl vrywater in die ondergrond van gronde waar die B horison veel meer klei as die E horison bevat kan akkumuleer. Die aansameling van vrywater in die ondergrond is noodsaaklik vir tonnelvorming. Dus het donker gronde en gronde met ‘n lae klei akkumulasie indeks ‘n lae potensiaal vir tonnelerosie.

DEDICATION

This work is dedicated to Jesus Christ, Who has proven Himself faithful throughout this study. His Word is true:

Even the youths shall faint and be weary,
And the young men shall utterly fall,
But those who wait on the Lord shall renew their strength;
They shall mount up with wings like eagles,
They shall run and not be weary,
They shall walk and not faint.

-Isaiah 40:30-31

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AAS: Atomic Absorption Spectroscopy

AWR: Air-to-Water Permeability Ratio

CBD: Citrate Bicarbonate Dithionate

CEC: Cation exchange capasity

COC: Complexed organic carbon

DEM: Digital Elevation Model

EC: Electrical Conductivity

ECEC: Effective Cation Exchange Capasity

ECaP: Exchangeable Calsium Percentage

ESP: Exchangeable Sodium Percentage

EMgP: Exchangeable Magnesium Percentage

FAO: Food and Agricultural Organisation of the United Nations

NDVI: Normalised Difference Vegetation Index

OC: Organic carbon

OM: Organic matter

SAR: Sodium Absorption Ratio

SARCCUS: Southern African Regional Commission for the Conservation and Utilisation of the Soil

SLEMSA: Soil Loss Estimation Model for Southern Africa

SOC: Soil organic carbon

USLE: Universal Soil Loss Equation

WD: Water Dispersible

WRB: World Reference Base

WSA: Water Stable Aggregates

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INTRODUCTION

The Kingdom of Lesotho, or the Kingdom in the Sky as it is referred to in tourism circles, is a beautiful country completely surrounded by the Republic of South Africa. It is the home of the Basotho, a nation birthed in 1818 when King Moshoeshoe formed alliances between clans and chiefdoms of Southern Sotho speaking people living in what today is the Eastern and Northern Free State and Western Lesotho (Lesotho Government, 2007).

Unfortunately Lesotho is also internationally known for its severely eroded landscape (Showers, 1989), which is a serious threat to the arable land of the country. Dongas (the local term for gullies) cut through the landscape, giving it the appearance of a jigsaw puzzle. As a country with little natural resources, agriculture plays an important part in the country's economy. In 1999, 18% of the gross domestic product was contributed by agriculture. This is mostly practised on a subsistence level, by approximately 85% of the population which live in rural areas (Van Straaten, 2002).

This study investigates the extent of gully erosion in a sub-catchment in the Maphutseng valley of Lesotho. This valley lies in the Lowlands, the area of Lesotho with the highest population density, agricultural activity and level of soil erosion. Maphutseng is one of the areas in Lesotho which is the most degraded (Rydgren, 1990).

The choice of study site was made because Growing Nations, a missionary organisation, is in the process of starting an agricultural training centre there. The aim is to train trainers, coming from all over Lesotho, who would then go back to their homes and continue the training there. The curriculum is locally developed, but based on Farming Gods Way (www.farming-gods-way.org), a conservation agriculture method developed in Zimbabwe especially for small scale farmers (August Basson, personal communication).

The aims of the study are:

1. To establish the main variables which control erosion in this sub-catchment.
2. To determine to what extent certain soil properties contribute to the soils' erodibility in this sub-catchment.
3. To identify soil properties whereby areas of unstable and stable soils can be delineated. This property needs to be easily identifiable in the field.

The first Chapter is a literature review on geomorphological investigations into gully erosion and soil erosion parameters discussed in this thesis. It also includes a section on research on soil properties that has been done in Lesotho.

Chapter 2 introduces the study site, and discusses the intrinsic variables contributing to the erodibility of the area. It also outlines the history of soil erosion in Lesotho and explains the effects that extrinsic variables have had on soil erosion.

In Chapter 3 the spatial variability of the gully features in the sub-catchment is investigated, to identify the main factors controlling gully erosion in this sub-catchment.

Chapter 4 analyses the soil properties and their influence on soil erosion. As the effect of soil properties on aggregate stability and dispersion are often masked by each other, no strong correlation between any one soil property and dispersion could be seen. Thus segmented quantile regression was used as the statistical means to do the analysis.

The conclusions drawn from the study, as well as suggestions for future research activities in this field have been included in Chapter 5. It also includes a section written in layman's terms on how to combat soil erosion. This was done in an effort to bridge the gap between scientists and the local farmers, who are in desperate need of the knowledge gained by research.

Various maps, soil profile descriptions, soil analytical data, laboratory methods, gully parameter data, statistical data and calculations referred to in the text but not directly involved in the discussions are attached as appendices.

CHAPTER 1: GULLY GEOMORPHOLOGY AND THE SOIL PROPERTIES AFFECTING IT

1.1. Geomorphological investigations into soil erosion

The geomorphology of gully erosion has been relatively well studied in Southern Africa (for instance: Faber and Imeson, 1982; Nordström, 1988; Shakesby and Whitlow, 1991; Garland and Broderick, 1992). Gully formation, growth and shape are usually correlated with different landscape parameters such as relief, climate, vegetation, and anthropogenic factors. Soils are included in some studies (Nordström, 1988; Rydgren, 1993) but usually only on a basic level. The focus of these studies vary but normally lead to conclusions concerning the gullies' origin, the processes active in the gully, the factors driving the active processes, and the period of the erosion cycle which the gully is in.

Beckedahl *et al*. (1988, p. 251) stated that "*soil systems in the Southern African region exist as thresholds within finely balanced states of dynamic equilibrium*." Rao (1980, p. 179) defined a threshold as "*the point where a stimulus initiates a response*." Soil erosion research abounds with threshold values for various factors including slope gradients, rainfall intensities, and soil properties (for instance: Patton and Schumm, 1975; D'Huyvetter and Laker, 1985; Rydgren, 1990; Bloem and Laker, 1994).

Concerning gully erosion a systemic threshold rather than a single factor threshold is often applicable; meaning that all the factors affecting gully erosion hold the system close to equilibrium. When this equilibrium is disturbed, a response which might be gullying, is induced which will operate until the system is in relative equilibrium again. Various factors can contribute to the system approaching equilibrium and even a seemingly insignificant change in the system can be responsible for the threshold to be crossed. Nordström (1988) applied this approach to gully erosion in Lesotho. Kakembo (1997) postulated that the rapid formation of gullies in the Peddie district during the mid 1950's to mid 1970's occurred due to a chain of events which probably started around the early 1900's, implying a systemic threshold being reached to induce gully erosion. The chain of events included land use changes, wet and dry cycles, and decreasing vegetative cover.

The crossing of thresholds causes erosion to occur in cycles, where periods of relative equilibrium will be interrupted by periods of instability, leading to erosion or deposition (Nordström, 1988). Shakesby and Whitlow (1991) studied gullies showing signs of an erosion cycle with the following steps: (1) infill, (2) comparative stability, and (3) past gully entrenchment. Blong (1970) described a similar erosion cycle.

Evidence for cyclic erosion have been reported by De Villiers (1965) who studied pediment surfaces which have been alternatively subjected to erosion and aggregation by soil creep periods. Furthermore in Zimbabwe, Shakesby and Whitlow (1991) found that sediment in a gully there was probably deposited in the eighteenth and nineteenth centuries.

According to Nordström (1988) a gully system is nearing the end of the current erosion cycle if there is a steep slope above the gully heads, a large percentage of gully heads have extended unto bedrock, the system has a low extension/expansion ratio, there is a sharp decline in erosion rate, there is a decline in the absolute number of discontinuous gullies, and there is a predominance of rectangular cross sections in the gully

Garland and Broderick (1992) found the extent of erosion in the Tugela catchment to be shrinking, which could mean that the current erosion cycle is nearing its end. According to Garland *et al*. (2000) the deepening of gullies is not mentioned in the South African literature. In fact, some gullies studied are becoming shallower due to the accumulation of sediment. He concluded that this implies that many gullies have attained a base line, which could mean that in general South Africa is entering the period of infilling and deposition in the natural cycle of erosion, although different parts of the country may be at different stages.

Nordström (1988) showed in her study that different catchments, although having the same climate, can be in vastly different stages of the erosion cycle. The results from the study by Firth and Whitlow (1991) support this finding. In a study of three different areas in communal lands on different parent materials in Zimbabwe they found that these areas had vastly different gully densities, ranging between 230 and 1556 m/km^2. The gully growth for nine selected gully headcuts selected from these areas ranged between 1.5 and 12.3 m/year.

The processes active in the gully can be different to the ones which initiated the gully. It is important to know which processes are dominant in a gully system as it will determine which measures for reclamation should be taken.

The drainage pattern of a gully system often shows which patterns are responsible for the formation of the gullies. When surface runoff is responsible for the gully, bedrock properties and topographical conditions normally determine the pattern of the gullies (Nordström, 1988). Hanvey *et al*. (1991) studied two gullies that developed from surface runoff in the confluence zone of incipient drainage lines.

Human induced gullies often show which factor initiated its growth, for example when a gully runs along a cattle track or contour bank (Nordström, 1988).

Where cracking soils lead to piping which eventually forms gullies, the gully pattern shows the system of cracks wherein the pipes developed. Then the drainage pattern tends to be more trellised or rectangular in shape (Nordström, 1988).

Nordström (1988) found piping to be present in all the catchments she studied. Piping is an indicator of dispersive soils and accumulation of free water in the subsoil, as these are some of the prerequisites for piping to occur. The other prerequisite is that the accumulated free water must have an outlet to flow to (Fletcher and Carroll, 1948; Thornes, 1980). Thus piping often causes tributary gullies after a main gully has formed, as the main gully provides an outlet for the accumulated free water.

According to Nordström (1988) Leopoldt and Miller (1956)[1] classified gullies as being continuous or discontinuous. Continuous gullies form part of a drainage network and normally extends upslope from the main gully and can form because of surface runoff. Discontinuous gullies can start anywhere in the landscape as a headcut. Discontinuous gullies can become continuous gullies as they extend into the drainage network. For this reason, a decline in discontinuous gullies shows that the gully system is nearing the end of the erosion cycle (Nordström, 1988). Often discontinuous gullies are linked to the main gully by piping. These will be classified as continuous gullies once the pipe roof caves in.

Generally gullies classified according to their cross section are classified as either V or U shaped (Nordström, 1988). Rowntree (1991) found V-shaped gullies to be cut into host material which encourages runoff and U shaped gullies entrenched in host material prone to mass instability, piping, and undercutting.

In the present study it was observed that different sidewalls of the gully could have different shapes. This especially happens at a bend in the gully, where one side is being undercut forming a U shaped side, whereas the other side will then form a V-shaped side.

Faber and Imeson (1982) mentioned that gullies in Lesotho can be classified according to the mechanism of their formation. They made a distinction between gullies caused by runoff and gullies formed by piping through subsurface flow. Imeson and Kwaad (1980) included type of runoff initiating the gully into their gully classification system.

The factors affecting gully erosion have been determined by mapping the erosion extent and the different factors (for instance slope, geology, soils, etc.). By superimposing a map of the gully extent onto the maps of different soil erosion factors, it can be seen which map units of the factors correlate the best with soil

[1] Leopoldt, L.B. & Miller, J.P., 1956. Ephemeral streams – hydraulic factors and their relation to the drainage net. U.S. Geol. Survey Professional Paper 282-A, 37p.

erosion. These factors are thought to have the biggest controlling influence on gully formation in the area. Kakembo (1997) used this method in the Peddie district of the former Ciskei and concluded that the causative factors of gully erosion there was a complex interaction between anthropogenic and physical variables.

Some researchers divide the area they work on into grid squares and assign a value for each factor on each grid square. This enables a statistical analysis of the data. Using this method, Weaver (1989) found that rainfall, soils, geology, veld type, and presence and absence of forest were the most important variables to be incorporated into a model used to explain the spatial variation in soil erosion. Nordström (1988) concluded that due to the complex nature of soil erosion one factor alone would not cause the crossing of an erosion threshold, but it is rather the combined effects of different factors which causes sudden soil erosion.

1.2. The effect of soil properties on erosion

Soil properties determine soil erosion in two ways, namely by its influence on the runoff and its aggregate stability.

1.2.1. Influence on runoff

Water infiltration rates into the soil and the soil's water holding capacity are the two factors controlling a soil's influence on runoff. To ensure zero runoff, the infiltration rate of water into the soil must be higher than the water addition rate by rainfall and run-on on the soil surface. When the water addition rate exceeds infiltration rates, runoff will occur which can cause soil erosion. On steeper slopes both the amount and kinetic energy of runoff will be higher than on gentler slopes (Van Deventer *et al.*, 2002), because of less time for the added water to infiltrate into the soil. High intensity rain also allows little time for water infiltration and the high intensity thunderstorms which falls over most of Southern Africa is thought to contribute greatly to the erosion problem in the region (Laker, 2004).

Soil texture, the tendency of the soil to crust and the soil water content during a rainstorm influences the infiltrability of a soil. Water infiltrates quickly into coarse textured soils, but only a little water can be retained in the soil. When the soil has reached saturation, the rest of the water will run off. Fine textured soils can hold much more water, but the infiltration rate is lower. The soil water content during a rain storm determines how much water it could still hold. Runoff would be induced sooner on soils which are near water holding capacity.

In duplex[1] soils the water infiltration rate is governed by the low infiltration rates of the B horizon, rather than the faster infiltration rate of the A horizon. During a rainfall event, water will quickly infiltrate into the

[1] Soils with a relatively permeable topsoil abruptly overlying a very slowly permeable diagnostic horizon which is not a hardpan (Soil Classification Working Group, 1991)

A and E horizon, but not into the B horizon. Thus a perched water table will form in the E horizon. When the water saturation level reaches the soil surface, infiltration excess is reached and runoff will start. Probably a bigger problem on duplex soils is the lateral subsurface flow at the contact zone between the E and B horizons. It is known that the formation of soil pipes often starts here (Rooyani, 1985). When soils are dispersive, this effect is aggravated.

Mills *et al*. (2006) showed that the dispersive particle size smaller than 0.1 mm determines the susceptibility of a soil to crusting. Dispersion is caused either by physical raindrop impact or by chemical mechanisms, where the clay platelets develop a similar charge which repels each other. The dispersed particles are then moved along with water until the soil pores they move into become too small and clog the pores. Thus a crust forms (Medinsky, 2007). Crusting significantly reduces the infiltrability of a soil (Hillel, 1980, p. 112).

1.2.2. Aggregate stability

Aggregate stability is the second soil property which influences soil erosion. When a soil has stable aggregates its erodibility will be small. Tisdall and Oades (1982) suggested that an aggregate hierarchy exists where micro aggregates (<2 µm) consisting of clay platelets and organic molecules bind together to form micro aggregates (<250 µm) which in turn bond to form macro aggregates (>250 µm). The micro aggregates are stabilised against disruption by several mechanisms wherein organo-mineral complexes play a central role. In further studies it was revealed that aggregate hierarchy exists in soils where organic matter is the main stabilising agent of the aggregates (Oades and Waters, 1991). In oxisols where oxides are the main stabilising agents, aggregate hierarchy does not exist. When an aggregate breaks up into silt and clay particles, no aggregate hierarchy exists (Oades and Waters, 1991).

According to Amézketa (1999) the literature suggests that structural breakdown starts when macro aggregates disintegrate into micro aggregates. Dexter (1988), however, stated that when the lowest order of soil structure is destroyed, the larger hierarchical orders are simultaneously destroyed. The ultimate example of this is clay dispersion.

Dispersion is a time dependent chemical process (Amézketa, 1999), where there has to be sufficient water soil contact for a sufficient amount of time. Watts *et al*. (1996) found the critical amount of water needed for dispersion to be close to the plasticity limit.

There are several ways in which aggregate stability can be tested. These different methods resulted because of the different sizes of aggregates, different ways of disruption, and methodical reasons (Amézketa, 1999). This creates difficulties when results from different trials are compared to each other and also when aggregate stability is correlated with soil erodibility or crusting (Amézketa, 1999).

The most widely used parameter to describe the stability of macro aggregates is "Water Stable Aggregates" (WSA; Amézketa, 1999). This is tested by wet sieving with a method that is normally based on the one reported by Kemper and Rosenau (1986), although different methods abound at virtually every step (Amézketa, 1999). According to Truman *et al.* (1990) this test imitates the slaking forces exerted on a soil by flowing water. Thus it is expected that when runoff is the main initiator of erosion that the %WSA will correlate well with erodibility.

The stability of micro aggregates is quantified by dispersion tests. Again numerous tests exist. Rienks *et al.* (2000) used the air-to-water permeability ratio (AWR), the Emerson or crumb test and dispersion index with the double pipette method as indices of soil dispersibility. They found that the dispersion index had weak correlations with the AWR and Emerson test, whereas the AWR and Emerson test had no significant correlation. They concluded therefore that unknown factors which influence dispersibility must be influencing the results of at least one of the tests. It is known that the Emerson test does not necessarily show a positive result when a dispersive soil is tested (Marius de Wet, Department of Civil Engineering, Stellenbosch University, 2009 personal communication).

The soil properties influencing dispersion are the organic carbon (OC) content of the soil, the amount of "free" Fe and Al present in the soil, the relative ratio of basic cations on the exchange sites, the CEC, the dominant clay minerals, and the electrical conductivity (EC) and pH of the soil solution (Amézketa, 1999; Rienks *et al*., 2000; Laker, 2004; Bronick and Lal, 2005).

There exists some controversy about the role of OC in dispersibility. Goldberg *et al.* (1988) found OC to be negatively correlated with soil dispersion. Heil and Sposito (1993a; 1993b) account this effect to the blocking of positively charged clay mineral edges by negatively charged organic carbon, the complexation of polyvalent cations by OM and overlap of adsorbed organic polymer layers causing steric repulsion. However, according to Amézketa (1999), Czyż *et al.* (2002)[1] reported that the content of readily-dispersible clay is smaller when the OC content of the soil is greater.

Various reasons for these anomalies exist. WSA have been found to be stabilized by OC (Tisdall and Oades, 1982; Goldberg *et al.,* 1988). Organic bonds protect macro aggregates from disintegrating, but after these bonds have been broken OC will contribute to dispersion through electrostatic forces (Amézketa, 1999). Thus the stability of the organic bonds between macro aggregates will determine the correlation between OC and dispersion.

[1] Czyż, E.A., Dexter, A.R. & Terelak, H., 2002. Content of readily-dispersible clay in the arable layer of some Polish soils. p. 115–124. *In*: M. Pagliai & R. Jones (eds.). Sustainable land management. Environmental protection. Advanced Geoecology 35.

It is also the disposition of the OM which is important in aggregate stabilisation (Tisdall and Oades, 1982). Dexter *et al*. (2008) found that readily dispersible clay correlates well with the portion of the clay fraction which is not complexed with organic matter. Furthermore they found that in France the fraction of complexed organic carbon (COC) correlates well with OC when there is little OC in the soil. When there are a lot of OC present COC correlates well with the clay fraction of the soil. The transition between OC and clay correlated OC in the study occurred at 2% OC.

Although oxisols do not form stable macro aggregates (Oades and Waters, 1991), there is good evidence that Fe and Al have a positive effect on micro aggregate stabilisation through cationic bridging and formation of organo-metallic compounds and gels (Amézketa, 1999; Bronick and Lal, 2005). Because of this it is generally accepted that red soils are more stable than non-red soils (Thompson, 1986; Smith, 1990; Van der Merwe *et al.*, 2001). This does not hold true for all circumstances. According to the TRACOR report (1984)[1], as quoted by Laker and Smith (2006), a red Sterkspruit soil, derived from mudstone of the Tarkastad subgroup, was found to be severely eroded.

The relative effect of Fe and Al is still disputed. Various authors (Frenkel and Shainberg, 1980; Keren and Singer, 1989) found Al polymers to be more stable than Fe polymers, although the opposite have also been reported (Shainberg *et al*., 1987).

Bivalent cations such as Ca^{2+} and Mg^{2+} can form bridges between clay particles and OM and thus improve soil structure (Bronick and Lal, 2005). Na^{+} on the other hand is a highly dispersive agent which directly enhances breakups of aggregates (Bronick and Lal, 2005). This led to the formation of two soil property parameters SAR and ESP, which shows the relative amount of Na^{+} to stabilising cations in the soil suspension and cation exchange positions respectively.

In pedology an ESP of 15 is used as the critical value above which a Natric horizon is defined in the Soil Taxonomy (Soil Survey Staff, 1999) and World Reference Base (WRB; IUSS Working Group WRB, 2007). Much lower ESP values have, however, been found to initiate dispersion of soils. Bloem and Laker (1994) found an ESP above 2% could be a causal factor of chemically dispersive soils, while D'Huyvetter and Laker (1985) found that erosion exceeded acceptable limits in some soils with an ESP value of 2.5%.

In the study by Van der Merwe *et al*. (2001) the most highly erodible soil had an ESP of only 0.12%, but it also lacked structure stabilising agents such as Fe and OM. The soil with the highest ESP (7.8%) studied

[1] TRACOR, 1984. Lubisi dam catchment area. A survey of the condition of the catchment, existing land use and recommendations to stabilize the area. Report of an investigation by J. Ellis-Jones and M.C. Laker. Tracor, Umtata.

was found to be "… *not necessarily erodible*." Thompson (1986) studied a highly weathered sesquioxidic soil which could not be dispersed even at an ESP of 40%.

This shows that other soil factors may strongly override the effect of ESP on dispersion. Levy (1988) grouped the soil he studied into three categories regarding ESP:

- Hardly affected
- Affected at high ESP levels only
- Affected at all ESP levels

Although Mg is a divalent cation, there are researchers who showed that high Mg levels can be detrimental to soil structure. Sumner (1957) found that the Ca:Mg ratio could be an indicator of erodibility, with low Ca:Mg values corresponding to higher erodibility, whereas in the study of Bloem and Laker (1994) a Ca:Mg ratio of less than one was one of the probable causal properties of dispersive soils. Yadav and Girdhar (1981) also found an increase in soil dispersibility when the soil was leached with decreasing Ca:Mg ratio water. The effect was more pronounced on non-calcareous soils and when the SAR of the leaching water was higher.

The effect of Mg has been ascribed to direct and indirect mechanisms. In the direct mechanism soils are more susceptible to dispersion when Mg occupies more of the cation exchange sites. This might be because of the smaller ionic radius and larger hydration number and ionic potential of Mg than Ca, which leads to a larger hydration shell and thus weaker bonds between the Mg ion and the clay particles (Zhang and Norton, 2002).

The indirect way in which Mg influences soil dispersibility is by allowing more Na to be adsorbed onto the exchange sites than when Ca is the complementary cation (Curtin *et al*., 1994). Thus it is Na which is responsible for the higher dispersion, but Mg facilitated the adsorption of Na on the exchange sites.

Nel (1989) warns that Mg will have a negative impact on the physical condition of the soil if:

- Interlayered silicates or illite is the dominant clay mineral
- The exchangeable Ca:Mg ratio is low
- There are no $CaCO_3$ concretions in the soil
- Fe or organic material has the most important influence on the stabilisation of soil aggregates

Ca^{2+} is regarded as a stable cation and adds to aggregate stability when added to a soil by replacing Na and Mg on exchange sites (Armstrong and Tanton, 1992). According to Hofmeister's lyotropic series the decreasing order of cations enhancing dispersion is $Ca^{2+} < Mg^{2+} < K^{+} < Na^{+}$ (Van Olphen, 1977).

It has been shown that CEC and specific surface area are related to stable aggregates (Dimoyiannis *et al.*, 1998). This will be the case where polyvalent cations act as bridges between negatively charged clay particles and organic molecules, thereby reducing the repulsive electrostatic forces between them (Bronick and Lal, 2005).

Levy (1988) found that a soil's susceptibility to dispersion and crusting decreases in the order of dominant clay mineral of smectite > illite > kaolinite. Frenkel *et al.* (1978) showed that adding a little (2%) smectite to a kaolinitic soil led to increased dispersion of the clay particles. This effect was not clear in Levy's experiment, although he stated that a little bit of smectite in a kaolinitic or illitic soil probably did impede the water movement through it. Stern (1990) investigated the effect of clay mineralogy on sheet erosion and found that "*smectite contaminated*" kaolinitic soils had final infiltration rates comparable to that of illitic soils, with pure kaolinitic soils' infiltration rates being about three times higher. Amorphous clay minerals, originating from volcanic rocks are very stable (Bronick and Lal, 2005). Even when it weathers, it forms 1:1 clay minerals or oxides, which are also very stable (Powers and Schlessinger, 2002).

Dispersion decreases when the EC of the soil solution increases (Amézketa, 1999), as there is a higher osmotic gradient causing cations to go into solution.

Dispersion increases as the soil pH increases (Amézketa, 1999), because the negative charge on the clay particles also increases. Calcareous soils have been found to be more stable than non-calcareous soils though (Yadav and Girdhar, 1981). In soils where pH dependent charge clay minerals are dominant, the pH at the point of zero charge is the pH where the least amount of dispersion will occur (McBride, 1994).

1.3. Soil erosion research in Lesotho

In spite of all the efforts to control erosion in Lesotho, very little has been done to understand the properties of the soils (Showers, 2005). Although the effect of soil properties on soil erosion is relatively well understood, it is also well known that in different situations different soil factors may cancel out each other's effect (Rienks *et al.*, 2000). Thus it is necessary to understand the interaction of different soil properties at the location where the gullying occurs.

Two scenarios show the need for a better understanding of the soil in Lesotho clearly. In the application of SLEMSA (Soil Loss Estimation Model for Southern Africa) to produce a soil erosion hazard map for Lesotho (Chakela and Stocking, 1988; Stocking *et al.*, 1988) the soils derived from basaltic parent material received a relatively low rating, indicating a relative high erodibility. This was partly responsible for the allocation of an extremely high erosion hazard rating to most of the highlands of Lesotho, and thus a relative low rating for the lowlands. Smith *et al.* (2000), in a study which included soil scientists, found the erodibilities of basalt derived soils to be very low to low.

The other scenario which showed the need for a deeper understanding of soil properties is quoted by Showers (2005, p. 278). Apparently there was a debate among Lesotho's technical advisors about the effect of trees on duplex soils. Some advisors actually reasoned that the tap root of the tree would be useful in breaking up the water impermeable layer. Of course the heavy clay which is responsible for the impermeable layer cannot be broken, as it just swells again the next time it becomes wet.

The first soil assessment in Lesotho was carried out by Carroll and Bascomb (1967), who mapped soil associations for the whole of Lesotho on a scale of 1:250 000. This map was followed by the "*Soils of Lesotho*" (Conservation Division, 1979), where different soils were described according to a Lesotho classification. According to Rydgren (1993), this was partly updated by Cauley (1986)[1] with the "*Benchmark soils of Lesotho.*"

A few catchment sized soil classification studies were also undertaken. According to Showers (2005), in one of them, Binnie and Partners (1972)[2] coined the term duplex soils. This term was used to describe a soil type with an abrupt textural change from a coarse textured topsoil to a fine textured subsoil. The Estcourt and Sterkspruit soil forms of the South African soil classification (Soil Classification Working Group, 1991) are duplex soils. According to the Lesotho classification (Conservation Division, 1979) the Ts'akholo, Maseru, Sephula and Patsa soil series are duplex soils.

Duplex soils are the soils on which most of the deep, wide, and active gullies in Lesotho have formed (Rooyani and Badamchian, 1986). These soils are prone to piping (Chakela, 1981). Rooyani (1985) studied the soil properties which influence this phenomenon. His focus was on the contact zone between the E and B horizons, as this seems to be the position where the piping initiates. Six striking differences between the E and B horizon were indentified, namely:

- An abrupt textural change occurs from sandy loam or loam to clay or clay loam.
- E horizons are bleached with no structural development, while the B horizons have well developed prismatic structure.
- The upper part of the B horizon has a low chroma and distinct mottles, signs of wet and dry cycles.
- The SAR values are significantly higher in the B horizons than in the E horizon. The (Mg+Na)/Ca values increase proportionally to the SAR values from the E to the B horizons and is below one in the B horizon.
- Less expandable clay minerals (kaolinite and illite) occur in the E horizon, while more expandable clay minerals (illite and smectite) dominate in the B horizon.

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[1] Cauley, M., 1986. Benchmark Soil of Lesotho – their classification, interpretation use and management. Office of Soil Survey, Conservation Division, Ministry of Agriculture, Maseru, Lesotho, 110 p.

[2] Binnie and partners, 1972. Lesotho, study on water resources development. Report No 3, soils. UNDP/IBRD. Lesotho.

- The B horizon possesses significant higher amounts of organic matter, "free" Fe and total Mn than the E horizon.

The soil properties which facilitate dispersion (higher SAR, more expandable clay minerals) seem to overwrite the stabilising soil properties (increase in organic matter and "free" Fe), leading to a dispersive soil.

Rooyani (1985) also postulated the following mechanism for piping formation in these duplex soils: because of the textural difference between the upper story (A and E horizons) and the lower story (B horizon) a capillary fringe is formed at the contact zone. This enhances the dispersive chemical reactions. The dispersive clay particles further clog the soil pores in the B horizon, which hinders downward water movement into the subsoil, which leaves the cracks at the upper part of the subsoil as the only place to accommodate excessive water. This allows the dispersed clay sized particles on the walls of these cracks to be removed, which leads to the deepening and widening of the cracks. Subsequently holes which form in this manner join to form a pipe. The direction of pipe development is governed by the slope aspect and gradient, as this controls the lateral subsurface water flow. The subsurface water flow eventually drains into existing gullies or onto bottomlands and depressions. Continuous wet and dry cycles repeat this process, whereby pipes grow until the roof eventually caves in and a gully is formed.

Furthermore Rooyani (1985) found that pipes formed on soils with an ESP of less that 15. Thus the criterion of an ESP of 15 to separate soils that have been adversely affected by excessive sodium cannot be generalised.

Other researchers who included soils in their studies include Majara (2005), who found that the land degradation between 1989 and 1999 was more closely related to the claypan soils than any other soil type. The claypan soils are the soil association according to Carroll and Bascomb (1967) which includes the duplex soils.

Rydgren (1993) grouped the soils from the same sub-catchment as this study into five different soil types. Not all of these soil types could be classified according to the Lesotho classification system. A discussion on these soil types is included in Chapter 3. He furthermore compared runoff and soil loss from plots for three of these soil groups. These three soils constitute a reddish soil, with a loam to sandy loam topsoil texture, becoming finer with depth (red Valsrivier), a soil of varying colour with a topsoil texture of sandy loam to sandy clay, also becoming finer with depth (Valsrivier), and a duplex soil (Estcourt). The names in brackets show the closest resemblance to the South African classification (Soil Classification Working Group, 1991). The South African soil form names will be used in the discussion of these results.

Surprisingly the soil loss data showed that the red Valsrivier soil lost more than twice the average amount of soil than the Estcourt and Valsrivier soils. Rydgren (1993) explained this by the fact that the plots were too small for gullies to develop and the high erodibility of duplex soils are connected to their extreme potential for gullying.

Rooyani and Badamchian (1986) included an estimation of the soils' erodibilities (K-value) according to the USLE monograph, which was first published in the "*Benchmark soils of Lesotho*" (Cauley, 1986). In it the highest K-value is 0.6 for the Patsa and Maseru soils. The other duplex soils K-values are Sephula – 0.58, and Ts'akholo - 0.39.

No reference of a verification of these values could be found. This needs to be done as the USLE predicts soil loss due to sheet erosion and not due to gully erosion. Imeson and Kwaad (1980) stress that the soil properties defining soil erodibility in relation to sheet erosion may be different from the soil properties influencing gully soil erodibility. Thus these values may be misleading for the most eroded areas of Lesotho.

1.4. Conclusions

Gully formation is a cyclic process controlled by systemic thresholds. Even small changes in factors controlling gully erosion can push the system though a threshold and induce rapid gullying. Gullies in the same climatic region can be in vastly different stages of the erosion cycle. Certain gully parameters, such as drainage pattern, shape of the cross section, and whether or not piping is present can hint at how the gully had formed. Gullies can form either by runoff, or by subsurface flow.

Geomorphic investigations into the spatial distribution of gullies and soil erosion factors can show which factors exerts the largest amount of control over gullying in a specific area.

Soil properties influence erosion by its effect on infiltration and aggregate stability. Aggregate stability can be measured on different size scales. Disruption of the smallest aggregates will lead to the disruption of bigger aggregates. Clay dispersion is the ultimate example of this. The size of the stable aggregates which correlate to erosion shows by which mechanism gullies form. A correlation between WSA and gully erosion indicated that the gullies formed by runoff, whereas when dispersion correlates well with gully density, piping is implicated. Several soil properties influence aggregate stability. These factors often cancel out each other's effect and the controlling soil property may be different in different locations.

Very little research has been done in Lesotho on the soil properties controlling soil erosion. Where research has been done, the focus was on soil classification and the properties of duplex soils. A better understanding of the effect of soil properties on erosion is needed to effectively combat erosion.

CHAPTER 2: UNDERSTANDING SOIL EROSION IN THE MAPHUTSENG VALLEY

2.1. Site description and intrinsic variables of the Maphutseng valley

In the following section, the research site is described and the intrinsic erosion variables affecting soil erosion of the Lowlands will be discussed. As Maphutseng lies in the Lowlands, this is also applicable to Maphutseng. Special reference to the study area is made in the case of certain variables.

2.1.1. Location of the Maphutseng valley

The study site is located in the Maphutseng valley of the Mohale's Hoek region of Lesotho. It lies in the Lowlands of Lesotho, which is one of Lesotho's four geomorphic regions, namely the Lowlands, the Senqu River Valley, the Footslopes and the Highlands (Rooyani and Badamchian, 1986). A map of the geomorphic regions is attached in Appendix 1.1. Most of Lesotho's arable land lies in the Lowlands, a relatively flat area, which makes it possible for cultivation to take place. However, this is also the area with the highest population density and extent of soil erosion (Showers, 1989).

The geographical centre point of the study site is: S 30.20°; E 27.48°. It stretches from the top of Thaba Linoha in the north at the highest point (2044 m) to the Maphutšeng River (1420 m) in the south. Its position on a map of Southern Africa is shown in Figure 2.1.

2.1.2. Intrinsic erosion variables

2.1.2.1. Rainfall

According to Laker (2004) the only rainfall parameter used in the prediction of water erosion is rainfall erosivity. Stocking *et al*. (1988) defines rainfall erosivity as: "… *the potential power of rain to cause erosion through the double effect of raindrop splash detaching soil particles and the total amount of rainfall plus its intensity supplying water to overland flow to transport soil particles*." This is a function of the amount of rain, the rainfall intensity, the raindrop's size, shape, and terminal velocity, and the wind speed (Gerrard, 1981; D'Huyvetter and Laker, 1985; Laker, 2004).

The rainfall erosivity in Southern Africa is low according to world standards (Garland, 1995), as the annual rainfall is comparatively low. However, the intensive thunderstorm type rain that is the main type of rain in Lesotho is believed to contribute a lot to the erosion problem (Laker, 2004). The sporadic nature of the rain, with heavy torrential rainstorms following prolonged droughts, is also a major contributor, as this allows for rain to fall on bare, unprotected soil (Weaver, 1989; Laker, 2004).

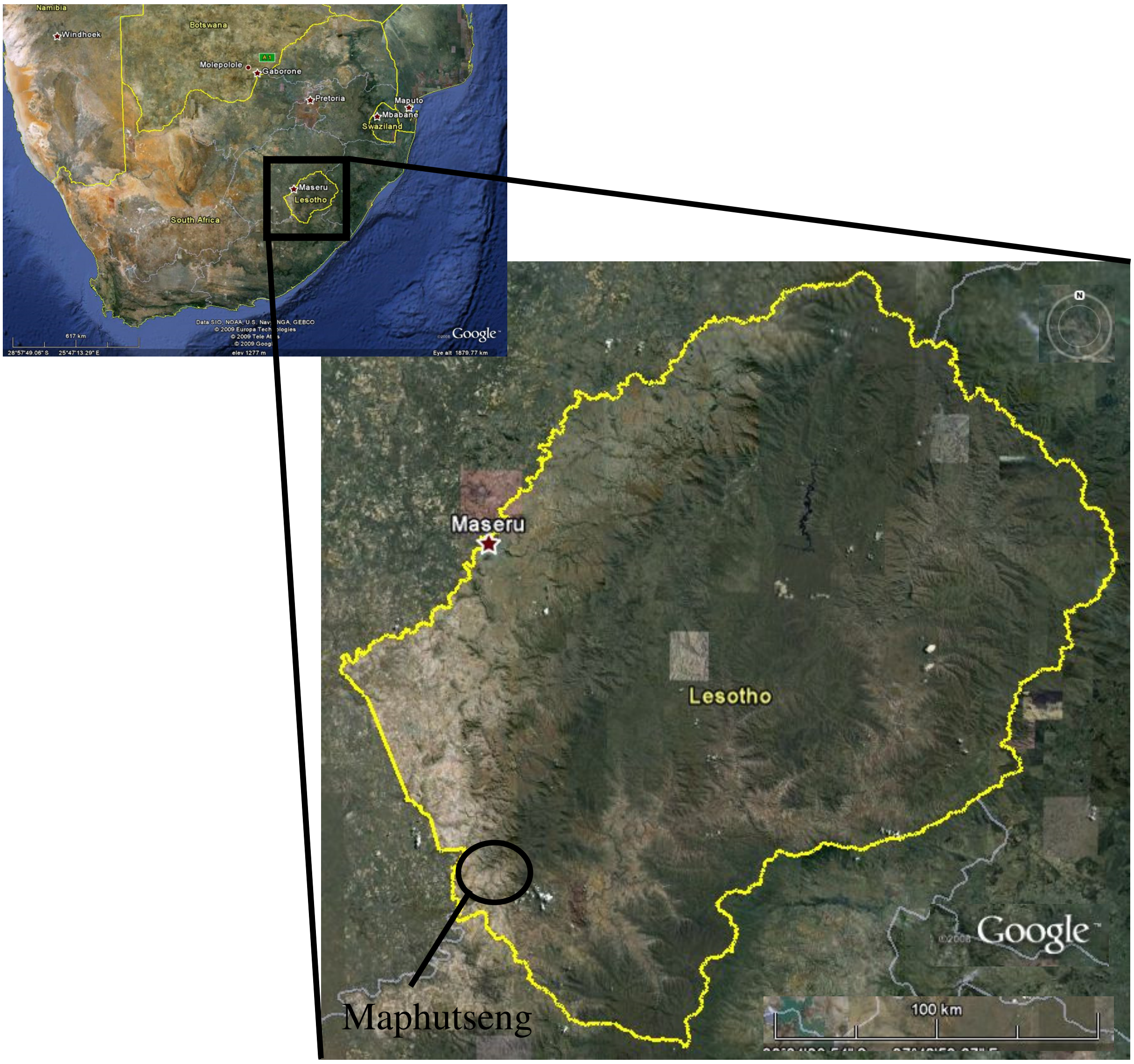

Figure 2.1: The Maphutseng Valley in relation to Southern Africa and Lesotho. (Google Earth, accessed 2009-04-02)

The mean annual precipitation measured at the Mohale's Hoek weather station is 740 mm. Mohale's Hoek lies approximately 5 km north of the study area and is the closest weather station to Maphutseng. Rainfall varies considerably with seasons, with the bulk of the rain falling during the summer months i.e. October to April. The highest average monthly rainfall occurs in February (111 mm) and the lowest in July (12 mm). The dominant rainfall type is intensive thunderstorms. The rainfall also varies a lot between years.

Figures 2.2 and 2.3 show the respective average and annual monthly rainfall measured at Mohale's Hoek weather station. Although there is a 16-20 year yearly rainfall cycle (Nordström, 1988; Rydgren, 1993), both Kakembo (1997) and Nordström (1988) stated that the monthly rainfall peaks are better than annual rainfall to show the occurrence of extreme rainfall events.

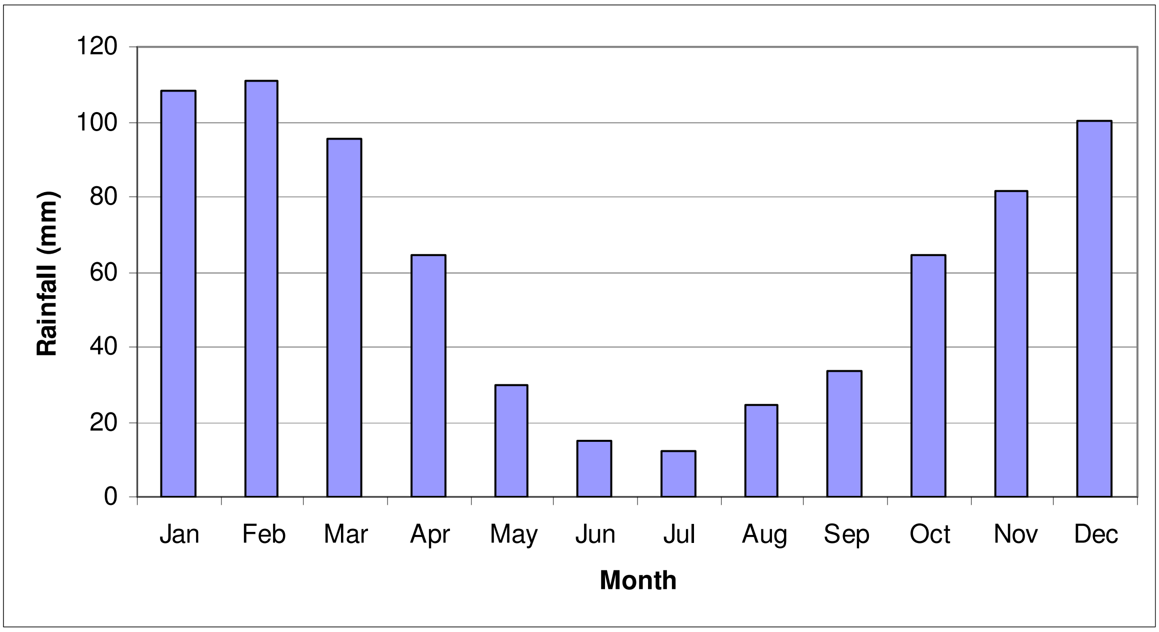

Figure 2.2: Average monthly rainfall for Mohale's Hoek for the years 1938-2008 (Adapted from data provided by the Lesotho meteorological service)

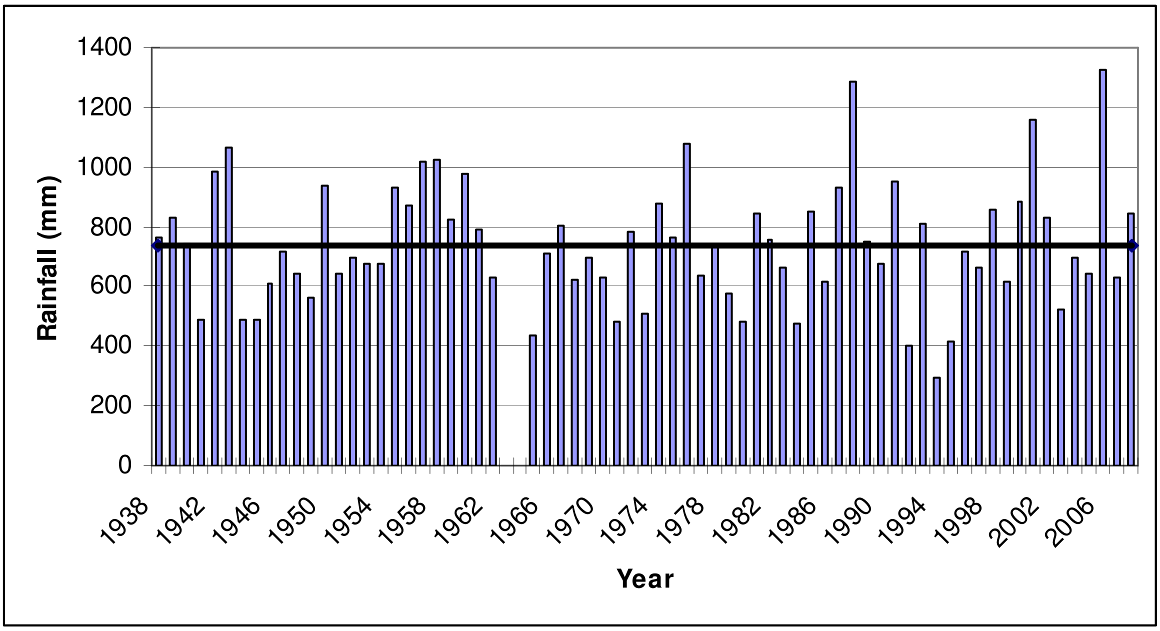

Figure 2.3: Annual rainfall for Mohale's Hoek for the years 1938-2008 (Adapted from data provided by the Lesotho meteorological service). The black line shows the average annual rainfall for this time. No data is available for 1963 and 1964.

What is striking from both graphs is the big variability in the data. Figure 2.2 shows clearly that the bulk of the rain falls in summer, which means that every year the area goes through a dry-wet cycle. Between 1950 and 1980 Nordström (1988) identified 14 erosive rainfall events from the Mohale's Hoek weather station based on monthly rainfall data. These are events where an extraordinary wet month followed a time of below average rainfall months, based on the average for each month.

Rydgren (1993) found that in terms of erosion, no such thing as a normal rainfall year exists in Maphutseng. Any year, wet or dry, could be catastrophic or insignificant depending on the extreme events occurring in that year. The extreme event impact is clearly shown by the following findings of his study: during three rainy seasons (1988-1991), he recorded 60 runoff events. One of these events was responsible for 25%, and three runoff events for 47% of the total soil loss.

Furthermore, Rydgren (1993) stated that the rainfall in Maphutseng is significantly lower than in Mohale's Hoek. He based this statement on comparisons between the Mohale's Hoek weather station and a four year rainfall record from Maphutseng which was kept during his study, local opinion, and vegetation growth. Thus any erosion predictions for soil loss in Maphutseng based on the rainfall record for Mohale's Hoek seem dubious.

2.1.2.2. Relief

Relief influences soil erosion in two ways; directly with slope which determines where and at what speed runoff water would accumulate, and indirectly as a soil formation factor, having a major influence on the type of soil that form and thus its erodibility.

Runoff increases proportionally to the increase in the steepness and length of the slope (Rooyani and Badamchian, 1986). Chakela and Stocking (1988) found that 80% of the area of Lesotho has an average slope of above 20%. Smith *et al*. (2000) found that with no vegetation cover, the long, steep slopes of the Lesotho Highlands rendered the land susceptible to erosion.

However, the gullies are concentrated more in the Lowlands, where slopes are not so long and steep. This correlates with the findings of Liggitt (1988), who found that slope gradient and gully frequency have an inverse relationship.

The most important reason for this is that less steep slopes are areas of sediment accumulation and restricted drainage. Deep, unstable soils tend to develop here (Laker, 2004). Add to this an accumulation of runoff water from the upper slopes, bare soils left by cultivation, and overgrazing on what is often the more nutritious feed and we have the ideal setting for gully erosion (Liggitt and Fincham, 1989; Laker, 2004; Laker and Smith, 2006). This can occur because of the shearing strength of the runoff water, or by piping when a perched water table accumulates in the subsoil.

Slope shape and aspect have indirect effects on soil erosion. The slope shape determines whether runoff water will be diverged or concentrated, while the aspect influences the vegetation cover. In the Highlands, Smith *et al*. (2000) found north facing slopes to be warmer and under higher grazing pressure, to have less plant available water and to receive more light than south facing slopes. This results in less vegetative cover on the north facing slopes, leading to more erosion.

The study site encompasses a steep concave south facing slope. The slope gradient reaches approximately 50° in the highest parts of the mountain included in the study site. This creates the ideal circumstances for runoff water to accumulate.

2.1.2.3. Vegetation

Stocking *et al*. (1988) rates vegetation as: "*... arguably the most important factor in the erosion process in Southern Africa.*" They state this because not only is it the best way of curbing erosion (Laker, 2004), but it is also the soil erosion factor which is the easiest to be manipulated by man (Stocking *et al*., 1988). The natural vegetation of Lesotho is grassland (Acocks, 1975), which is the best vegetation cover in terms of soil protection (Snyman, 1999). However, the natural vegetation has been altered to a large extent due to cultivation and overgrazing.

Mucina and Rutherford (2006) produced a map of the vegetation for South Africa, Lesotho, and Swaziland. According to this map the natural vegetation types that occur in Maphutseng are Zastron Moist Grassland (Gm1), Senqu Montane Shrubland (Gm2) and Western Lesotho Basalt Shrubland (Gd9) (Mucina and Rutherford, 2006). This vegetation map is shown in Appendix 1.2. In Maphutseng, most of the natural vegetation has been replaced by cultivation, leaving soil bare for most of the year.

2.1.2.4. Soils

According to the soil associations map of Carroll and Bascomb (1967) the dominant soil type in the Maphutseng valley is the claypan soils of the Maseru set, with small areas of fersiallitic soils, fersiallitic soils changing to claypan soils and vertisols in topographic depressions. On the outskirts of the valley, where the slopes are steeper, lithosols can be found, both on lava and on sedimentary rocks. In small areas these lithosols are on rocks rich in ferromagnesian minerals.

The following soils occur in the study site: Lithosols on lava (basalt of the Lesotho formation) can be found around Thaba Linoha. The Clarens formation is overlain with lithosols on sedimentary rocks (sandstone). Along the Maphutseng River lies vertisols of the topographic depression. The rest of the area consists of claypan soils of the Maseru set, with a small area of fersiallitic soils.

Rydgren (1986) included a soil map for this area at a larger scale than the one of Carroll and Bascomb (1967) in his publication. According to this map the soils found in the study site are mostly Ts'akholo, Patsa, and Leribe soils, with Basalt and Sandstone Rockland occurring where these different rock types are overlain with shallow soils. There is also a considerable area of gullied land and colluvial soils (Appendix 1.3).

A detailed description of these soils is given by the Conservation Division (1979). As mentioned in Chapter 1, the Ts'akholo and Patsa soils are duplex soils. The difference between them is the topsoil texture and soil colour. Leribe soils are reddish soils. The soil resembling the red Valsrivier soil in the study by Rydgren (1993) is a Leribe soil. Basalt- and Sandstone Rockland soils are shallow soils which are named for the rocks on which they occur. Gullied land is classified on the gully features rather than the soils. These gullies cut through soils which are mostly of the Ts'akholo and Patsa series. Colluvial soils usually occupy sloping to steep areas at the base of sandstone escarpments, where sandstone soil materials which have fallen from the escarpments had mixed with Red Bed sediments which had accumulated at the escarpment's base.

2.1.2.5. Geology

Geologically the study site encompasses four different formations. These are the Lesotho (basalt), Clarens (cave sandstone), Elliott (mudstone red beds and sandstone) and Molteno (shale, mudstone, sandstone) formations. Major rock types are named in brackets. Dolerite dykes can be found on the outskirts of the study site. Various fractures also cross through the area (Directorate of Overseas Surveys, 1981).

As mentioned before, Smith *et al*. (2000) found soils developed from basalt in the Highlands to be stable. In contrast to this Laker and Smith (2006) mentions that soils developed from the red beds of the Elliott formation are highly erodible.

2.2. Extrinsic variables

Strömquist (1990) stated that the severe land degradation in Lesotho is most probably caused by historical changes of land use and a concentration and increase in population density. A case for this is to be made when a borderline comparison is made between the Lowlands of Lesotho and South Africa, where the intrinsic variables are much the same, but an obvious difference in land degradation can be seen (as can be seen in Figure 2.1, p. 16).

To understand the effect of extrinsic variables, a short erosion history of Lesotho is first given to understand how the extrinsic variables change with time. Afterwards the ways in which these changes influenced soil erosion will be discussed.

2.2.1. A brief soil erosion history of Lesotho

Soil erosion in Lesotho is not a recent phenomenon. According to Showers (1989), who made an account of the gullying history in Lesotho from personal correspondence of the first missionaries and European travellers in the then called Basutoland, crevices or ravines did exist in the early 1830's. These gullies were not the dominant landscape features. However, accounts of accelerated erosion and gully formation became more numerous from this time onwards (Showers, 1989).

Signs of accelerated gullying which started around the mid 1800's include gullies which had developed along roads and on some mission stations by the 1880's, apparent gully erosion on government reserves by the 1890's, and that gullies had become the main landscape features in areas where missionaries frequently travelled (Showers, 1989).

Three events happened around this time which all had a profound influence on soil erosion in Lesotho, namely: the introduction of the plough as cultivation tool, the fixation of the border of Lesotho in 1869 and an increase in demand for grain in South Africa from the European Settlers (Casalis, 1861; Nordström, 1988; Showers, 1989; 2005).

With the fixation of the border in 1869, the Basotho lost a great deal of its arable land. The Caledon River, which now is the border of Lesotho, had previously been the middle of the valley wherein they dwelt. In return for this the Basotho received the mountainous area to the east of the Caledon River. This area is largely uninhabitable, due to steep slopes and a harsh climate. This, together with immigration from South Africa resulted in a population concentration in what today is known as the Lowlands of Lesotho (Showers, 2005).

Despite a healthy agricultural sector, (Lesotho was a net exporter of wheat until 1920) in the first decades of the 20th century reports of eroded land became more frequent, with most of the gullied areas being associated with pediment slopes and hills (Showers, 1989).

At this time the animal population in Lesotho peaked. After the rinderpest and droughts of 1886-1887, the animal population was drastically reduced. However, this led to the introduction of veterinary services, and the animal population increased strongly until it peaked in 1930. The great drought (1930's) was responsible for a large decrease in animal numbers. The animal population has not yet returned to the 1930 level (Nordström, 1988). According to Nordström, (1988) Tiedeman (1983)[1] suggested that the veld was so degenerated by overstocking by this time that a new, lower stocking equilibrium had been reached.

Sir Alan Pim compiled a report on the economic position of Basutoland for the British Government. In it he stated that approximately 10% of the arable land of Basutoland was threatened by soil erosion. No gullies were observed in the mountains. He also recommended that a soil protection scheme should be adopted in the areas under threat of soil erosion (Pim, 1935).

This resulted in the first official nation wide anti-erosion campaign, which took the form of the building of contours throughout the lowlands of Lesotho, from 1937 to 1950. These structures were built by the authorities with little involvement by the farming communities (Chakela, 1999). By 1954, 80% of the lowlands and all sloping land in the foothills were protected by contours or grass strips and buffer strips were established in the mountains (Nordström, 1988). The maintenance of these anti-erosion structures was left to the farmers (Chakela, 1999).

Between 1950 and 1966 a village based approach was applied to conservation, wherein an agro ecological plan for the whole country was drawn up. It is uncertain whether this plan was ever implemented. Various pilot projects were launched during this time, none of which led to wider implementation (Chakela, 1999).

Since 1966 an integrated approach to soil conservation was followed which involved village committees. Again the focus was on the building of structures, which had to be done by machines, to minimize the labour requirement (Chakela, 1999).

Tree planting was also a way that the government tried to combat soil erosion. According to Nordström (1988), Powell and Wellings (1983)[2] reported that 40-60 million trees were planted in Lesotho between 1936 and 1972. There does not seem to be any effect of it though. Potter (1982[3], quoted by Nordström, 1988) mentioned that only 1% of Lesotho's area is planted with woodlots and natural groves. The tree species planted included: *Pinus*, *Cupressus*, *Populus* and *Eucalyptus* (Nordström, 1988).

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[1] Tiedeman, J.A., 1983. Range Research and Development in Lesotho – an End of Tour Report, August 1979- October 1983. Agricultural Research Technical Information Report RD-R-34. Research Division, Ministry of Agriculture, Maseru, Lesotho, 53 p.

[2] Powell, P. I. & Wellings, P.A., 1983. The Lesotho woodlot project: progress problems and prospects. Development Studies Southern Africa, Vol. 5, 350-370, Benso, Pretoria.

[3] Potter, R.V., 1982. History of Tree Growth in Lesotho. Presented to Forestry Training Course for CA's and ACO's, August 30- September 3, 1982, Maseru, Lesotho, 7 p.

Since the 1990's the focus has shifted again, this time addressing the problem from the farmers' point of view. The idea is to increase production through conservation (Chakela, 1999).

Unfortunately the effectiveness of these programs have not been assessed (Showers, 1989) and in spite of all that effort the erosion just escalated. The 10% of arable land which was threatened by erosion in 1935 (Pim, 1935), now seems to be a small percentage. In the agricultural census of 1960, 8.8% of the arable land of Lesotho was deemed to be severely and 25.5% slightly affected by gully erosion (Mojorele, 1963[1], quoted by Nordström, 1988). By 1986, an erosion map of the Lesotho lowlands produced by Strömquist *et al*. (1986) showed practically all of the Lowlands to be moderately or severely affected by erosion. Only small pockets of areas were only slightly affected. Majara (2005) using 1989 and 1999 Landsat satellite images showed that 28% of the land in the Lowlands had degraded between 1989 and 1999. This was calculated by subtracting the respective (Normalised Difference Vegetation Index) NDVI values from 1989 from those of 1999. Negative values showed degradation. This value should even be higher, as 1999 was a wetter year than 1989. This shows that despite all the efforts to curb soil erosion, the problem is escalating.

2.2.2. Effect of land use and population density changes

The plough dramatically changed the way of cultivation by the Basotho. Before this, cultivation was done with hoes and the plant material was left on the soil surface. Planting of crops, of which sorghum was the main type, occurred by the broadcasting of seed, which led to a good ground cover. Fields were also rotated between cropping and grassland. A broad buffer strip of grassland surrounded each field (Casalis, 1861; Showers, 1989).

Germond (1967, p. 72) mentions that cultivated slopes remained relatively intact before the advent of the plough. Ploughing induces erosion when the ploughing is not done exactly on the contour. Even a small deviation can initiate the creation of a rill which can lead to the formation of a gully. Even when done on the contour, the increased infiltration may cause subsurface flow and piping on piping prone soils. The formation of a plough pan at the plough depth can create a water impenetrable layer, leading to lateral subsurface flow where piping may occur. The plough also allowed a larger area to be cultivated (Nordström, 1988). Other than leaving the soil bare, ploughing is also responsible for a rapid decline in organic matter, an agent of soil stability (Mills and Fey, 2003). The positive effect on soil erosion of maintaining a crop residue cover on the field has been shown by various authors (Mallett *et al*., 1981; Lang and Mallett, 1984)

[1] Mojorele, C.M.H., 1963. 1960: Agricultural census Basutoland. Part 5: Land classification and farming practises. Agricultural Department, Maseru, Lesotho, 64p.

The population density increase in the last half of the 1800's meant that land was not freely available anymore. This, together with a greater demand for grain and the usage of the plough meant that areas previously left to grazing was now cultivated. This off course led to more grazing pressure on the areas left to grassland. The crop rotation system was also abandoned (Nordström, 1988; Showers, 1989).

Fields also tended to be smaller. Smaller fields mean more grass strips around fields, which are conducive to erosion, especially when they run across the contour. Even if the grass cover is well maintained, water tends to converge at the border between the grass strip and the field, creating concentrated flow which could lead to rills and then gullies (Nordström, 1988). Rydgren (1993) found that the main contributor to soil loss is concentrated runoff, as it has a greater shearing strength and a higher sediment transport capacity.

A higher population density also meant more roads and paths, which were more frequently travelled. Foot paths are known to often be the starting point of gully formation (Laker and Smith, 2006). Concerning drainage, roads were exceptionally badly built in Lesotho at that time. The drainage water was either concentrated next to the road or onto an open field, in both places leading to gully formation (Pim, 1935; Showers, 1989).

The rapid increase in animal numbers in the first decades of the 19th century, together with the decreasing size of grazing land must have led to overgrazing. The negative effect of overgrazing to land degradation is well known (Snyman, 1999; Boardman *et al.*, 2003).

Showers (2005) argues that the contours built by the British Government accelerated rather than contained erosion. The study by Nordström (1988) provides evidence for this claim. She found that between 12% and 59% of gullies in the eight catchments she studied had been initiated or the growth thereof accelerated by contours.

Contours may initiate gullies in a variety of ways. When the contour wall is not high enough to contain the runoff, it will flow over the contour, causing waterfall erosion on the down slope side of the contour wall, which will lead to the breaking of the wall (Nordström, 1988). A contour wall which allows water to converge, rather than to diverge, will also lead to a break in the contour wall. The entire terracing system of a farmland can be destroyed as the result of a single broken contour wall (Schmitz and Rooyani, 1987). A lack of maintenance on contour walls also leads to their demise. Chakela (1999) mentioned that the lack of maintenance of contours was still a problem in 1997. Little has changed since then.

Even if a contour is well built, it may cause gullies by the concentration of the runoff water along the contour (Showers, 2005). On dispersible soils, piping may occur due to the higher water infiltration along

the contour (Nordström, 1988). Beckedahl and De Villiers (2000) studied a case where a road culvert caused such increased infiltration, which led to the formation of pipes and ultimately gullies.
The planting of trees did not help either. The first reason is that trees do not generally grow in Lesotho (Showers, 1989), which accounts for the little success rate in establishing trees.

Secondly trees are not the best type of vegetation to combat erosion. Kulander (1986) studied sediment transport under different vegetation types on duplex soils in the Thaba Bosiu area of Lesotho. She found that the maximum sediment concentration under grassland was 2.32 g/l, 9.38 g/l under Pine trees and 51.3 g/l under Eucalyptus trees. Thus the trees had a much worse effect on soil loss than the grass. Soil loss was measured as mass of sediment per volume of overland flow. The reason for the great extent of soil loss on the Eucalyptus site could be ascribed to the lack of a protective field layer of vegetation (Strömquist, 1990). Rydgren (1993) observed that only plant cover which covers the soil surface effectively protects the soil from soil loss.

Thirdly, on piping prone soils tree root enhanced water infiltration may lead to the formation of gullies through piping. Old trees growing in sinkholes, observed by Nordström (1988) give evidence to this statement.

Often the traditional land tenure system in rural African areas is given as a reason for the observed accelerated erosion in these areas (Laker and Smith, 2006). According to Rydgren (1993) the land tenure laws of Lesotho was laid down in "The Laws of Lerotholi" in the early part of the 20th century. It stated that every married man who was a member of a village should be granted one residential plot to build the family home. Three fields were also added to this for cultivation (Rydgren, 1993). The three fields were scattered around the village to ensure an equal share of fertile land and to protect farmers against pests and hail. Fields could be taken away when left fallow for two years or when a farmer produced more than his household needed (Nordström, 1988).

The grazing lands of the village was open to anyone but was managed by the village chief and his range riders (Rydgren, 1993). In the summer, animals were sent to pastures in the mountains (Wellings, 1986[1], as quoted by Nordström, 1988). In winter the animals were brought back to the village and agricultural land reverted back to grazing land. This did not allow farmers to implement different management systems such as cultivated fodder (Rydgren, 1993).

[1] Wellings, P., 1986. Lesotho: crisis and development in the rural sector. Geoforum 17 (2), 217-237.

In 1979 the government changed this system to one which allows for a 99-year lease of the land. However, by 1992 very few leases have been granted. The further one moves into the rural areas, the more the old system is still in place. Thus two land tenure systems are effectively in place (Rydgren, 1993).

It is argued that communal land degrades as no one looks after land of which the continued use is not guaranteed. Common grazing areas also tend to be overgrazed as it is in no one's interest to diminish their grazing stock as the feed they eat does not belong to anybody (Laker and Smith, 2006). Furthermore different management systems as the norm cannot be implemented by different farmers (Rydgren, 1993). Rees (1984) contends that the problem is much more complicated than this. According to him African subsistence farmers neglect soil conservation as they have limited resources. The resources that they have are used either for short term survival, or on things offering better returns, such as education.

2.2.3. Land use in the study site

The main land use on the study site is cultivation. All fields are contoured. Some of the fields have been abandoned in connection with soil erosion. Parts of two villages also lie on the sub-catchment. In the southern village there is a school, lying just outside the borders of the study site. This influences the study site though, because children from the Northern village commute daily to the school, leaving various tracks, which could lead to gullies. The areas too steep for cultivation are left under natural vegetation.

2.3. Conclusions

The intrinsic variables of the geomorphic system have rendered the Lowlands susceptible to erosion. Land use changes and population increases in this area starting from the mid 1800's, resulted in the widespread crossing of a geomorphic threshold leading to the severe land degradation observed today. Maphutseng, being part of this area, suffered the same fate.

CHAPTER 3: GEOMORPHOLOGICAL ANALYSIS OF GULLY EROSION IN A SUB-CATCHMENT OF THE MAPHUTSENG VALLEY

3.1. Introduction

Multiple studies of soil erosion have shown that gully formation is a complex, cyclic phenomenon, governed by localised thresholds influenced by intrinsic and extrinsic variables (Liggitt, 1988; Frith and Whitlow, 1991; Garland and Broderick, 1992). It is often difficult to identify the reason for the gully formation, as even a small change in any variable can push the geomorphological system through a threshold value, leading to the destabilisation of the system, which might lead to erosion. The mapping of the spatial variability of the gully extent and erosion factors is one way to try and determine the factors exerting the most control over gully formation (Nordström, 1988; Kakembo, 1997). In Lesotho though, very little of these studies include detail soil maps, which could mean that the effect of soil on gully formation is underestimated.

In this Chapter, the spatial extent of gullying is correlated with the spatial extent of different erosion factors. The first objective was to produce a soil map for the areas where the most gullying occurs, so that soils could be included into the geomorphological investigation. It is hypothesized that soil type will play a major role in controlling gully extent.

The main aims were to determine which factor exerts the largest control over the gullying process on the study site, which processes initiated the gullies, which processes are active and at what stage in the erosion cycle the different areas of the catchment is.

3.2. Material and methods

3.2.1. Soil map and map units

Soils were mapped for a part of the study site after doing a soil survey in November 2008. Sixty-two profile pits from across the study site were classified using the South African soil classification system (Soil Classification Working Group, 1991). The profile descriptions for the sixty-two profiles are shown in Appendix 2.2. Before classification the main landform, slope shape, the position in the landscape, aspect, land use, and plant growth (type and extent of ground cover) were noted according to the guidelines of the FAO (2006). Slope gradient was determined with an Abney level, and slope length to the end of the field or break in the slope (where the profile pit was not in a field) was visually estimated.

For each horizon the depth, wet and dry Munsell colours (Munsell, 2000) and soil structure were noted. Texture class, clay percentage, coarse fragments and sand grade were subjectively determined according to the FAO guidelines (FAO, 2006).

The degree of wetness was estimated on a scale of 1-10, with 10 showing wettest and 1 the driest soil profiles. Parent material was estimated according to the minimum data set for describing soil profiles of the ARC-ISCW Soil Survey Staff (2005). Where possible transitional soil forms existed, it was also noted.

Soil samples were taken from each horizon, from which pH in a 1:2.5 ratio to both water and 1M KCl solutions as well as EC in a 1:5 water extract were measured in the laboratory.

In April 2009 seventeen modal profiles were classified and sampled for laboratory analysis. These profiles were chosen to represent the main soil forms identified during the first soil survey. The analyses of these samples will be discussed in the next Chapter.

Soil map units were defined using soil information from the profiles described. A soil map unit represents a grouping of dominant similar soil forms that occur in a specific area and is associated with a specific parent material. Table 3.1 shows the soil map units. The mapping of soil map units was not done for the whole sub-catchment, but only for the area where the highest gully density occurred, to allow for more detailed mapping. ArcView 3.2 (Environmental Systems Research Institute Inc., 1996) was used to digitize the surveyed polygons.

The modal soil profiles are distinguished from the sixty–two survey profile pits by the numbering method. The modal profile pits are numbered with an M, while the survey profile pits are numbered with an L.

Table 3.1: Description of soil map units

Soil map unit	Parent material	Characteristic feature	Dominant soil forms
Basaltic	Basalt	Stable granular structure	Milkwood, Mispah
Sandstone	Sandstone	Shallow sandstone bedrock	Glenrosa, Mispah
Duplex	Unconsolidated material	Abrupt textural change between top and subsoil	Estcourt
Blocky	Unconsolidated material	Non-Red blocky B horizon	Valsrivier, Swartland, Sepane, Bonheim
Red Blocky	Unconsolidated material	Red blocky B horizon	Valsrivier, Swartland
Mudstone	Red Bed Mudstone	Steep slope, Mudstone	No soil forms described

3.2.2. Geomorphological investigation

The spatial relationships that exist in the study site were investigated using available aerial photographs (1957 and 2004), geological and topographic maps, a DEM with a 30m resolution (ASTER GDEM, undated, a product of METI and NASA) and Google Earth images. Appendix 1 includes the aerial photographs, geological map, and the DEM. All images were ortho-rectified using ENVI software (ITT Visual Information Solutions, 2008). Slight differences in the ortho rectification occur due to the different scales of the media.

The resolution of the two aerial photographs differs. The 1957 photograph has a scale of 1:36 000, which gives a pixel size of 2.8 X 3.2 m, while the scale is 1:50 000 with a corresponding pixel sixe of 4.2 X 4.8 m for the 2004 photograph. This was not seen as a problem as Google Earth could be used to help with the 2004 mapping. The Google Earth image for Maphutseng was also taken in 2004 with SPOT 5, which has a resolution of 2.5 X 2.5 m pixel size. (SPOT Image, 2007). Both photographs were taken in April and the Google Earth image in May.

3.2.2.1. Soil erosion factor maps

Four sub-catchments were delineated using the delineate catchment tool in ArcGIS 9.2. This included the study site as well as three other sub-catchments (sub-catchment 1 – sub-catchment 3) which appeared to have extensive gullying, in close proximity to the study site (Figure 3.8; p. 49).

For the study site, other erosion factors were also mapped. Slope was derived from the DEM with the relevant tool in ArcGIS 9.2 (Environmental Systems Research Institute Inc., 2009), geological information was extracted from the geological map, and the land use was mapped by hand as polygons in ArcView 3.2 from the aerial photographs. Tables 3.2, 3.3 and 3.4 describe the map units for the different erosion factors.

Table 3.2: Slope class map units

Slope class	Degrees	Percent
1	0-8	0-14
2	8-20	14-36
3	20-50	36-119

In Westernized countries, fields are normally cultivated up to 12% (7°) slopes, with areas of higher slopes being left to grazing land or woodlots. In small countries such as Lesotho, with very little level land, areas with slopes above 12% are also cultivated for food production (Rooyani and Badamchian, 1986). The 8° upper boundary for the first slope class was chosen as it closely corresponds to the slopes which are cultivated in the study site. The second slope class boundary (20°) was subjectively chosen to delineate steep from very steep slopes.

Table 3.3: Description of geological formations*

Formation	Rock types	Characteristic features
Lesotho	Basalt	Massive
Clarens	Sandstone	Cave sandstone White or yellow Fine grained
Elliott	Sandstone	Red and brown Feldspathic Fine and medium grained
	Mudstone	Light green, red and purple Sandy
Molteno	Sandstone	Yellow and white Coarse or fine grained
	Mudstone	Green, buff and purple

*Information obtained from Directorate of Overseas Surveys (1981)

Table 3.4: Description of land use map units

Map Unit	Description	Common features
Natural Vegetation	Not directly altered by man	Shrubs, grass
Village	Area around the place where people live	Houses, roads, paths, small fields
Cultivation	Fields cultivated for food production	Fields, contours
Abandoned Land	Former fields abandoned in connection with soil erosion	Gullies, broken contours, abandoned fields

The abandoned land area is an area where most of the fields have been abandoned in connection with soil erosion. Either the fields were abandoned due to soil erosion, or soil erosion has occurred because the fields had been abandoned. This question will be discussed later. Some fields in the cultivation area have been abandoned; however, this is due to social reasons and is not linked to soil erosion.

Soils, geology, and topography did not change in the time frame of this study, thus the same map was used for both the 1957 and 2004 gullies. The land use can change in this timeframe, but stayed largely the same. The villages became more densely populated and slightly bigger, and the abandoned land was cultivated in 1957. All the cultivated land had already been contoured in 1957, probably in the late 1930's (Showers, 2005).

A flow accumulation map was derived from the DEM, with the relevant tool in ArcGIS 9.2. This map shows the size of the area from where water will flow to a certain point. Thus the darker the colour of a pixel, the larger the area from where runoff will flow towards that pixel. The pixel size is 900m^2 (Figure 3.2; p. 37).

3.2.2.2. Gully parameters

The gully extent of the study site was mapped for 1957 and 2004 from the two aerial photographs and Google Earth images. This was done in ArcView 3.2, by drawing line features over the gullies observed on the aerial photographs. This method resembles the ones used by Nordström, (1988) and Kakembo, (1997). Nordström, however, did not have the use of GIS technology at that time.

It was noted whether the gully heads were continuous or discontinuous, if they had reached bedrock and what the slope was at the headcut. As discussed, Nordström (1988) used these parameters as indicators of the position in the erosion cycle that a landscape occurs. The slope was noted in classes, with each class representing 5°. Thus slope class 1 represents a slope of 0-5°, slope class 2 represents 5-10° etc. These classes differed from the slope classes for the slope factor map, as three classes are too broad to pick up differences in slopes above headcut.

For the other three catchments, mapping of the gullies was only carried out for 2004, as they do not appear on the 1957 photograph. The same headcut parameters were noted for the slope class of the headcut.

The gully densities for each map unit of the different erosion factors were calculated, as well as the gully head density, percentage discontinuous gully heads and percentage gully heads which have reached bedrock.

3.2.2.3. Sheet erosion

Sheet erosion was mapped for the study site as polygons in ArcView 3.2 from the 2004 aerial photograph, Google Earth, and field observation. The classification that Strömquist *et al.* (1986) modified from the

SARCCUS classification (SARCCUS, 1981) was used. Table 3.5 gives a description of the different sheet erosion classes. Because the field observation played a big role in the actual classification it was not done for the 1957 aerial photograph.

Table 3.5: Description of sheet erosion classes (Strömquist *et al*., 1986)

Sheet erosion Class	Definition	Descriptive attributes
1	Sheet erosion not visible on aerial photograph	Decent plant cover
2	Sheet erosion obvious on aerial photograph	Poor plant cover Extensive sediment deposits
3	Much or all topsoil removed	Gullies and rills

The same gully parameters that were determined for the erosion factors were determined for the sheet erosion classes.

3.3. Results and discussion

3.3.1. Soil map and map units

The soil map is shown in Figure 3.1. The map units correspond well with the five soil types Rydgren (1993) described in the same sub-catchment. The extent of these soil types was, however, not shown on a map. The reconnaissance map which he published (Rydgren, 1986) for a larger area which included this sub-catchment, differs quite a lot from the one produced here. Rydgren's (1986) map is given in Appendix 1.3.

In the following discussion of the soils, some of the laboratory analyses (Appendix 2.1.2.-2.1.6.) of these soils are included. The next Chapter deals with the laboratory analyses and example profile pits for each of these soil map units are included there (Table 4.2, p. 57-59), together with some of the soil properties.

Basaltic soils

The basaltic soils occur in the area covered by the Lesotho formation. They comprise of Milkwood and Mispah soil forms. The main difference between the two soil forms is the soil colour. Basaltic soils are shallow (<450 mm), sandy loam to loam soils. They tend to have dark colours and contain high levels of carbon. The pH is neutral to slightly basic (6.5-7.7). The aggregate structure is medium granular. Their aggregate stability is very high and they are non-dispersive. On the map of Rydgren (1986) this map unit corresponds to the basalt and sandstone rockland and lithosols. Rydgren (1993) did not investigate basaltic soils.

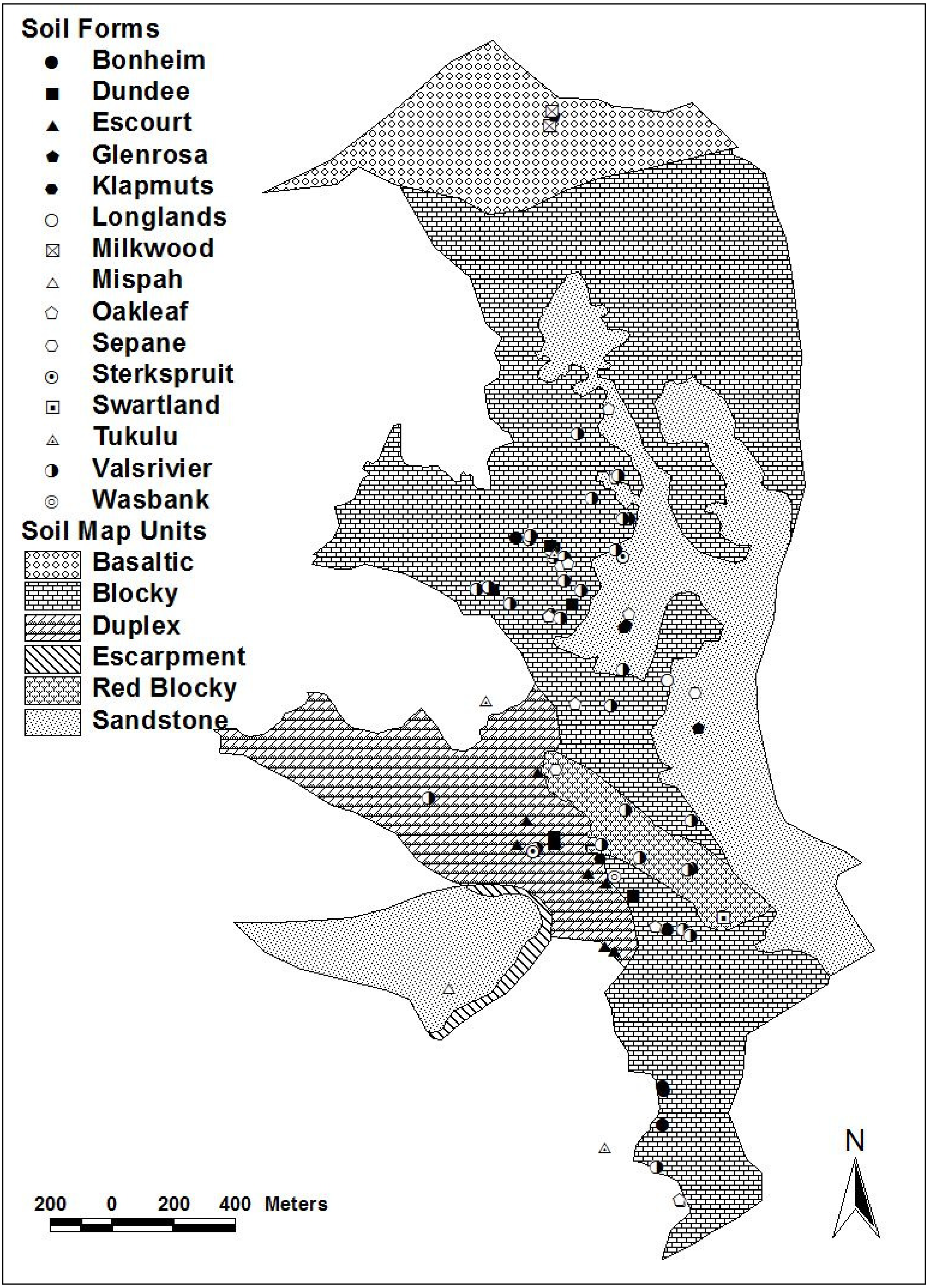

Figure 3.1: The soil map showing the profile pits, classification and soil map units

Sandstone soils

The sandstone soils occur on areas where the sandstone of the Elliott formation is quite shallow. The map unit includes Glenrosa, Oakleaf and Mispah soil forms. They are acidic (pH 5.5), shallow (up to 700 mm) soils with a topsoil texture of sandy loam, with slightly more clay in the deeper horizons. The soil colour varies from red or yellow to greyish. The structure is normally weak fine subangular. They have an average dispersibility and aggregate stability.

The sandstone soil map unit corresponds with the soil type 1 of Rydgren (1993), which was classified as the Ntsi soil series in the Lesotho soil classification system. The area occupied by the sandstone soils matches the area shown as the Patsa and Ts'akholo with patches of Leribe soil units on the map published in Rydgren (1986). The Patsa and Ts'akholo series are considered to be duplex soils. Rydgren (1986) however stresses that this map is only preliminary, "*made by airphoto interpretation and field control*". This could be the reason for the discrepancy between the two maps, as the sandstone soils appears as light shades of grey on the aerial photographs. This could have been mistaken for the sandy topsoil of a duplex soil.

Duplex soils

The duplex soils are mostly Estcourt form soils with some areas of Valsrivier and Sepane forms in between. The topsoil is bleached, with a sandy loam or loamy sand texture. Although the E horizon clearly shows signs of clay eluviation, in some profiles the E horizon has a finer texture than the A horizon. A statistical analysis of the particle size fractions confirmed that there is a lithological discontinuity between these profiles A and E horizons. The author suspects that the original A horizon has been eroded away and the new A horizon is formed from windblown sand deposits. There is an abrupt transition between the E and B horizons. The prismacutanic B horizon has a texture that varies between sandy clay loam and clay. Its colour also varies from grey to red, and mottles are common. The pH of the soil tends to hover around neutral (6-8). The structure of the upper layer (A and E horizons) is either subangular or apedal, whereas the B horizon structure is prismatic or coarse blocky. The upper layer has a very low %WSA, but in the lower layer, the %WSA is relatively high. All the soil horizons are dispersible though, except for some red B horizons which are stabilized by Fe oxides. Piping occurs on the area covered by the duplex soils.

The duplex soil map unit corresponds to the duplex soil type described by Rydgren (1993) and to the area covered by gullied land on the map in Rydgren (1986). This fits well with the current map, as the area covered by duplex soils is highly gullied.

Red Blocky soils

The red blocky map unit covers the area where red Valsrivier soils are the dominant soil form. The topsoil texture is loamy sand to loam and it becomes finer with depth, leading to a clay loam or clay subsoil. As the name implies the subsoil colour is red, although bleached A horizons are common. The soil is moderately acidic (pH 5.9-6.4). The structure of the topsoil is weak fine subangular blocky and of the subsoil is moderate coarse blocky. The %WSA of the subsoils tend to be high, but this is not the case for the A horizons. The soils are mostly non-dispersive, but some topsoils are exceptions to this rule.

This soil unit corresponds to the soil type 2 from Rydgren (1993), which resembles the Berea and Rama soil series of the Lesotho classification. On the map in Rydgren (1986), the area covered by red blocky soils is also shown as Patsa or Ts'akholo with patches of Leribe soils. The Leribe soil series is a reddish coloured soil which will fit into the red blocky map unit.

Blocky soils

The blocky soils include blocky subsoils with melanic and orthic A horizons. Although it was expected that the difference in topsoil would influence the soils' erodibility, no distinction between these two diagnostic horizons were made on the map, for reasons which will shortly be discussed.

The Bonheim soils, which have a melanic A horizon on a pedocutanic B horizon, are clayey with a slightly acidic to slightly basic pH which increases with depth (topsoils: 6.0-6.7; subsoils: 6.5-7.8). The soil colour is dark, although mottles may occur due to some water logging in the deeper layers below the B horizon. Structure is moderate fine to coarse blocky. These soils are stable with a high percentage of water stable aggregates (%WSA) and relatively low dispersibility.

Rydgren (1993) described a soil type 4, which has the same properties as this soil. It has features of both the Maseru (dark variant) and Pechela soil series of the Lesotho soil classification. He concluded that this soil has a strong tendency to form gullies, as they occur around the drainage ways where gullies develop. Another reason for their close relationship with gullies could be that they develop from basaltic parent material, which washes down from the mountain in these drainage channels. Thus they are found around gullies, not because of their instability, but rather because of the parent material in which they develop. One might argue that the basaltic material cannot be stable as they have moved downslope. However, the laboratory results confirm that these soils have stable aggregates. They also occur on very steep slopes (up to 50°), on which it is expected that material will move down slope.

The high correlation between the melanic blocky soils and gullies is partly the reason why these soils were not mapped as a separate unit, as it would mislead the spatial variability investigation as to which soils are the most conducive to gullying. The other reason is the small area which these soils occupy, which makes it difficult to map. This is probably why they do not appear on the soil map in Rydgren (1986).

The blocky soils with the orthic A horizon are the most common soil form in this sub-catchment. The topsoil texture varies between sandy loam and silty clay loam, which becomes finer to clay loam with depth. Soil forms occurring on this map unit are Valsrivier, Swartland, and Sepane. In some soils the clayey subsoil can be quite deep, with the development of an AB horizon in between the A and the pedocutanic B horizon. Strictly speaking, the soils with the AB horizons are classified as Oakleaf form soils, however, they still fit in well with the blocky soils as described here. The pH of these soils is moderately acid to slightly basic (5.9-7.6). The colour of the topsoil varies between bleached and dark, but does not become dark enough to be a melanic A. The B horizons are dark. The structure of the topsoil is weak fine subangular to moderate coarse blocky and the B horizon is moderate fine to coarse blocky. There is variation in the %WSA of the A horizons, ranging from very low to moderately high. The B horizons have high %WSA values. The dispersibility of the A and B horizons of these soils tend to be below average.

Soil type 3 of Rydgren (1993) largely corresponds to this soil map unit. Rydgren (1993) could find no series in the Lesotho classification for this soil type. This shows one flaw in the Lesotho soil classification. It allows for soils with fine structure and for duplex soils, leaving soils with intermediate structure and texture to be fitted into series where they do not belong. On the map in Rydgren (1986), these soils are classified as Ts'akholo with patches of Leribe soils.

Mudstone

The mudstone soil map unit does not represent a specific soil, but a bare area where the mudstone occurs at the surface. It is included on the soil map for completeness sake. The area where it occurs is an escarpment of a 30 m drop over a horizontal distance of 20 m. It is too small for gullies to develop on and thus will not be discussed any further.

3.3.2. Geomorphological investigation

3.3.2.1. Flow accumulation

The flow accumulation map for the study site is shown in Figure 3.2. The legend shows the area size in hectares from which flow will accumulate. Most of the large gullies follow the natural drainage lines. This suggests that the large gullies in this area have formed by accumulation of overland flow.

There are some areas where the gullies do not follow the flow accumulation paths. The reason for this is uncertain. In some parts the gullies run along a border where the sandstone and mudstone rocks of the Elliott formation meet. This could indicate an old drainage path being followed rather than the flow paths determined from the topography of today. Once a gully is formed, it cuts off the runoff water that would have ended up in another flow path. A situation like this was noticed by Faber and Imeson (1982) who measured runoff from gullies near Roma in Lesotho. Water flow from one gully did not contribute much to the overall runoff as the growth of another gully intercepted the runoff which would normally have ended up in the first gully.

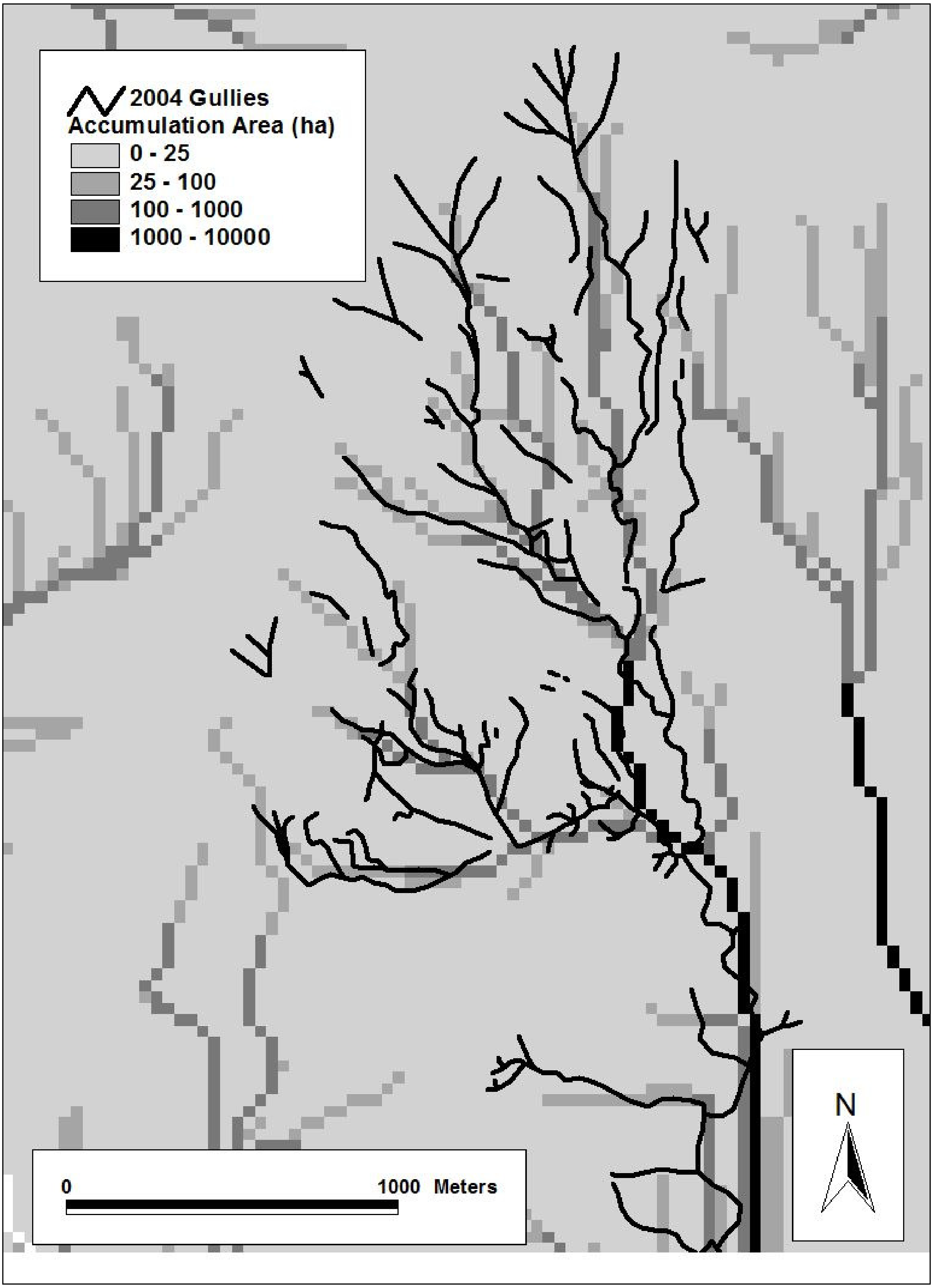

Figure 3.2: The flow accumulation for the study site, showing the 2004 gullies

No signs of piping were observed in the areas where the runoff deviated from the flow paths. Also, as will be seen in the next Chapter, the soils that occur around these areas (blocky, red blocky, and sandstone) are not considered dispersive. Thus, it is safe to assume that the main gullies formed because of overland flow.

On the area covered by duplex soils smaller tributary gullies do not follow the flow accumulation paths. Most of these gullies appeared after 1957. Some of the new gullies follow old foot paths. The duplex soils are dispersive (see next Chapter) and signs of piping occur there.

3.3.2.2. Gully parameters

Figure 3.3 shows the gully density on the areas occupied by various soil erosion factors. These values are very high and show how heavily eroded the study site is. Only the lowest gully density, 1.4 km/km^2 on the sandstone soil map unit is comparable to the highest gully density recorded by Frith and Whitlow (1991). The gully densities of the area they studied ranged between 0.23 and 1.6 km/km^2. The average gully density for the whole sub-catchment in 2004 was 6.4 km/km^2, which is four times as high as the highest from Frith and Whitlow (1991).

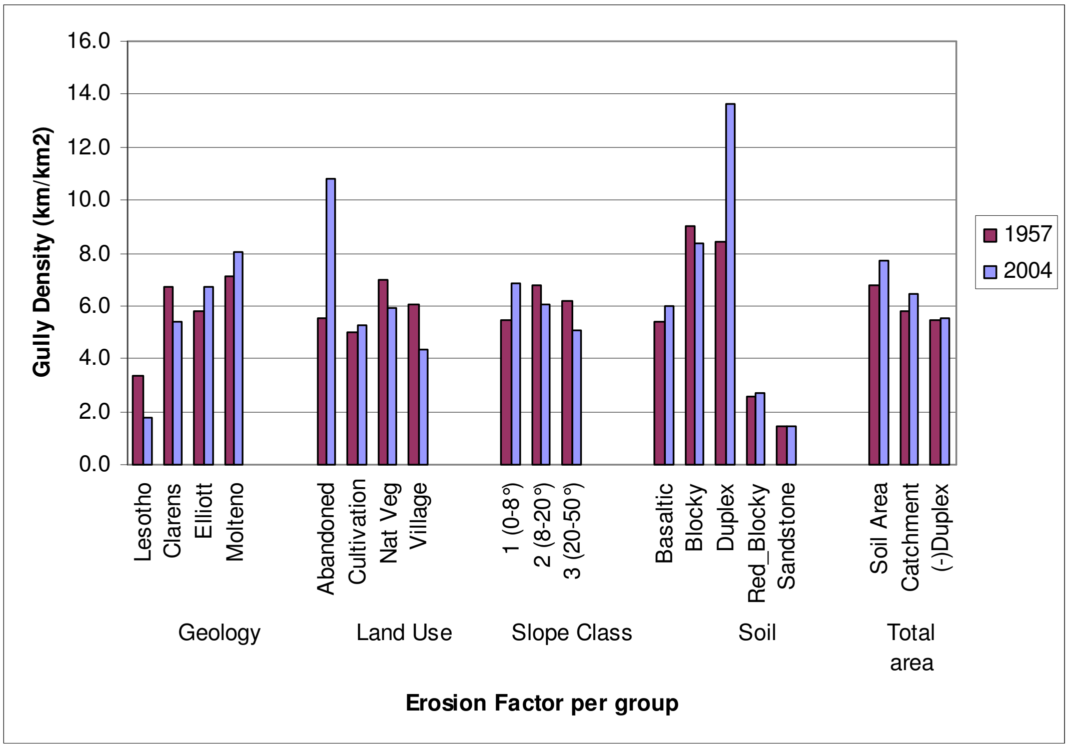

Figure 3.3: Gully density in 1957 and 2004 for the areas covered by various erosion factors

Included on the graphs is an area labelled the (-) Duplex. This represents the data for the whole catchment without the duplex soil area. These values will form part of the discussions later on.

Soil map units

Figure 3.3 also displays the large variability between the gully densities of the different areas of the soil map units. The highest and lowest gully density occurs on the areas covered by different soil map units. This shows that of all the erosion factors, the gully density is best linked to the soils, which means that somehow the soils of the study site exert a controlling effect on gully formation.

For 1957, the gully density of the different soil map units decreases in the order of blocky (9 km/km^2), duplex (8.4 km/km^2), basaltic (5.4 km/km^2), red blocky (2.5 km/km^2), and sandstone (1.5 km/km^2). This is somewhat surprising as it was expected that the highest gully erosion would be on the duplex soils. When one turns the attention to the 2004 data, another picture emerges though. The gully densities on the soil map units are then in the order from high to low: duplex (13.6 km/km^2), blocky (8.4 km/km^2), basaltic (6.0 km/km^2), red blocky (2.7 km/km^2), and sandstone (1.4 km/km^2).

This indicates a large amount of gully extension on the duplex soil area between 1957 and 2004. Figure 3.4, which shows the gully extension for the different factors, confirms this. The extension on the duplex soils was 5.2 km/km^2, or 111 m/km^2/year, which is much higher than the 86 m/km^2/year of the Maseru 2 catchment, which had the highest extension rate of the eight catchments studied by Nordström (1988).

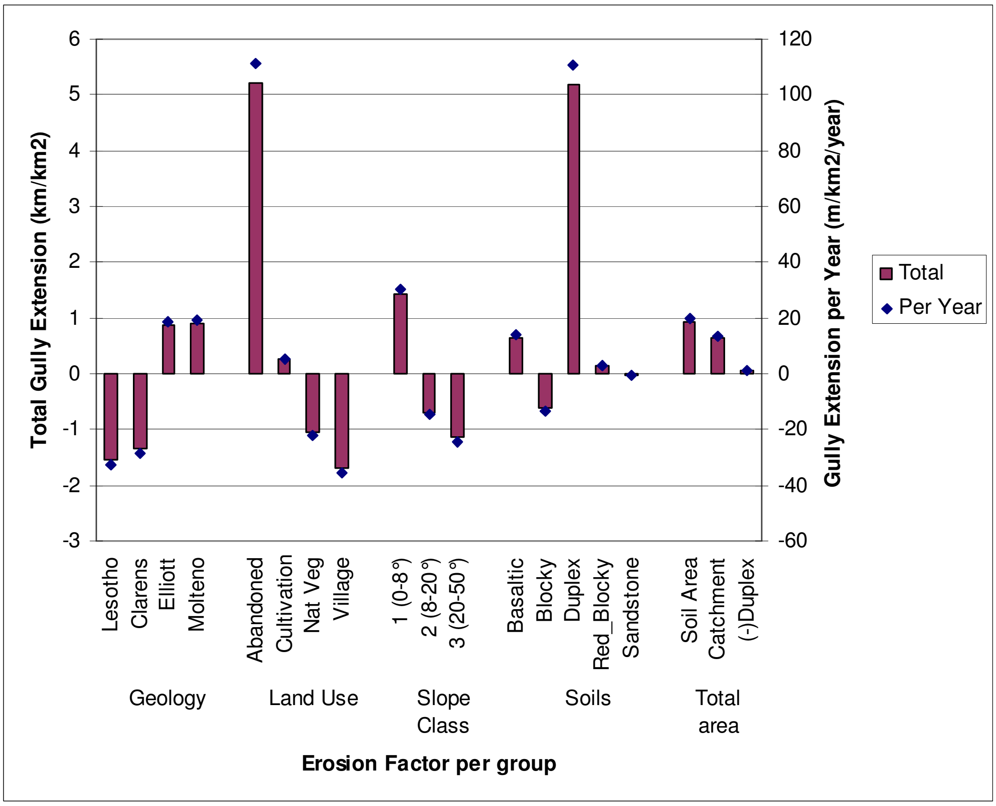

Figure 3.4: Gully extension between 1957 and 2004 for the areas represented by various erosion factors

One has to keep in mind though that the gully densities Nordström (1988) reported was for the whole catchment, which will include areas of rapid extension as well as relative stable areas. The extension rate for the whole catchment in this study is only 13.4 m/km^2/year and 19.5 m/km^2/year for the area covered by the soil map.

Nordström, (1988) measured the extension rates in different time spans of 11, 18, and 30 years. Both the highest and lowest extension rates were found in the shortest time span, which shows the erratic nature of soil erosion. The longer the time span the more the extension rates are averaged. This means that the maximum extension rate is higher than that which was measured. In this study the time span quite long at 47 years, making it inaccurate to compare it to studies with a relative short time span.

Interestingly, the gully density on the blocky and sandstone soils decreased. There are some 1957 gullies which filled-in by 2004. These are mostly found on the upper slopes, around the northern village. No conclusions can be drawn as to why these gullies stabilised, although it seems that in some of them it is due to the establishment of vegetation. There have been land reclamation projects operating in this area (Rydgren, 1993). The filled-in gullies could be due to a positive effect of these projects.

The reasonably high gully density on the basaltic soils was not expected, as the soils are reported to be stable (Smith *et al*., 2000). However, these soils occur on very steep slopes, (up to 50°), which will produce a lot of runoff. Thus, although the soils are stable, the runoff is just so much that gullies develop in any case. There was only a slight increase in gully density between 1957 and 2004, showing that the gully system on the basaltic soils is reasonably stable.

Figure 3.5 shows the gully head density for the various erosion factors in 1957 and 2004. The gully head parameters for the soil map units, the area covered on the soils map and the whole catchment is shown in Figure 3.6. Table 3.6 shows the average slope class above the gully heads for the different soil map units. As there are no relevant gully heads on the sandstone and red blocky soil map units, these are not shown on either Figure 3.6 or Table 3.6.

The gully head density in 1957 for the soils varies between 0 and 28 heads/km (basaltic). This is in accordance with the findings of Nordström (1988), where the gully head density varied between 4 and 32 heads/km in the eight catchments studied.

The gully head density in the duplex soil area increased tremendously and in 2004 it was 63 heads/km. The discontinuous gully heads, however, comprised only 7.7% of these gully heads, which means that the newly formed gullies were mostly tributaries of the main gullies. Piping does occur in the duplex soil area, which makes the low percentage of discontinuous gully heads somewhat surprising, as discontinuous gullies often form through pipes that only partially cave in. This indicates that the gullying cycle is nearing its end, even on the duplex soils, as in a mature gully system the discontinuous gullies have extended into each other to form a continuous gully system (Nordström, 1988).

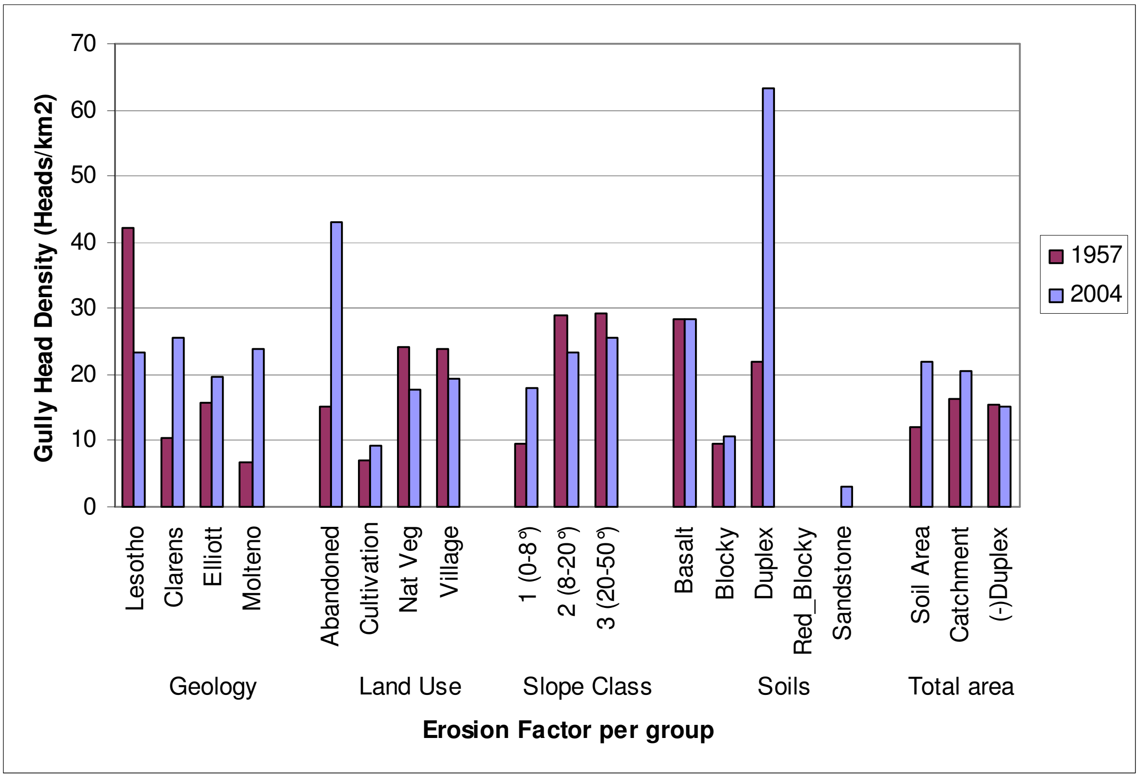

Figure 3.5: Gully head densities for the different erosion factors

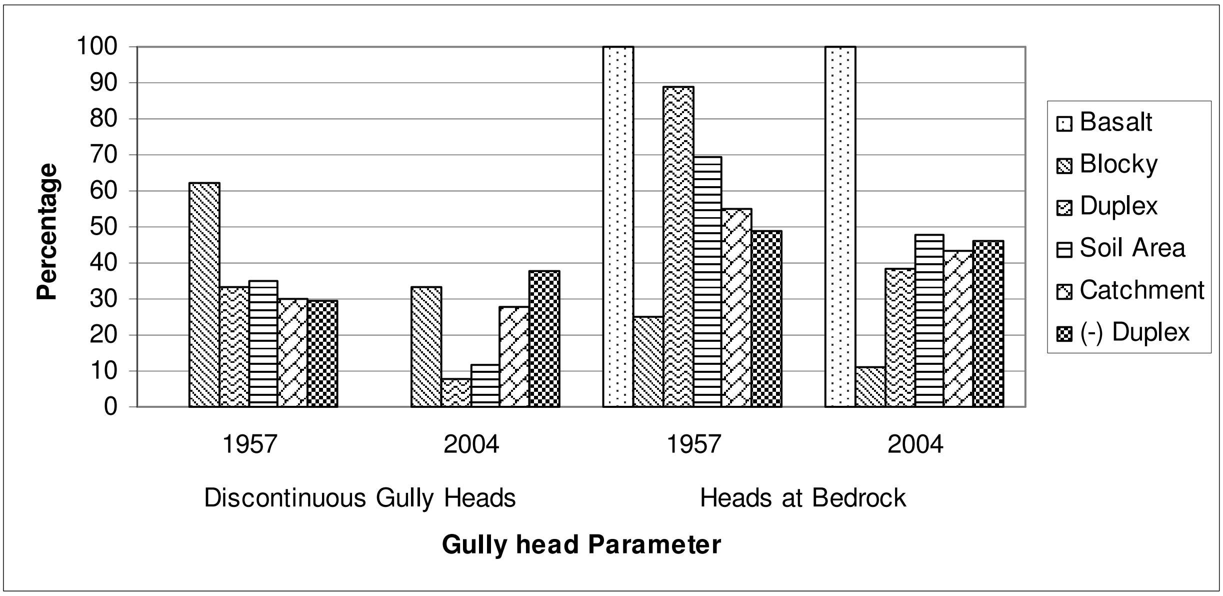

Figure 3.6: Gully Head Parameters for the soil map units, the area covered on the soil map and the whole sub-catchment

Table 3.6: Average slope class for the gully heads on the soil map units

	Average slope class*	
	2004	**1957**
Basaltic	5.5	5.2
Blocky	2.0	2.4
Duplex	1.6	2.1
Soil Area	2.2	3.0
Catchment	2.6	3.2

*A slope class represents 5° (see 3.2.2.2., p. 31)

The gully system on the basaltic soils is very stable and has been since 1957, as all the gully heads have reached bedrock (for 1957 and 2004), and the average slope class above the headcuts were 5.5 in 2004 and 5.2 in 1957. Furthermore the actual amount of gully heads stayed exactly the same.

In comparison with this the percentage of headcuts at bedrock for the blocky soil group was 25% in 1957 and only 11.1% in 2004. The average slope class at the headcuts also decreased from 2.4 to 2. These figures suggest a young, unstable gully system, but are somewhat misleading. Most of the gullies on the blocky soils cut straight through the area and have their headcuts at bedrock higher up the slope in the basaltic soils or outside of the soil survey area. Also of the eight headcuts in 1957, four have filled-in and they are not regarded as gullies anymore. Another 2004 headcut did not feature in 1957, as it was a continuous gully then. Subsequently the area above the 2004 headcut filled-in between 1957 and 2004 and two separate headcuts have formed. The reason for the infilling is unknown, but could have something to do with the road (for example: gully filled-in artificially to protect the road), as the 2004 headcut is situated just below the road.

The gully heads at bedrock in the duplex soils bring an interesting point to the light. There were 8 headcuts at bedrock in 1957, which comprised 88.9% of the headcuts. This would suggest a stable gully system. However in 2004, 10 gully heads are at bedrock, but they only account for 38.5% of the gully heads. This large decrease shows that the formation of new gully heads overshadowed the extension of existing headcuts in this area. As was discussed before, most of these new gully heads are tributaries of the main gullies. This indicates that the main gullies have a large influence on the formation of the new gullies, and thus also on the moving of a stable gully system through a threshold which induced a new sequence of gullying.

The fact that there are no gully heads on the red blocky soils and only one on the sandstone soils, suggest that these soils are quite stable and that the gullies found in them have cut further into other areas.

The gully systems on all the soils seem quite stable, except for the duplex soils. On the latter a new sequence of gullying started somewhere after 1957 due to the crossing of an erosion threshold.

Considering the whole catchment, it seems to be at the end of the erosion cycle. Gully density and gully head density increased slightly, whereas the percentage discontinuous gully heads and heads at bedrock decreased. These differences are due to the changes which occurred on the duplex soil area.

The stability of the erosion system outside of the duplex soil area is confirmed when the focus turns to the (–) Duplex area, which shows a picture of an erosion system in equilibrium. For this area the gully density and the gully head density stayed practically the same, while the percentage of gully heads at bedrock decreased slightly from 49% to 46%. The only parameter which might indicate a non-stable system is the discontinuous gully heads. This figure increased by 9% from 29% to 38%, which would indicate a system where new gullies have formed. However, on closer inspection of the data, it is seen that only four new discontinuous gully heads formed. This is not much over a 47 year period, especially when considering the serious extent of gullying in this area. Furthermore, the percentage of discontinuous gullies is artificially increased by the 4 gullies which filled-in, as discussed earlier.

Thus it can be concluded that the sub-catchment, excluding the duplex soils, has been at the end of an erosion cycle since 1957, except for the duplex soil area, where a new erosion cycle started some time after 1957. The impact on the duplex soil area is so severe, that practically all differences for the whole sub-catchment in the gully erosion parameters mentioned can be ascribed to the accelerated erosion on the duplex soil.

As the changes in soil erosion parameters for the other erosion factors are largely determined by the soil on which they occur, it will not be discussed in detail and only interesting points will be discussed. Tables showing the erosion parameters for all the map units of the different erosion factors are included in Appendix 4.

Geology

For the geological formations, the gully density in 1957 ranged from high to low in the sequence of Molteno (7.1 km/km^2), Clarens (6.7 km/km^2), Elliott (5.8 km/km^2), and Lesotho (3.3 km/km^2). This sequence changed in 2004 to Molteno (8.0 km/km^2), Elliott (6.7 km/km^2), Clarens (5.4 km/km^2) and Lesotho (1.8 km/km^2). This change in sequence is largely due to the increased erosion on the duplex soil area, of which 81% lies on the Elliott formation. The duplex soils have, strictly speaking, developed in unconsolidated material, but occur on the area occupied by the Elliott formation on the Geological map.

The 2004 results concur with the literature (Laker and Smith, 2006), from which a stability sequence in order of increasing stability of Elliott, Molteno, Clarens, Lesotho would be expected, except that the Molteno formation has a higher gully density than the Elliott formation. The reason for this is that a few factors exaggerate the gully density on the Molteno formation. It has a small size, occurs where two main drainage lines converge, and 27% of the Molteno area is covered by duplex soils, which is a larger percentage than what would normally be expected on the Molteno formation. Thus the Molteno formation area in this sub-catchment has an abnormally high gully density in comparison with other areas covered by the Molteno formation.

Land Use

All four land use map units had average gully densities in 1957 ranging between 5 km/km^2 (Cultivation) and 7 km/km^2 (Natural Vegetation). This changed in 2004 as the gullies on the abandoned land map unit extended with 111.2 m/km^2/year, which, as in the case with the duplex soils is even higher because of the long time span of the study.

The gully extension on the abandoned land is the only area that is close to the range of the gully extension of the duplex soils (Figure 3.3, p. 38). To know whether the causal factor is the soil type or management of the area, one must answer a chicken and egg question. Did the field erode heavily because it was abandoned, or was it abandoned because it became unproductive due to gully erosion? Although this study cannot conclusively prove the point, there are some facts which suggest that the gullying caused the land to be abandoned.

As discussed previously, the land tenure system allows for every married man to receive up to three fields in different areas (Nordström, 1988). Thus it is highly unlikely for an area as large as the abandoned land area to suddenly be abandoned for some social reason such as a farmer leaving to work in South Africa. It may be that because of poor returns the farmers had to stop producing on one of their fields and it might be that the fields in this area had the lowest fertility and was subsequently abandoned. However, it is unlikely that all the farmers in that area will suddenly decide not to cultivate one of their fields. It may be that one field was abandoned and gullying started there, spreading to the other fields, which led to them being abandoned too. According to Schmitz and Rooyani (1987) the breaking of one contour can soon lead to the destruction of a whole contour system. However, there are abandoned fields and broken contours in the cultivated areas which have not yet led to gullies, so it is unlikely that abandonment of one field is the sole cause of soil erosion. Thus the case that it was erosion that led to abandonment is pretty strong, which leaves soil type as the factor which played the biggest role in the current erosion cycle of the sub-catchment.

Slope class

No phenomenon other than what could be expected from the soil discussion occurred on the different slope classes. Slope class one showed the most gully extension, as the duplex soil area occurs in this slope class.

3.3.2.3. Hypothesis of gully formation

A hypothesis for how the gullies formed can now be put forward. The main gullies and a few of the tributaries occur along flow lines. Such gullies will be formed in any case and do not depend on the host material. Dardis and Beckedahl (1991) tested the rock mass stress of gullies and found that V-shaped ravines cut through rocks of a large range of rock mass strengths. According to Rowntree (1991) this type of gully is cut by surface runoff. The gully system outside of the duplex soil area seemed stable at 1957 and has since been stable. This leads to the assumption that their formation was driven by hydrology. Because of the shape of the sub-catchment, all the runoff water tends to concentrate, leading to the formation of gullies. The runoff for this area should be large, because of steep slopes and shallow soils on the upper slopes, limiting infiltration.

From the runoff gullies tributary gullies started to form after 1957. It seems that the soil type plays the biggest controlling factor in the formation of these tributaries, as the gully extension was largely confined to the duplex soils. What caused this gully system to cross a threshold to induce gullying is not clear, but a few factors should be discussed.

A possible reason for the formation of the new gullies formed on the duplex soils is the construction of contour walls in the late 1930's, which was discussed in Chapter two. The fact that the crossing of the erosion threshold only occurred more than 20 years later, does not nullify this argument as piping is a slow process, dependent on several wet-dry cycles. In the next Chapter it is shown that the duplex soils are dispersive and prone to piping, which strengthens this argument.

Other factors which could have contributed to the crossing of the erosion threshold include: a more intense use of the land when the grazing land of this area was converted to cultivated fields (Nordström, 1988), erratic rainfall events (Rydgren, 1993; Kakembo, 1997) and the declining of crops, leading to less vegetation cover (Laker, 2004)

It should also be noted that two large gullies, which occurs on the area not covered by the soil map, had developed after 1957 from footpaths. Thus footpaths are also a causal factor of gully formation in this sub-catchment. The development of gullies on footpaths is a well known phenomenon (Laker and Smith, 2006).

3.3.2.4. Correlation between gully and sheet erosion

The data for the correlation between sheet erosion and gullying, shown in Tables 3.7 and 3.8, is only tentatively put forward. The reason for this is that it is difficult to classify sheet erosion in the field (Laker, 2004) and even more so from aerial photographs. The extent of the sheet erosion classes is shown in Figure 3.7.

Table 3.7 shows that the gully density decreases in the order of sheet erosion class 3 > 1 > 2. That sheet erosion class 3 correlates well with gully density is not surprising, as it is part of the definition. It is also known that gullies effect a large area around them (Laker and Smith, 2006), increasing the damage caused by sheet erosion. Nordström (1988) noted that sheet erosion was correlated with shallow piping creating badland environments. Sheet erosion class 3 occurs on areas which can be classified as badlands.

Table 3.7: Gully length and density on the sheet erosion map units

Sheet erosion class	Size		Gully Length		Gully Density
	(ha)	(% of total)	(m)	(% of total)	(km/km^2)
1 (No apparent)	124.4	33.6	7750.8	32.5	6.2
2 (Moderate)	93.1	25.2	4178.6	17.5	4.5
3 (Severe)	152.5	41.2	11917.0	50.0	7.8
Whole catchment	370.0	100.0	23846.4	100.0	6.4

Table 3.8: Gully heads on the sheet erosion map units

Sheet erosion class	Gully Heads (#)	Gully heads per km^2	Discon-tinuous Gully heads (#)	Discon-tinuous Gully Heads (%)	Gully Heads at Bedrock (#)	Gully Heads at Bedrock (%)	Slope Class
1 (No apparent)	9	26.8	3	33.3	0	0	1.7
2 (Moderate)	17	67.6	7	41.2	10	58.82	3.5
3 (Severe)	50	121.3	11	22.0	23	46.00	2.5
Whole catchment	76	76.0	21	27.6	33	43.42	2.7

The difference between the gully densities on sheet erosion classes 1 and 2 can be explained by the sheet erosion map (Figure 3.7). Sheet erosion class 1 occurs around the areas where the main gullies meet, and thus have a large gully density, whereas sheet erosion class 2 occurs on the upper slopes. The gully head data (Table 3.8) confirms this, as on sheet erosion class 2 there are more gully heads and more gully heads at bedrock than on sheet erosion class 1.

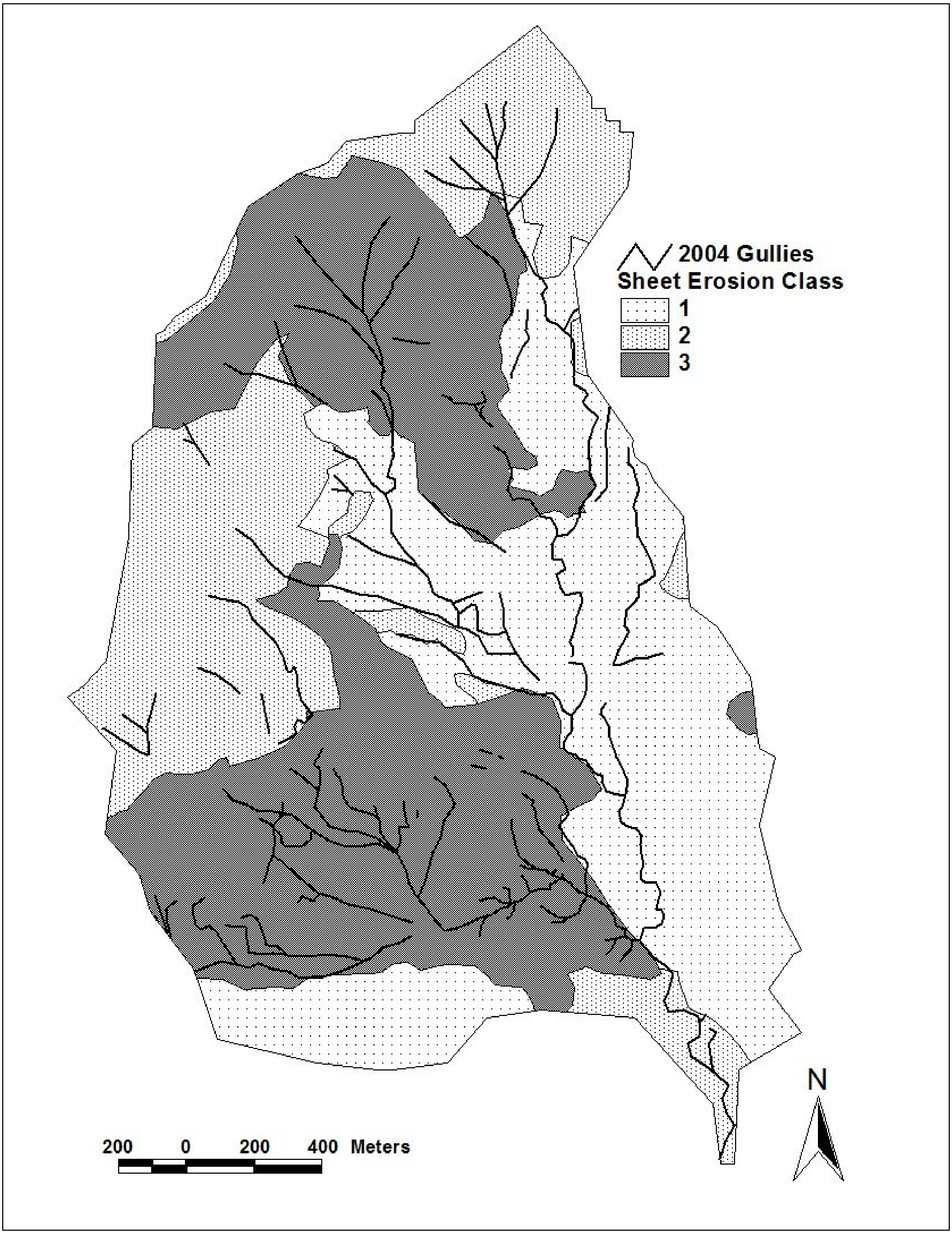

Figure 3.7: The sheet erosion and gully extent in 2004 (Classes are defined in Table 3.5, p. 32)

It is important to note is that sheet erosion occurs virtually across the whole area. These classes show relative differences in sheet erosion and cannot be compared with other areas. The classification used considers class 1 as no sheet erosion noticeable from aerial photographs, which is not the best medium to look at sheet erosion. Thus it does not mean that the area covered by sheet erosion class 1 is free from erosion.

3.3.2.5. Comparison between different sub catchments

The data for the study site and 3 other sub-catchments from the Maphutseng valley is shown in Table 3.9 and their extent is mapped in Figure 3.8. This shows that the different sub-catchments have vastly different levels of gully density, varying between 3.5 km/km^2 (sub-catchment 3) and 9.3 km/km^2 (sub-catchment 2). From Figure 3.8 it can be seen that sub-catchments 2 and 3 have two distinct zones of heavy gullying and relative stability. Thus although they definitely do not have the same gully characteristics as the main sub-catchment, they are alike as all three have distinct zones of gullying and relative stability. Sub-catchment 1 has a more uniform gully distribution.

Table 3.9: Gully parameters for the different sub-catchments

Area	**Size (ha)**	**Gully Length (m)**	**Gully Density km/km^2**	**Gully heads (#)**	**Gully head per km^2**	**Disc Gully heads (#)**	**Disc Gully heads (%)**	**Heads at Bedrock (#)**	**Heads at Bedrock (%)**
Sub-catchment 1	169.4	8866.5	5.2	32	18.9	9	28.1	15	46.9
Sub-catchment 2	184.8	17230.2	9.3	95	51.4	28	29.5	25	26.3
Sub-catchment 3	556.6	19279.2	3.5	71	12.8	9	12.7	16	22.5
Study Site	370.0	23846.4	6.4	76	20.5	21	27.6	33	43.4

From the above discussion it can be concluded that gully erosion is a highly localised phenomenon. Different catchments, or even different parts of the same catchments, will probably not show the same gully characteristics and thus results obtained from one catchment cannot directly be extrapolated to another catchment. Local conditions and local thresholds determine the extent of gully erosion in a specific area. This is in line with the findings if Nordström (1988), who also found the eight catchments she studied to all be in different stages of the erosion cycle.

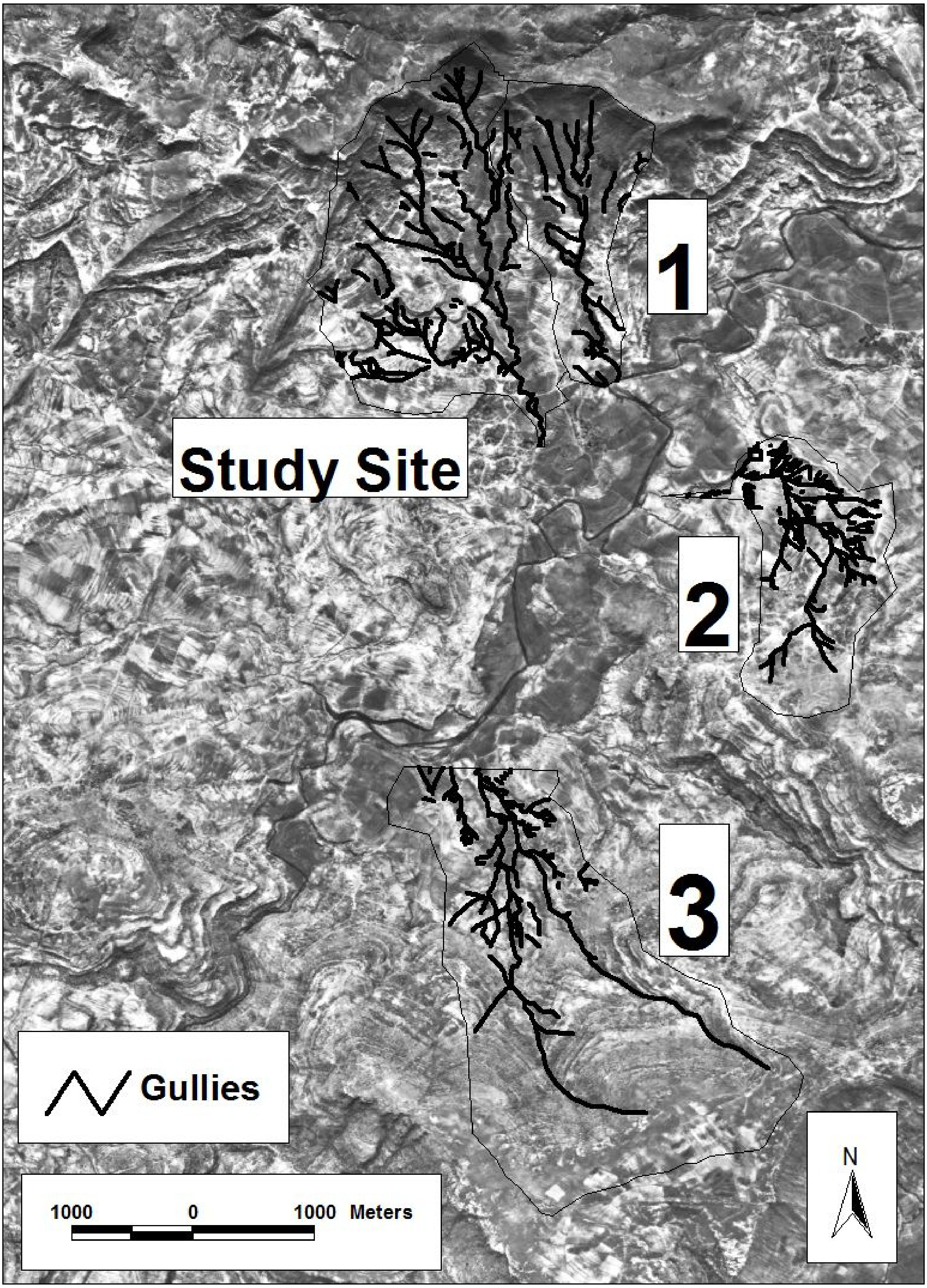

Figure 3.8: The gully extent in the different sub-catchments

3.4. Conclusions

From the discussion above it can be concluded that gully characteristics vary with space and time, depending on local factors and thresholds. Even inside a certain sub-catchment the gully extent will differ with highly local conditions.

In the study site the gully extension during 1957 until 2004 was correlated the best with the soils it occurred on. The duplex soils underwent severe gullying, whereas the rest of the sub-catchment stayed in a state of relative equilibrium. In 1957 the duplex soil area showed characteristics of a stable gully system, but somehow passed through an erosion threshold. The factors contributing to this is probably a combination of a more intense use of the area, the construction of contours, dry-wet periods and the declining of crop yields, leading to a smaller vegetation cover.

A hypothesis of how the gully system developed is offered. The main gullies formed by concentrated runoff from the steep slopes. These gullies have been there for a long time. The recent gullying activity is due to the crossing of an erosion threshold in the system and is confined to the duplex soil area. These gullies probably formed through piping.

This study shows that there are two types of gullies in this sub-catchment: Those formed through surface runoff and those formed through piping.

CHAPTER 4: SOIL PROPERTIES AFFECTING SOIL EROSION

4.1. Introduction

Although the interaction between soil properties and their effects on soil erosion has been relatively well studied internationally, it is known that these properties influence each other differently in different locations. Very little work has been done in Lesotho on the soil properties in relation to soil erosion. The aim of this Chapter is to identify the dominant soil properties which determine the soils' erodibility in the study site and to identify soil properties which could be used in the field to delineate areas of erosion hazard.

4.2. Material and methods

4.2.1. Analytical methods

The seventeen modal profile pits were sampled for laboratory analysis. These profiles were chosen to represent the most common soils occurring in the study site. Each master horizon was sampled on all three walls of the pit, vertically down the side of the wall, for the total length of the horizon. Pedoderm (top 2 cm of the soil surface) samples were also taken with a geological hammer from various places in close proximity to the pit. Three samples were taken from mudstones exposed to the atmosphere on gully walls or floors, and another three were taken from the shallow basaltic soils on Thaba Linoha. This was done to have some reference to the properties of possible parent materials of the soils.

The samples were marked in such a way that the number shows the type of profile pit, the profile pit number and the horizon from where the sample was taken. For example, M12B; M shows it is a modal profile, 12 is the number of the profile pit and the B shows that the sample is taken from the B horizon. When references in the text are made to certain samples, this is the way in which they will be numbered. Mudstone samples were numbered as M18-20, and the basaltic soils were represented by numbers M21-23.

All the samples were air dried and then passed through a 2 mm sieve. Various physical and chemical properties, which have been found to correlate with soil erosion in the past (Amézketa, 1999; Rienks *et al*., 2000; Bronick and Lal, 2005; Mills *et al*., 2006), were measured in the laboratory.

The pH was measured in water and 1M KCl in a ratio of 1:2.5 soil:solution. If the pH measured in KCl was less than 4.5, the titratable acidity was determined using a 0.1M NaOH solution and phenoftalien (White, 1997). Ca, Mg, Na, and K were determined by AAS (atomic absorption spectroscopy) from a filtered supernatant of a 1:10 NH_4OAc extract, (White, 2006), as well as from a filtered water saturated paste extract (US Salinity Laboratory Staff, 1954). EC was measured on the saturated paste extract. “Free” Fe, Al and Mn were determined by the citrate bicarbonate dithionate (CBD) method on selected samples which expressed strong red and yellow colours, all top soil samples and the six control samples (Mehra and Jackson, 1960). Total C and N were measured by combustion using EuroVector3000 elemental analyser in the topsoil and control samples. Particle size was determined with the pipette method (Gee and Bauder, 1986).

Munsell soil colour was converted to a relative numerical value with the equation of Mellville and Atkinson (1985). This equation calculates a soil colour value based on a reference colour. The reference colour used was 10YR2/1.

The dependent variables included a laboratory infiltrability index (Mills & Fey, 2004; Appendix 3.1), water dispersible silt and clay with the double pipette method (modified slightly from Soil Classification Working Group, 1991; Appendix 3.2) and macro aggregate stability with the wet sieving method (based on Kemper & Rosenau, 1986; Appendix 3.3). From the results of the water dispersible silt and clay test, two clay dispersion indices could be calculated, namely the total water dispersible clay (Total WD Clay), which is the dispersible clay expressed as a percentage of the total soil mass and the dispersion ratio, which is the dispersible clay expressed as a percentage of the total clay fraction present in the sample. The wet sieving aggregate stability test determined the percentage of water stable aggregates (%WSA) in the 1-2 mm size fraction of the soil sample. The infiltrability was done only on the pedoderm and control samples. Both the infiltrability and macro aggregate stability were done in triplicate.

From the data produced by the above mentioned methods, various calculations were done. Effective cation exchange capacity (ECEC) was calculated by the summation of all the exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, and exchangeable acidity). ESP, EMgP, ECaP, ECEC/Clay%, and Carbon adjusted ECEC/Clay% were among the soil chemical parameters calculated. A dispersion ratio which is the percentage of dispersible clay from the total clay percentage was also calculated. All the data for the different soil samples are shown in Appendix 2.1.2-2.1.6. and the formulas used for the calculations are shown in Appendix 6.

4.2.2. Statistical methods

The statistical investigation included a one way analysis of variance (Anova) on the dependent variables for the different horizons of the soil map units described in Chapter 3. This Anova showed that clay dispersibility is the factor which differ the most between the duplex soils and the other soil map units.

Pearson and Spearman correlations were determined for each variable with the dispersion ratio. This did not show conclusively which soil property exerts the largest influence on clay dispersibility.

A forward stepwise regression was then conducted with "free" Fe percentage, clay percentage, ESP, total carbon content, ECEC/Clay and carbon adjusted ECEC/Clay with some variations (all samples, only topsoil samples).

All these analyses were done in the Statistica computer program (Statsoft Inc., 2009), but as it proved inconclusive, there were reverted to segmented quantile regression. This was done according to the method described by Mills *et al.* (2006), based on the DRIS approach developed by Beaufils (1973)[1].

Cade and Noon (2003) states that quantile regression models are useful when the response variables are affected by more than one factor, when the response is different to different factors, when not all applicable factors are measured and when there is an interaction of multiple factors. Thus it is a powerful investigation tool for soil erosion studies where various complex interactions between contributing factors exist. According to Cade and Noon (2003), quantile regression has been used in a variety of studies on a variety of subjects, including plant self thinning (Cade and Guo, 2000)[2], prey and predator size relationships (Scharf *et al*., 1998)[3], and Mediterranean fruit fly survival (Koenker and Geling, 2001)[4].

The idea behind quantile regression is to fit a regression line through a part of a set of data points to create a response envelope. Inside of this envelope will be the zone of reality, where actual data points occur and outside of this envelope is the imagination zone, where data points could, but do not occur. The area inside the envelope represents the area where a certain percentage (depending on the quantiles chosen to create the envelope) of data points will occur. Figure 4.1, which has been adapted from Mills *et al*., (2006) explains this graphically. On the y-axis is the dependent variable, in this case the percentage of water dispersible clay. On the x-axis is the soil property that is studied. The regression line creates the envelope wherein most of the data points will occur. The zones of where potential maximal dispersion and predictably minimal dispersion may occur are shown. It is important to remember that the zone of potential maximum dispersion does not mean that dispersion will be maximal, but rather that it may be. As can be seen in Figure 4.1, there are some data points showing a low dispersibility in this zone. It is also good to note that the graphs do not necessarily show causality.

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[3] Scharf, F.S., Juanes, F. & Sutherland, M., 1998. Inferring ecological relationships from the edges of scatter diagrams: comparison of regression techniques. Ecology 79, 448-460.

[4] Koenker, R. & Geling, O., 2001. Reappraising medfly longevity: a quantile regression survival analysis. Journal of the American Statistical Association 96, 458–468.

The process with which the response envelopes are drawn is explained in detail by Medinski (2007). A short outline will be given here. The data points are sorted in increasing order according to the x variable. Then they are grouped into thin equal segments. Four data points per segment were used in this study. The amount of segments is a subjective choice, but does not influence the significance of the regression results (Mills *et al*., 2006). The 0.9 and 0.1 percentiles of the x-variable are calculated with the percentile function in MSExcel. Any percentile can be chosen, but 0.9 and 0.1 was used in this study to reduce the effect of outliers (as opposed to the 0.01 and 0.99 quantiles) and to enable the construction of a relatively smooth

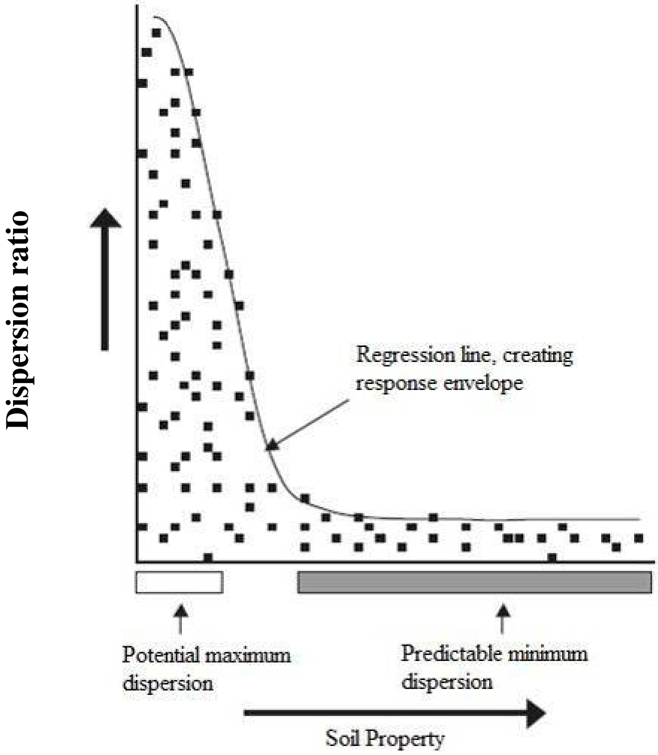


Figure 4.1: Graphical description of segmented quantile regression (Adapted from Mills *et al*., 2006)

boundary line (Medinski, 2007). For each segment the average of the y-variable is also calculated. The 0.1 and 0.9 quantiles are then plotted on the original scatterplot graph of the x and y variables. The best fit (highest R^2-value) trendline is chosen from the linear, logarithmic, second order polynomial, exponential or power functions and drawn through these quantile data points. The two trendlines make up the response envelope, which in this case encompasses 80% of the data points. When no sensible 0.1 percentile trendline can be drawn, it is often not shown on the graphs to ensure visual clarity.

4.3. Results and discussion

4.3.1. Correlation between dependent variables and soil map units

The Anova results for dependent variables for the different soil map units are shown in Table 4.1. Only the different horizons from the blocky, red blocky, and duplex soils were included in the Anova, as there were more than one replicate of each of these. The focus is on the difference between the duplex soils and the others, as the duplex soils are closely linked to soil erosion.

In Table 4.2 example soil profiles of the soil map units are shown with a few selected soil properties. All the soil profile descriptions and their properties are shown in Appendix 2.1.

Table 4.1: Average values of dependent variables for different horizons of the soil map units

Soil Map Unit	Horizon	%WSA		Total WD Clay		Dispersion ratio		WD Silt + Clay		Infiltration Index		Clay%	
Blocky	**A**	63.4	ab	3.03	a	12.3	a	16.08	ab	101.8	a	25.1	bc
Blocky	**B**	75.9	bc	2.93	a	9.90	a	15.32	ab			29.8	bd
Red Blocky	**A**	43.7	ab	2.45	a	12.85	ab	14.35	ab	78.70	a	19.3	abcd
Red Blocky	**B**	82.0	ab	1.85	a	4.60	ac	11.85	ab			40.0	b
Duplex	**A**	47.1	ac	2.80	a	40.5	b	12.78	ab	67.90	a	7.04	a
Duplex	**E**	32.2	a	4.57	a	36.8	bc	22.43	ab			14.4	acd
Duplex	**B**	67.1	ab	10.9	b	36.9	b	27.23	a			32.9	bd
Basaltic	**A**	93.5	b	0.00	a	0.00	a	5.0	b	315.1	b	14.0	ac

Different letters next to the averages show statistical differences at the 95% confidence level

The only big difference occurs for the Total WD clay and dispersion ratio. For the Total WD clay, the difference is between the B horizon of the duplex soils and all the other horizons. For the dispersion ratio, the duplex soil horizons differ from all the others, except the red blocky A horizon. The duplex E horizons also do not differ statistically from the Red Blocky B horizon. Nevertheless, the average dispersion ratios of the duplex soil horizons are much higher than that of the red blocky horizons. The results show that soil dispersibility is the dependent soil variable which distinguishes the duplex soils from the other soils and thus also the area of relative high erosion and the area of relative low erosion. These results concur with those of Miller and Baharuddin (1986) who found soil dispersibility to be closely linked to soil loss.

That there is no distinct significant difference for %WSA between the duplex soil horizons and the other soil horizons is in itself significant. Elwell (1986) found water stable aggregates smaller than 2 mm to be significantly correlated with both soil loss and runoff on a fersiallitic clay soil from Zimbabwe. However, Reichert and Norton (1994) did not find any correlation between WSA and soil erodibility and Bajracharya *et al*. (1992) found a negative correlation.

The lack of a significant difference for WSA between the duplex soils and the other soil forms, together with the differences for the dispersion ratios gives a hint as to the mechanism of soil erosion on the duplex soils. As discussed earlier, when WSA correlates well with soil erosion, runoff is the responsible factor for erosion. Piping occurs through a process where the subsoil disperse and therefore disintegrate, leading to gullies. This suggests that the accelerated erosion between 1957 and 2004 on the duplex soils occurred because of piping. This fits in with the occurrence of various sinkholes in the area. Figure 4.2 shows one of these sink holes. Nordström (1988) found that increased infiltration caused by contours had given rise to extensive gullying by piping in some of the catchments she studied. Furthermore Rydgren (2009, personal communication) observed how a major pipe formed and ultimately collapsed in the duplex soil area during the time (1984 - 1990) of his study in the same sub-catchment.

Figure 4.2: An example of sinkholes found on the duplex soils

This means that there are two types of gullies in this sub-catchment when gullies are classified by their formation. These gullies are caused by surface runoff, or by piping through subsurface flow. Faber and Imeson (1980) also reported observing these two different types of gullies in Lesotho.

This holds serious implications for the reclamation of gullied areas. In the next Chapter possible different ways of fighting erosion on areas with dispersive and non-dispersive soils are discussed.

The basaltic soils have very stable aggregates. From Table 4.1 it can be seen that they have a very high %WSA, no clay dispersion, very little silt dispersion, and a very high infiltrability. The reason for this very high stability in all measured variables may be the presence of amorphous clay minerals, which are associated with volcanic soils (Powers and Schlessinger, 2002). It is known that soils with amorphous clay minerals have stable aggregates and high soil organic carbon (SOC) contents (Torn *et al*., 1997; Powers and Schlesinger, 2002; Bronick and Lal, 2005). Their properties, which include a high surface area and highly variable pH-dependent charge, generally increase aggregation (Powers and Schlesinger, 2002).

Table 4.2: Examples of soil profiles of the soil map units

M12: Duplex	**Estcourt 1100**	**%WSA** %	**Dispersion ratio**	**pH** water	**EC** mS/m	**ECEC** cmolc/kg	**ESP** %	**Ca:Mg**	**Fe_{CBD}** %	**Total Carbon** %	**Clay Content** %	**Munsell Colour Dry**
	**Bleached Orthic A**	25.2	36.7	6.2	13.5	3.4	1.4	3.6	0.3	0.3	6.8	10YR6/3
	Gray E	17.7	55.2	7.3	25.7	3.1	3.9	5.4			6.8	10YR7/2
	Prismacutanic B	61.1	70.4	8.0	31.0	10.5	9.3	4.0			24.8	10YR6/3
M17: Melanic blocky	**Bonheim 1210**											
	**Melanic A**	90.7	3.5	6.1	21.2	17.7	0.4	0.7	1.2	2.8	35.9	7.5YR3/2
	Pedocutanic B	86.3	7.5	6.5	20.0	17.4	1.52	1.0			33.2	7.5YR3/1

Table 4.2: Continued

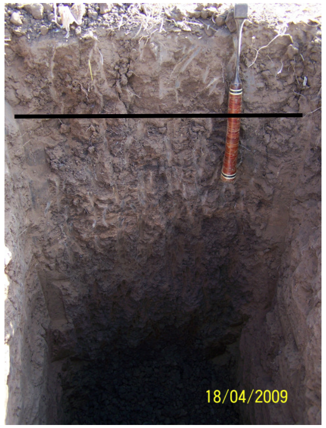
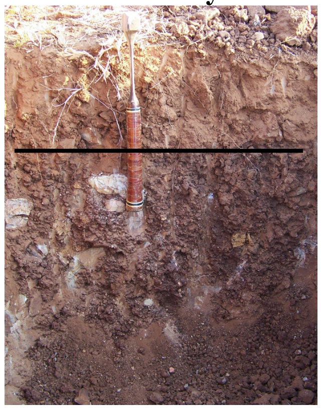
M9: Orthic Blocky	**Valsrivier 2111**	**%WSA %**	**Dispersion ratio**	**pH water**	**EC mS/m**	**ECEC cmolc/kg**	**ESP %**	**Ca:Mg**	**Fe_{CBD} %**	**Total Carbon %**	**Clay Content %**	**Munsell Colour Dry**
	**Orthic A**	35.0	22.2	6.8	20.2	11.3	0.6	5.0	0.7	0.8	16.8	10YR5/3
	Pedocutanic B	69.1	12.32	6.31	11.3	12.9	1.6	3.5			30.3	7.5YR4/1
M14: Red blocky	**Swartland 1221**											
	**Orthic A**	30.9	6.48	6.1	17.1	8.13	0.6	1.7	0.9	0.6	19.2	7.5YR5/6
	Pedocutanic B	92.2	3.29	6.2	8.00	16.0	0.9	1.8	1.7		37.8	5YR4/4

Table 4.2: Continued

M7: Sandstone	Glenrosa 1121	%WSA %	Dispersion ratio	pH water	EC mS/m	ECEC cmolc/kg	ESP %	Ca:Mg	Fe_{CBD} %	Total Carbon %	Clay Content %	Munsell Colour Dry
	**Orthic A**	45.0	6.7	5.4	14.4	4.5	1.1	3.0	0.7	0.5	18.6	7.5YR5/6
	Lithocutanic B	65.1	10.5	5.5	13.7	9.1	2.3	2.3	0.9		23.8	10YR7/4
M23: Basaltic	**Milkwood 1000**											
	**Melanic A**	94.6	0.00	6.9	29.1	30.1	0.5	2.35	0.45	4.85	17.5	10YR3/1

The dispersibility ratio was chosen rather than total dispersible clay as the dependent soil variable to correlate with other soil properties. The reason being that the dispersion ratio shows the tendency of clay to disperse, irrespective of the amount of clay present in the sample. Clay dispersibility does not show in dispersive soils with only small amounts of clay present when measured as total dispersible clay. The duplex A and E horizons are examples of this.

4.3.2. Correlations between soil properties and dispersion ratio

Although several soil properties are correlated with the dispersibility ratio at the $p = 0.01$ level, none of the correlations are very strong, with the highest R^2 value being only 0.53, for Fe+Al%. These results add substance to the statement by Rienks *et al*. (2000), that to some degree the effects of soil properties which influence dispersibility may cancel out each others effect. The strongest correlations exist for Fe%, Al%, soil colour, and ESP, which is expected from the literature as discussed previously. Interestingly there is no significant correlation with total carbon content.

The soil properties which have a significant correlation with dispersion ratio at $p = 0.01$ appears in Appendix 5.1. This Table also shows the R^2-values for the best linear fit, as well as the best fit between a second order polynomial, exponential, logarithmic, and power trend line.

The forward stepwise regression analysis was inconclusive as it did not improve any of the R^2-values when the analysis was carried out for the whole dataset. When only topsoil samples were analysed, an R^2-value of 0.79 was obtained by combining ESP and Carbon adjusted ECEC/Clay, which shows that the type of clay mineral does to some extent play a role in the dispersibility of the topsoils, although Carbon adjusted ECEC/Clay was not significantly correlated to the dispersion ratio.

4.3.3. Quantile regression analysis

4.3.3.1. Soil properties

The best fits of the boundary lines of the quantile regression are shown in Figure 4.3.

The environmental envelopes show a good fit around the data, with only the ECEC graph (b) having an R^2-value for the 0.9 quantile being below 0.89. The graphs show that minimum dispersion will occur in samples with high carbon content, a high ECEC, a high “free” Fe% and a low ESP. These results correlate well with the literature discussed earlier.

The average dispersion ratio of all the soil samples was 19.1. This value was substituted into the equations for the 0.9 quantile trendlines, to calculate the property thresholds for below average dispersion. Table 4.3 shows the samples which has a below average dispersion ratio and/or comply with at least one of the threshold value.

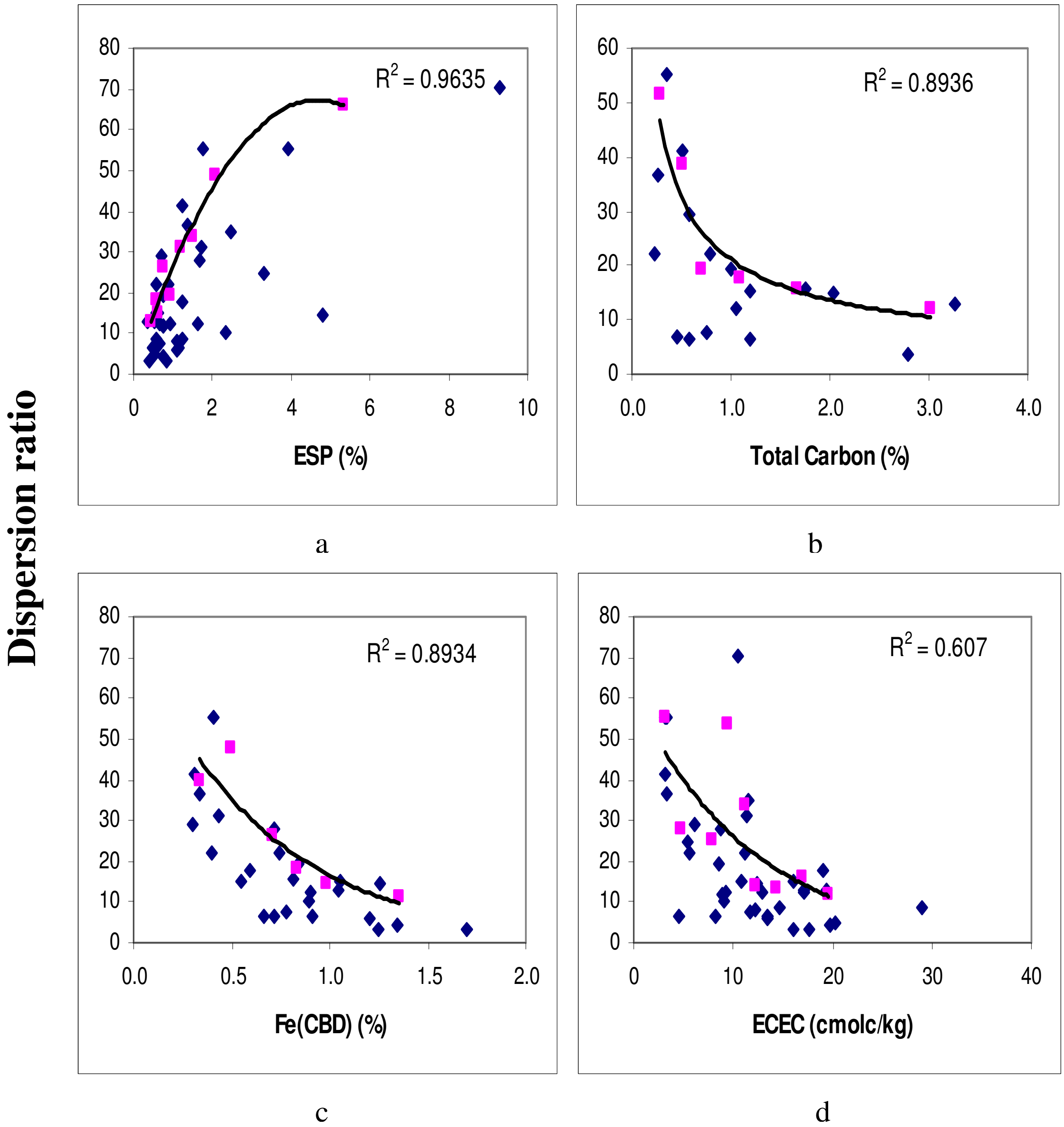


Figure 4.3: The 0.9 quantile environmental envelopes for the dispersion ratio and some soil properties The Y-axis represents dispersion ratio in each case. The data points for the 0.1 quantile have been omitted for clarity

The threshold values were compared to the values of the samples for these properties. Nearly all the samples showing a dispersion ratio below 19.1 complied with at least one threshold value (not including colour as colour is also a response variable).

Colour has been included in the table as it can be an indicator of soil dispersibility. It will be discussed later in this Chapter.

Table 4.3: Dispersion threshold values of some soil properties. The samples shown have a below average dispersion ratio and/or comply with at least one threshold value. Threshold values are shown in brackets and where a sample complies with a threshold value the value is highlighted. Omitted values have not been determined.

Sample	Dispersion ratio (<19.1)	Colour (<8.40)	Total Carbon (%) (>1.17)	ECEC (cmolc/kg) (>13.7)	ESP (%) (<0.68)	Fe_{CBD} (%) (>0.90)
Below average dispersion						
M2A	15.8	4.00	1.75	27.1	0.97	0.81
M2B	17.5	12.0		19.0	1.23	0.60
M5B	14.5	9.47		12.4	4.80	1.25
M6A	6.25	8.07	1.19	13.4	0.47	0.72
M6B	13.1	8.06		19.4	0.52	
M7A	6.71	13.0	0.46	4.53	1.14	0.66
M7B	10.5	20.2		9.06	2.34	0.90
M8A	12.3	8.55	1.05	9.22	0.67	0.91
M8B1	12.0	8.07		8.96	0.76	
M8B2	8.26	4.00		12.2	1.09	
M9B	12.3	8.00		12.9	1.62	
M10A	12.8	12.2	3.26	17.1	0.34	1.05
M10B1	4.62	4.12		20.3	0.55	
M10B2	4.14	8.25		19.8	0.73	1.35
M11A	7.47	8.55	0.76	11.6	0.66	0.78
M11B	8.50	4.12		28.9	1.22	
M13B	5.93	8.26		13.5	1.09	1.21
M14A	6.48	13.0	0.57	8.13	0.58	0.91
M14B	3.29	8.57		16.0	0.85	1.70
M15A	15.0	8.00	2.04	16.0	0.59	1.06
M15B	12.2	8.00		17.2	0.91	
M16A	15.2	8.06	1.19	10.8	0.60	0.55
M16B	8.81	8.00		14.6	0.58	
M17A	3.47	4.13	2.79	17.7	0.38	1.25
M17B	7.50	4.00		17.4	1.52	
Above average dispersion						
M9A	22.2	12.2	0.79	11.2	0.57	0.74

Of the three samples that did not comply with any of the threshold values, two of them were B horizons (M8: B1 and B2) which were not tested for carbon and Fe, but where the A horizon (M8A) complied with the Fe threshold. As Fe increases with depth in all modal profiles where the subsoil was tested for Fe except M2, it can be assumed that these two samples will also comply with the threshold values for Fe and Al.

The below average dispersion samples which did not comply altogether with any threshold value are M7A and M9B. The M7A sample has a carbon adjusted ECEC/Clay of only 20.4 cmolc/kg. The CEC values of kaolinite is 3-15 cmolc/kg clay and for illite 25-40 cmolc/kg clay (Rooyani and Badamchian, 1986). This means that M7A probably has a clay mineralogy comprising of a considerable amount of kaolinite. Six *et al*. (2000) reported a synergistic effect between oxides and kaolinite on aggregate stability. Thus although the Fe content in the M7A sample is lower than the threshold, the Fe will be responsible for larger than expected stability because of the presence of kaolinite.

M9B is dark enough to comply with the colour threshold. It was not tested for total carbon or Fe_{CBD}. Its topsoil also does not comply with the threshold values for these soil properties. It might be that it actually complies with the Fe threshold, as the Fe_{CDB} value of the M9A horizon is quite close to the threshold value at 0.74%.

Interestingly M9A is the only sample to show above average dispersion and to comply with one of the thresholds. Its ESP is 0.57, which is 16% below the threshold value for ESP. It does not comply with any of the other threshold values. This shows that even very little amounts of Na can cause the dispersion of a soil when no aggregation agents are present on the soil. This is the same behaviour as the dispersible soil studied by Van der Merwe *et al*. (2001) discussed in Chapter 1 (p. 9).

The M5B sample is worth mentioning. It is the B horizon of an Estcourt 1200 soil, has an ESP of 4.8 (the second highest of all the samples) but a dispersion ratio of only 14.5. It is stabilised by a high Fe content (1.25%). This sample is analogue to the Smithdale sample from the study of Seta *et al*. (1996), which had an ESP of 4.7 and Fe and Al concentrations of 1.9% and 1.6% respectively, but a dispersion ratio of only 2.7. Sample M5B shows that even in a sample with a relative high ESP for this area, if enough stabilising agents are present in the soil, it will have relatively stable aggregates.

The dispersibility ratios of all the samples vary between 0 and 70.4 (data for all soil samples are shown in Appendix 2.1), with an average value of 19.1. According to Hazelton and Murphy (2007) the minimum dispersion ratio falls in the negligible/aggregated category (<6%), the average in the slight category (6-30%) and the maximum dispersion in the very high (>65%) category. Hazelton and Murphy (2007) should only be used as a rough guide though as they quote the figures for the 5 μm size class, whereas this study used the 2 μm size class.

Hazelton and Murphy (2007) deem the values of ESP below 5 to indicate non-sodic soils; 5-10 is marginally sodic to sodic and above ten is strongly sodic. Thus all the soils in this trial except for sample

M12B are classified as non-sodic. The threshold value of 0.67 is very low by all standards. This confirms the views of Rooyani (1985) and Yaalon (1987) that sodicity is not needed for piping to occur. In their terms sodic means an ESP of 15%, so these values are extremely low. It shows that (as is the case with the M9A sample) in the absence of binding material soils will tend to disperse irrespective of the presence of a dispersing agent. Mg is not a dispersive agent in this case, as there is a negative correlation between dispersion ratio and exchangeable Mg and EMgP.

According to Hazelton and Murphy (2007) the classes for OC vary between 0.4% for extremely low and above 3% for very high. All values below 1% are deemed as low values. Thus the most values from this study will be low, with only a few samples having high carbon levels. The basaltic soils all contain carbon levels in the very high category. The threshold value of 1.17% is deemed to be moderate by Hazelton and Murphy (2007), which means that even moderate amounts of carbon can stabilise these soils. In this study total carbon was determined, which means that the organic carbon is even less. Not one of the soil samples tested positive for carbonates with 10% HCl in the field, so the contribution of the inorganic C to the total C is not expected to be very high.

The Fe_{CBD} values reported by Six *et al*. (2000) is 0.32 - 1.4%, which is comparable to this study. These values are much less than the extremely stable red soil studied by Thompson which was mentioned earlier. It contained 14.9% Fe_2O_3, which is comparable to 10.4% Fe.

The Fe/clay and Fe/(clay+silt) values were calculated and investigated in relation to the dispersibility ratio. The Fe/clay shows a positive correlation, but this is due to the large effect of small clay percentages which is used as the denominator. The Fe/(clay+silt) shows the same trend as the Fe values, but the correlation is not as strong.

The threshold value of ECEC (13.7 cmolc/kg) is a moderate value (Hazelton and Murphy, 2007) and is quite low when compared to the soils studied by Dimoyiannis, (1998) in Greece where the CEC ranged between 8.91 and 39.13cmolc/kg. Bloem and Laker (1994) investigated soil with CEC values ranging from a very low 0.97 cmolc/kg to a very high 49.8cmolc/kg. The ECEC values for this study ranged between 3.1 and 28.9 cmolc/kg.

Rienks *et al*. (2000) studied soils with a range of dispersibility ratios between 0 and 17.5 in Kwa-Zulu Natal, South Africa. These values are much lower than those of the soils studied in this study. The corresponding ESP values are much higher though. They range from 3.6% for the sample with no dispersion to 23.2% for a sample with a dispersion ratio of about 4. The highest dispersion occurred at a sample with an ESP of only 4.8. The varying results are to be expected as they sampled soils exposed in the gully sidewalls. The dispersible fraction of the soil would have been removed from the samples in different degrees before sampling. The time that the soil has been exposed to water flowing through the gully influenced the amount of dispersible clay removed.

In the USA Seta *et al*. (1996) studied the dispersibility of various Bt horizons from different soil types and their soil properties. The dispersion ratios they recorded ranged between 1.0 and 29.9%. These values are higher than the ones from this study for soils of comparable stability as they were shaken overnight (vs 5 minutes) in distilled water and thus had a much longer time to disperse. Thus although the dispersion values seem the same as the values from this study, the soils are actually more stable. The Smithfield sample discussed earlier comes from this study. All the soil properties of their study are comparable to the ones in this study (for instance: CEC: 12.3-27.1 cmol/kg, ESP: 0.7-4.7% and Fe: (0.48-3.5%), except for Al, where the values are much higher, ranging from 0.19–3.0%. The Al values for the soils in the current study ranged between 0.05 and 0.23%. These higher Al values probably account for the higher stability of the USA soils.

4.3.3.2. Parent material

An interesting phenomenon can be seen when the chemical soil properties are further investigated. Figure 4.4 shows the environmental envelopes drawn around the data points of certain chemical properties and dispersion ratio.

The EMgP graph (a) shows a relational envelope around the data points with a low dispersibility at high EMgP values. Figures 4.4 b and c shows that dispersibility is low at low ECaP and Ca:Mg values. These three graphs are contradicting the literature which was discussed earlier. Also the coarse sand graph (d) should have nothing to do with soil dispersibility, although it can clearly be seen that low dispersibility occurs at the higher coarse sand fractions (which are still not very high).

The explanation for these results is to be found in the parent material of the soils. As was discussed earlier, soils from volcanic origin tend to be stable because of the amorphous nature of the clay minerals (Powers and Schlesinger, 2002). Even when these clay minerals weather they still form stable clay minerals, being either 1:1 clay minerals or oxides (Powers and Schlesinger, 2002). It is also well known that soils derived from mudstones and especially from Elliott red beds are notoriously unstable (Laker and Smith, 2006).

De Villiers (1965) argues that one must view the parent material of a soil as the material wherein it forms, rather than the rock on which it forms. Pre-weathering and soil creep are two mechanisms he mentions which change the parent material of a soil, although it will still occur on the same geological formation.

Taking this view, many soils in the catchment, although occurring on the Elliott or Molteno geological formation will have an element of basaltic parent material through soil creep and surface wash from the upper slopes. Such soils will therefore exhibit some basaltic soil properties.

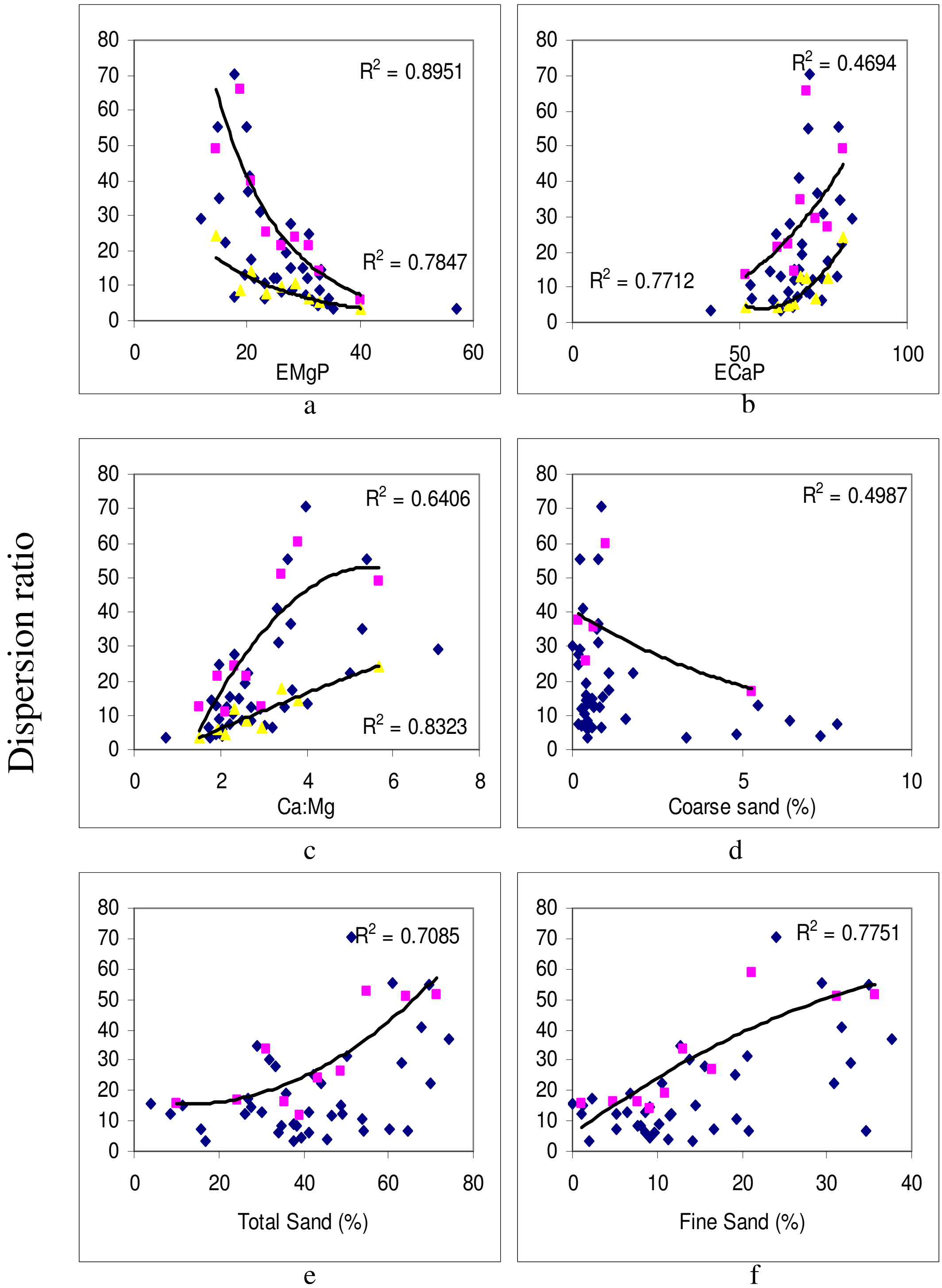


Figure 4.4: Environmental envelopes for the dispersion ratio and some soil properties. The Y-axis is dispersion ratio in each case. Where no sensible envelope could be drawn for the 0.1 quantile, the data points have been omitted for visual clarity. Where an environmental envelope is drawn in for the 0.1 quantile, the top R^2-value is for the 0.9 quantile and the bottom one for the 0.1 quantile.

Table 4.4 shows the average values and results of a one way Anova analysis on certain properties of the basaltic soils and mudstone samples. The value of the soil properties for the one Red Bed sample (included in the mudstone samples) is also shown.

Table 4.4: Certain properties of the Basaltic soils, Mudstones and Red Bed sample

Property	Basaltic soil			Mudstone			P-value	Red Bed
	Average	Std dev		Average	Std dev			
Coarse sand (%)	17.9	5.3	a	0.9	0.7	b	0.005	0.8
Fine sand (%)	9.6	2.3	a	3.7	1.7	b	0.02	5.37
Total Sand (%)	51.5	10.8	a	26.3	4.4	b	0.02	25.4
ESP	0.64	0.4	a	1.89	1.2	a	0.17	3.3
EMgP	29.4	0.5	a	18.6	7.5	a	0.067	10.93
ECaP	69.1	0.9	a	78.2	6.5	a	0.075	83.62
Exchangeable Mg (cmolc/kg)	8.10	1.1	a	3.0	1.5	b	0.009	1.27
Exchangeable Ca (cmolc/kg)	19.1	3.1	a	12.1	3.2	a	0.052	9.68
Ca:Mg	2.3	0.07	a	4.9	2.5	a	0.15	7.65
Colour	5.9	3.1	a	16.2	3.8	b	0.02	16.3

Different letters indicate a statistical difference at $p<0.05$

From Table 4.4 it can be deduced that a soil derived from basaltic material will have more coarse sand, fine sand and total sand than a soil derived from mudstone. Chemically it will possess more exchangeable Mg, (which leads to a higher EMgP) and less exchangeable Ca (leading to a lower ECaP). This leads to a lower Ca:Mg ratio. The ESP value will also be lower and it should show a darker colour than that of a mudstone derived soil. Although not all these properties are statistically different the trends are still clear. The differences are larger when the basaltic soils are compared to the red bed sample.

If the basaltic soil properties are compared to Figures 4.4, a, b, c, and d, it shows that the areas of minimum dispersion exist at the areas of maximum basaltic properties.

Figures 4.4 e and f do not show this correlation, but this is perfectly logical. When clay is dispersed, it will be eluviated, resulting in a relative enrichment of sand. Thus it makes sense that fine sand and total sand shows minimum levels of dispersion at low sand content levels. Coarse sand shows the opposite, which could indicate that the coarse sand originated from basalt rather than from Molteno formation sandstone. Some Molteno formation sandstones are coarse grained.

4.3.3.3. Indicators of erosion hazard

Soil colour can serve as an indicator of soil structural stability in this sub-catchment. Figure 4.5 shows the environmental envelope drawn around the data points for dispersion ratio and the dry soil numerical colour values. It shows that low colour values (dark colours) will have minimum dispersion, whereas soils with high colour values (light colours) may have high dispersion ratios.

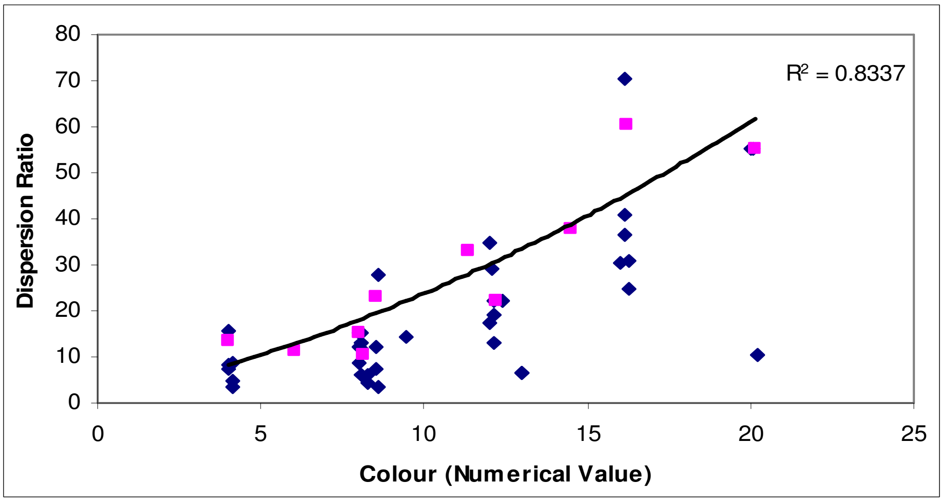


Figure 4.5: The 0.9 quantile environmental envelope for dispersion ratio and soil colour

The threshold value for dry colour as determined previously and shown in Table 4.3 (p. 62) is 8.4. Soil colours under the threshold value correspond to dry Munsell colours with Hues of 5YR, 7.5YR and 10YR, Values of less than 4 and Chromas of 3 and less. All the soils which fall within the threshold boundary comply to these dry colours and no soils that fall outside of the threshold boundary has a dry colour which falls in this standard.

It must be noted that although soil colour and dispersion ratio has a tight fit environmental envelope, soil colour is also a response variable. Thus dark colours does not cause aggregate stability, but is the result of other soil properties, such as carbon content and Fe, which influences dispersibility.

Despite a dispersive soil, there needs to be an accumulation of free water in the subsoil for piping to occur (Fletcher and Carroll, 1948; Brinkman, 1970). Free water may accumulate in the subsoil when a coarse textured topsoil occurs on a water impenetrable fine textured soil. Thus it should be able to identify areas susceptible to subsurface erosion by identifying areas where the soils strongly express clay accumulation in the subsoil.

To test this, the soil profiles' clay content of the B horizons was divided by the clay content of the A horizons. This value could be called the clay accumulation index. The average clay accumulation index for the soil map units is shown in Figure 4.6. Melanic and orthic blocky soils were separated, as their topsoil characteristics are different. Also included in Figure 4.6 is a value for the M1 profile. This profile lies outside of the sub-catchment, so it was not included on the soil map. It is a red Oakleaf form soil, presumably developed in sandy alluvium. What makes it interesting is that the dispersion ratio of both the top and subsoil is quite high at 22.2 and 31.3 respectively, but the area in which it occurs is not severely eroded. There are also no signs of piping in the area.

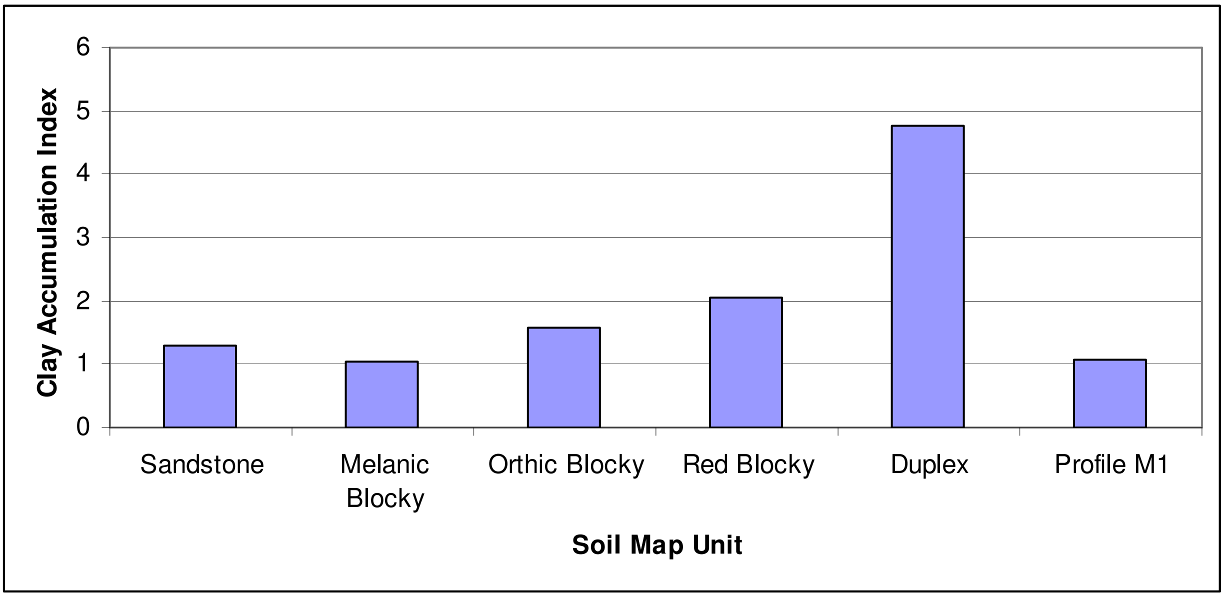


Figure 4.6: Average clay accumulation indices for the soil map units

It can be seen that the duplex soil has the highest clay accumulation index, which was expected. The other soil map units have a much lower clay accumulation index. Despite its dispersive nature, the clay accumulation index for profile M1 is very low at 1.07. Its red colour also shows that the soil is well drained. The reason for the lack of gully erosion on this dispersive soil area could be that a perched water table could not form in the soil.

This shows that the clay accumulation index of a soil is another soil parameter that can be used to identify erosion hazards. Light coloured soils which do not have a marked clay accumulation in the B horizon, also have a low erosion potential. By looking at Figure 4.6 it seems that the threshold value for the clay accumulation index lies somewhere above 2.

4.4. Conclusions

Recent soil erosion on the study site is controlled by soil dispersibility, rather than macro aggregate stability. This means that piping is probably the mechanism whereby the accelerated erosion on the duplex soils area started.

Thus there are two types of gullies in this sub-catchment: gullies formed by surface runoff and gullies caused by piping through subsurface flow. This holds serious implications for the methods used to combat erosion, as with the runoff, one needs to increase infiltration to decrease runoff and on the piping areas excessive infiltration must be avoided.

Soil dispersibility is not well correlated with any single soil property, which means that various factors are dominating soil erodibility in the different soil profiles and samples. The best correlations exist between dispersion ratio and “free” Fe and Al, ESP and soil colour.

The low threshold value for ESP means that in the absence of stabilising agents the soils will be dispersible. However, only moderate values of carbon, ECEC and “free” Fe are needed to inhibit dispersion.

Soil structural stability on the study site is linked to the soils’ parent material. This refers to the transported material wherein the soil formed, rather than the geologic formation whereupon it formed. Soils with properties resembling the basaltic soils’ properties tend to be more stable than other soils.

Soil colour can serve as an indicator of soil structural stability in this sub-catchment, as soil dispersibility is low where soils are dark coloured in the dry state. Stable soils also may have light colours, but unstable soils will not show dark colours. Dark colours have Munsell Values of less than 4 and Chromas less than 3. Light coloured soils with a low clay accumulation index are also deemed to have a low potential for piping.

CHAPTER 5: CONCLUSIONS AND RESEARCH RECOMMENDATIONS

5.1. Conclusions

There were two types of gullies found in the study site. The first type is caused by an accumulation of runoff water and occurs on the flow accumulation paths. The second type is controlled by the extent of dispersive soils and forms by piping through subsurface flow.

Between 1957 and 2004 the gully extension occurred mainly on the dispersive duplex soils. Most of the runoff gullies had been formed before 1957.

This study showed that gully systems on different sub-catchments and even parts of sub-catchments differ in the position of the erosion cycle they are. Thus the factors influencing gully erosion are highly local and the initiation of a gully system is dependent on the crossing of a local erosion threshold.

When there is a lack of binding soil agents, such as sufficient amounts of carbon, “free” Fe and a high CEC, soils will be dispersive, even with very low ESP values. Moderate levels of binding agents stabilise the soils sufficiently to ensure below average dispersion.

The parent material of the soil has a definite effect on the soil’s dispersibility. The parent material is not the geologic formation whereupon the soil develops, but rather the material wherein it develops. Soils showing characteristics of a basaltic parent material are less dispersive than other soils.

It is hypothesised that the gullies formed by the following mechanism: The main gullies in the sub-catchment formed through runoff from the steep mountain slopes. These gullies existed before 1957. The gully erosion may have been accelerated at some point, but are now in a state of relative equilibrium. After 1957 the duplex soil area passed through an erosion threshold, where severe piping resulted in the initiation of the gully system in place today. The piping is confined to the dispersive duplex soils and the runoff gullies provided the outlet necessary for the perched water table.

In this sub-catchment, soil colour can be used to delineate relative non-dispersive soils. Soils with dark dry colours, i.e. Munsell colours with Values of 4 or less and Chromas of 3 or less are relatively non-dispersive. Lighter colours may also be non-dispersive. A clay accumulation index, showing the ratio of subsoil to topsoil clay percentage can further show areas prone to subsoil erosion. In soils with a low clay accumulation index, perched water tables cannot develop, which is a prerequisite for piping. Soils with a high clay accumulation index are prone to piping.

5.2. Research recommendations

The research focus should turn to the fight against soil erosion. Theoretically if the crossing of an erosion threshold will induce the rapid formation of a gully system, then a stabilisation of the system could keep the system erosion free.

So many conservation projects in Lesotho have not yielded the expected results, partly because of a lack of understanding of the soils' influence in the soil erosion process. This should be rectified.

The two different gully systems identified in this study show a need for different conservation measures. On runoff gullies, the concentration of runoff water should be prohibited, whereas on piping gullies, excess infiltration into the subsoil should be avoided. Possible ways of reaching these objectives, which should be tested, will now be discussed.

The first research need is to find an easy way for the local Basotho farmers to identify piping prone soils. This will enable them to know which type of conservation measure could be performed on which areas. The soil properties (colour and clay accumulation index) identified in this study as indicators of piping potential could be used. The formulation of a field soil dispersibility test which could be performed by the local Basotho farmers will also facilitate the demarcation of sensitive soils.

On dispersive soils research projects should investigate various ways of conservation. The first is to increase the amounts of stabilising agents in the soil. The easiest of this is probably organic carbon, which could be done by vegetative growth. According to the literature, a grass species should work best (Kulander, 1986; Nordström, 1988). By keeping the piping prone areas under permanent pasture, organic carbon levels will be increased and the water content of the soils will also be decreased by transpiration.

Another way to combat erosion is to cut off the pathways of lateral subsurface flow. Baillie *et al.* (1986) mentioned that deep ripping and cross ripping to break up existing pipes could be the start of a typical management sequence in a slightly piped area. This is probably not a conceivable idea in rural Lesotho. It will also not be useful on the 6 m deep gullies which Nordström (1988) observed in certain catchments.

The infilling of gullies by check dams will also block the subsurface flow pathway. Caution must be taken with the building of check dams though, as a check dam in dispersive soils will probably lead to the dispersion of the gully walls around the check dam, which will accelerate erosion and render the check dam useless.

Lastly the addition of chemical ameliorants (for instance: lime or gypsum) could be investigated to change the cation composition on the exchange sites of clay minerals. Na could be leached out and replaced by stabilising cations such as Ca. This study shows though that this will only be effective when stabilising soil properties are first increased to moderate amounts.

Conservation measures on non-dispersive soils should increase infiltration and not allow for runoff water to accumulate. Rydgren (1993) found that soil loss from runoff plots were much less than the soil loss from the catchment as a whole. The reason was that soil loss increases dramatically when rill and gullies are part of the erosion system. Thus field plots must be big enough to allow for the formation of rills and gullies to be able to assess the impact of a conservation measure.

The best way to ensure infiltration is to maintain a decent vegetation cover. Conservation measures which could be investigated include: conservation agriculture, correct rangeland management, and discriminate burning to stop veld encroachment.

However, the present author shares the opinion of Rydgren (1993, p. 91) that "*local initiative is crucial*" to combat erosion. This can only be done when the local community understands the erosion problem and are willing to adapt present management systems around this. Thus research findings will only prove useful when the relevant information can be passed on to the agricultural officers and rural farmers of Lesotho.

5.3. Conservation Methods in Layman's terms.

To promote the sharing of information with the people who need it, this last section has been included in the study. The aim is to explain the erosion problem and conservation methods in a language which can be understood by the local farmers. This section can be translated into Sesotho and be used by the local agricultural officers and non-governmental organisations working in Lesotho to help spread erosion awareness. Preference has been given to easily understandable language rather than scientific correctness.

5.3.1. Combating the erosion problem

When planting a crop, soil is a valuable resource. It can hold water and contains the food necessary for your plants to grow. When your soil washes away, it means that you have less plant food and water on your field. Your plants will not grow that well, meaning that you will harvest less food, for the same amount of effort you put into your crops. A donga that eats into the land also makes the area you have to plant crops smaller. When there is a donga in your field, more soil will wash away than when there is no donga in your field.

This applies to grazing land as well. Soil erosion means there is less grass for your cattle to eat, which means that they will not be fat and strong, as they have to walk long distances to find enough grass to eat.

Soil erosion is a problem which must be fought by the whole village. No matter where a donga starts, it will grow into other areas, eating fields as it grows. Once a donga has formed it is really difficult to stop. The best way to stop erosion is to stop it from starting.

There are two types of dongas. The first starts when the soil cannot hold all of the rain. When this happens, water flows away and takes soil along with it. When this water that flows on top of the soil forms a river, it may take along so much soil that it will cause a donga to form. This type of donga can occur anywhere.

Here it is important to have as much rain as possible go into the soil. This rain water will be available for plants to use, and will also not flow away and take the soil along with it.

Crops can be grown on these areas. Ways to ensure a good crop is to plant your seed on time, to pull out weeds regularly and to add manure, ash and fertilizer to the soil if it is possible.

One way of allowing rain to go into the ground is by using a farming method the experts call "Conservation Agriculture". It has been used in America, South Africa, Zimbabwe and other African countries, where it has helped to stop soil erosion. Before Europeans came to Lesotho, your forefathers also used this method.

With this method, you do not plough but you dig a small hole with a hoe where you want to plant the seed. The rest of the soil is not disturbed. The old plants of the last year's crop are left on the ground. Animals should not be allowed to eat these old plants. The old plants allow for more rain to enter the soil, and stop the sun from drying the soil. Your crop will then have more water to grow with, meaning you will produce more food for less trouble.

Another good thing of this method is that you can start to prepare your field as soon as you have harvested, so you do not have to work very hard in one small time. Also when the rains are late, you can still plant on time, as you do not have to wait for the rains to plough.

The other type of donga forms by water flowing under the ground. The water eats the deep soil making a pipe where water easily flows through. The more water flowing in the pipe, the faster it will grow. Eventually the pipe will be so big that the roof will cave in, and a donga will be formed. This is a dangerous type of donga as one cannot see the donga until the roof caves in.

Luckily these dongas only form on certain soils. In Maphutseng, light coloured soils with a lot of clay in the deeper soil layers are soils where these dongas might occur.

Areas where you think that this type of donga might form must not be cultivated. Not even small fields on this area must be cultivated, as a donga can develop there, which will lead to dongas forming on the whole area. Grass must be planted and be allowed to grow. The grass will take out water from the soil, to stop it from flowing below the soil surface. It will also hold onto the soil to keep it from flowing away. Animals must not be allowed to eat this grass, until it is growing very strongly and the whole area is covered by a thick mat of grass. Remember that if a donga starts to form here, it will make it impossible for anything to grow on this area, and no grass will remain for the animals to eat. Trees must not be planted on this area as trees allow more water to flow underground.

On all areas the grass must be protected from being eaten too much by animals. When grass is eaten too much, there is less grass to make seed for next year and then less grass will grow, meaning less food for your animals. Also soil on areas where no plants are growing is very easily washed away by rain.

If the village can establish a large area of thick growing grass, you can use a different method of feeding your animals. With this method, animals are kept in the kraal. The herdsboy's job will be to go and cut enough grass for the animals and bring it to them. This will allow a lot of good things to happen. The animals will not have to waste energy to walk far to get to the food, meaning they will be fatter and stronger. Also their manure will be in one place, which makes it easy to collect it. This manure can be used to make fire, and that which is too much can be put on the field, making the crops grow better. The herdsboy will not have to sit and look after the animals for the whole day and will be able to go to school or work in the fields during this time.

One of the most important things to remember in the fight against soil erosion is that the whole community must work together to stop it. If one man causes a donga to start on his field, or allows his cattle to eat too much of the grass and it struggles to grow next year, the whole village will suffer.

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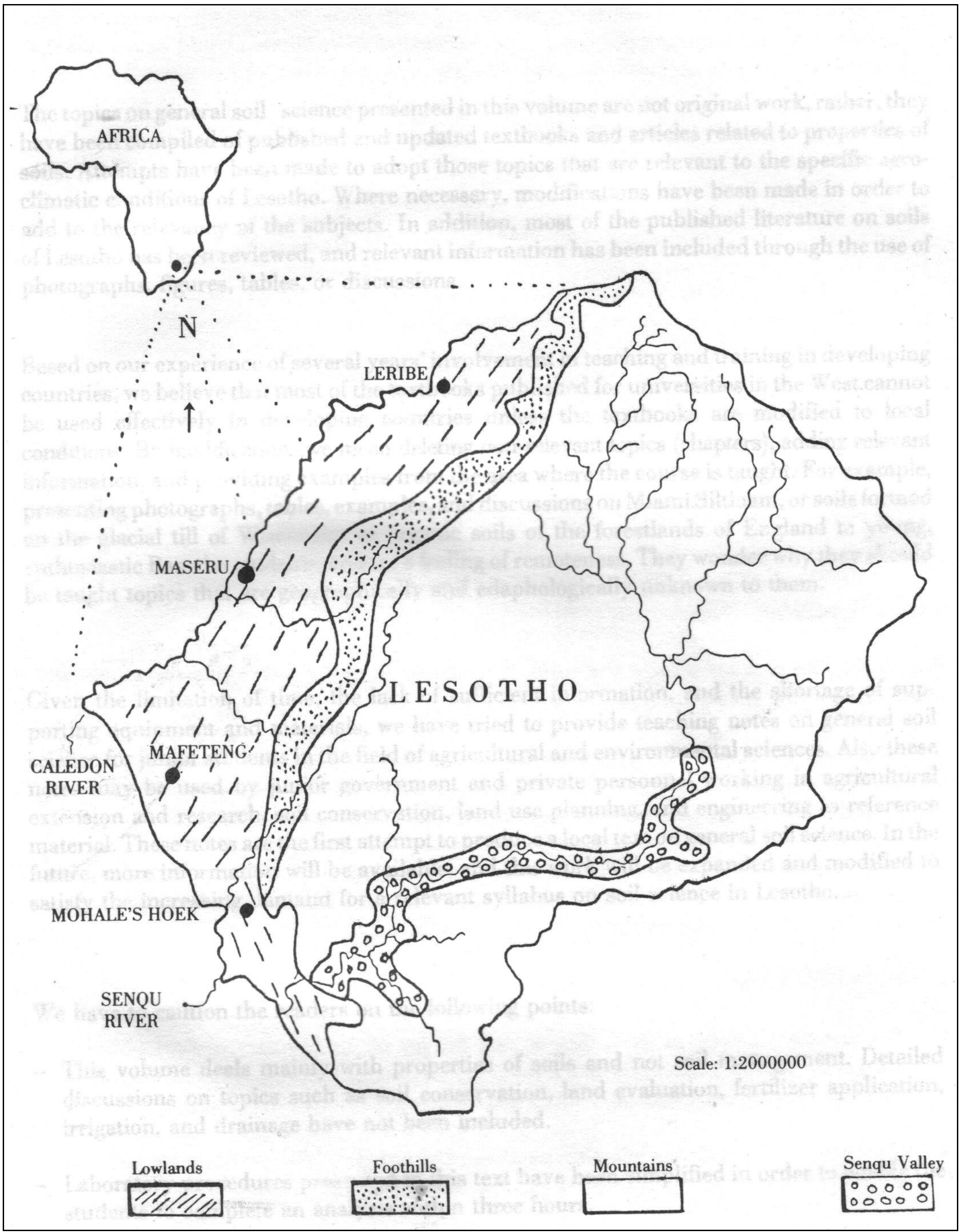
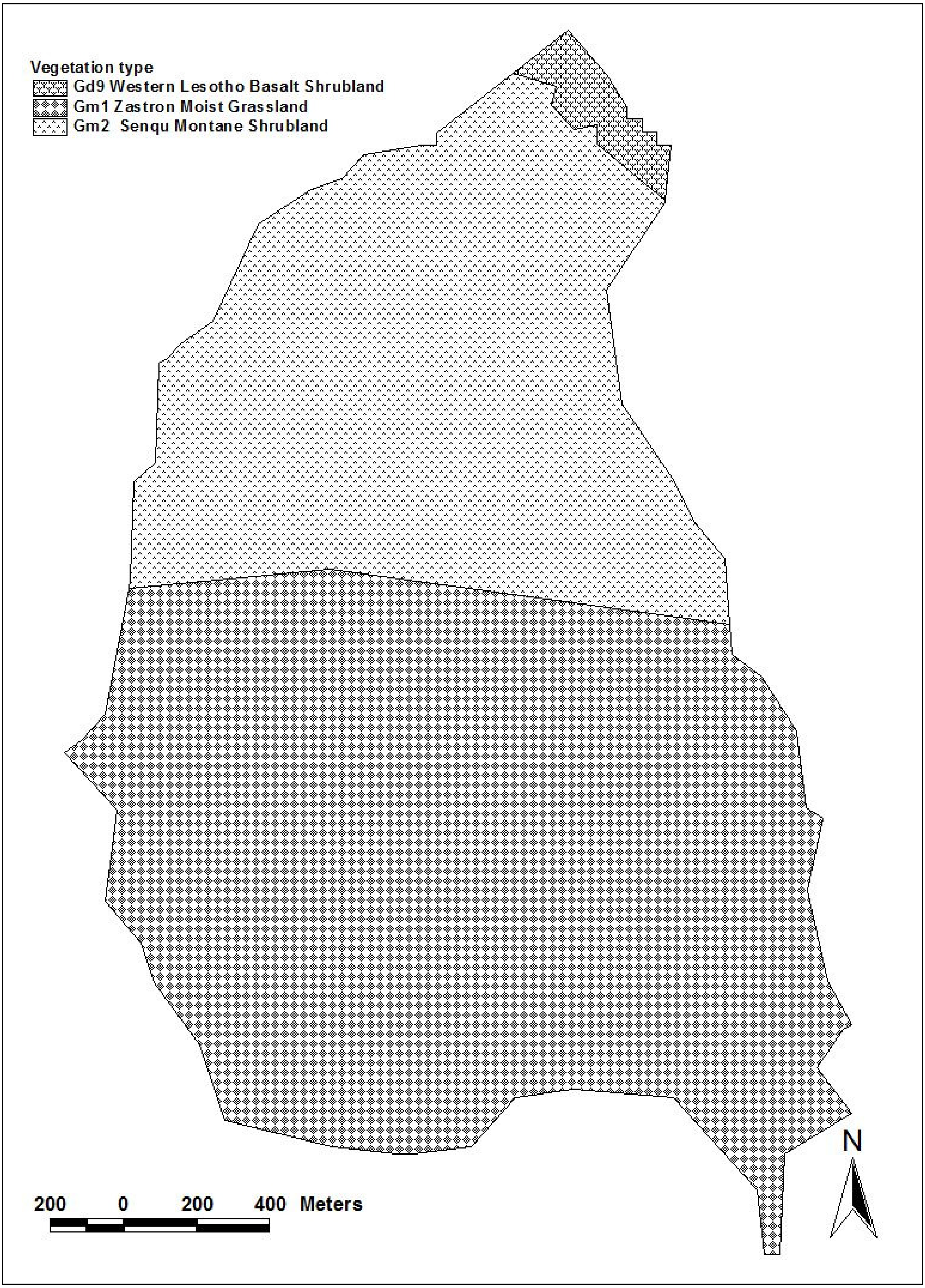
APPENDICES

Appendix 1: Maps used in the study



Appendix 1.1: The geomorphic zones of Lesotho (from Rooyani and Badamchian, 1986).



Appendix 1.2: Vegetation Map for the study site (from Rutherford and Mucina, 2006).

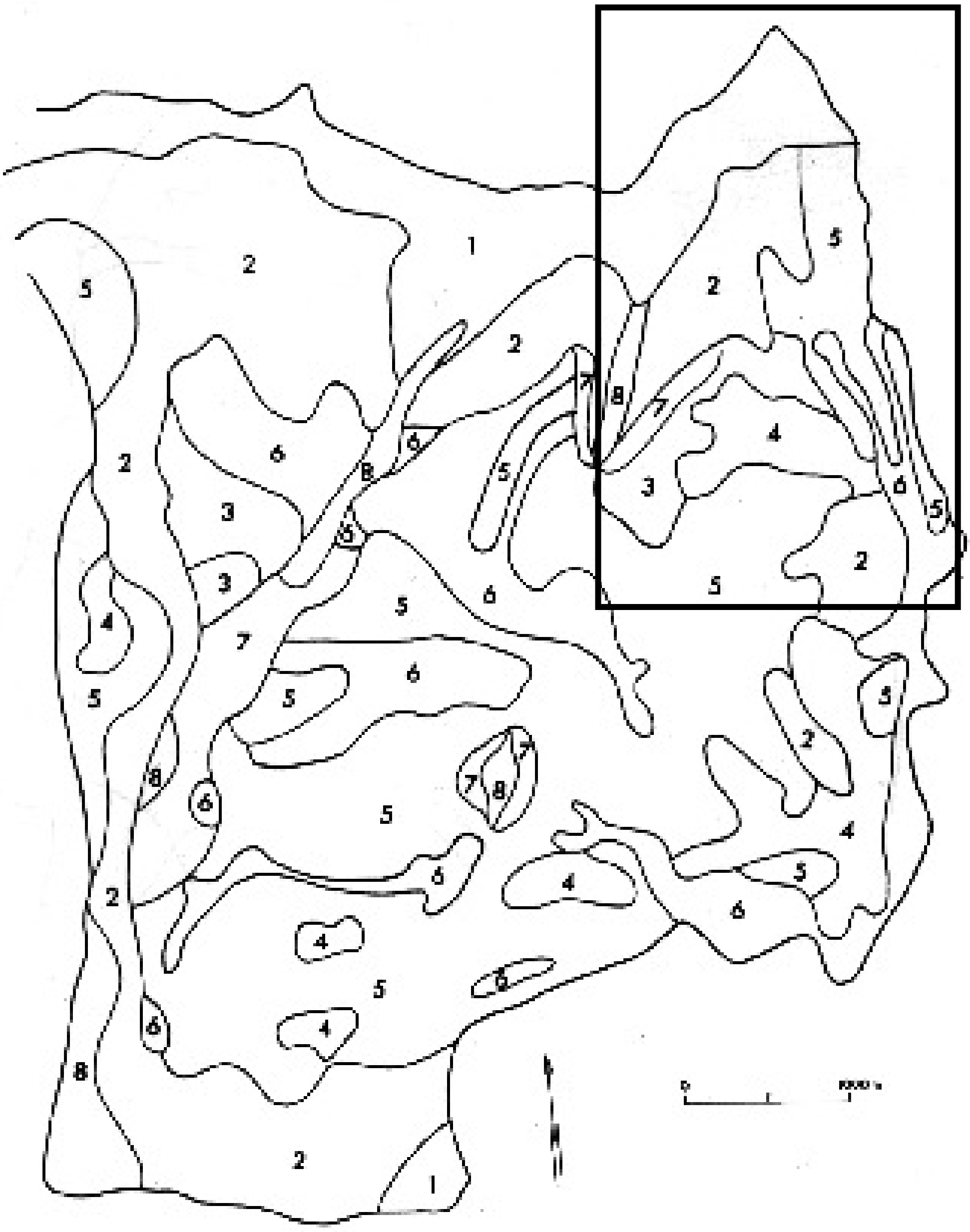
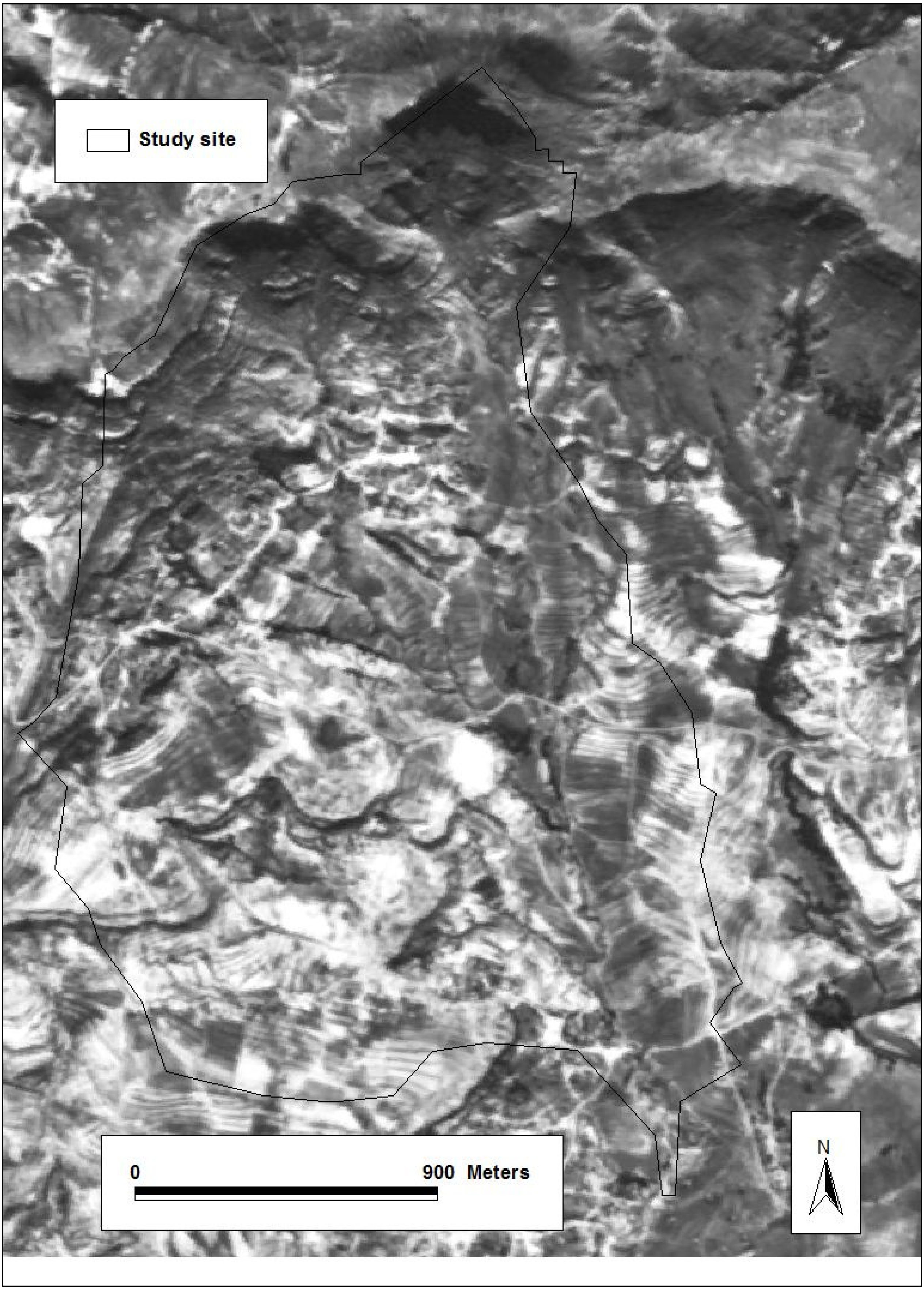


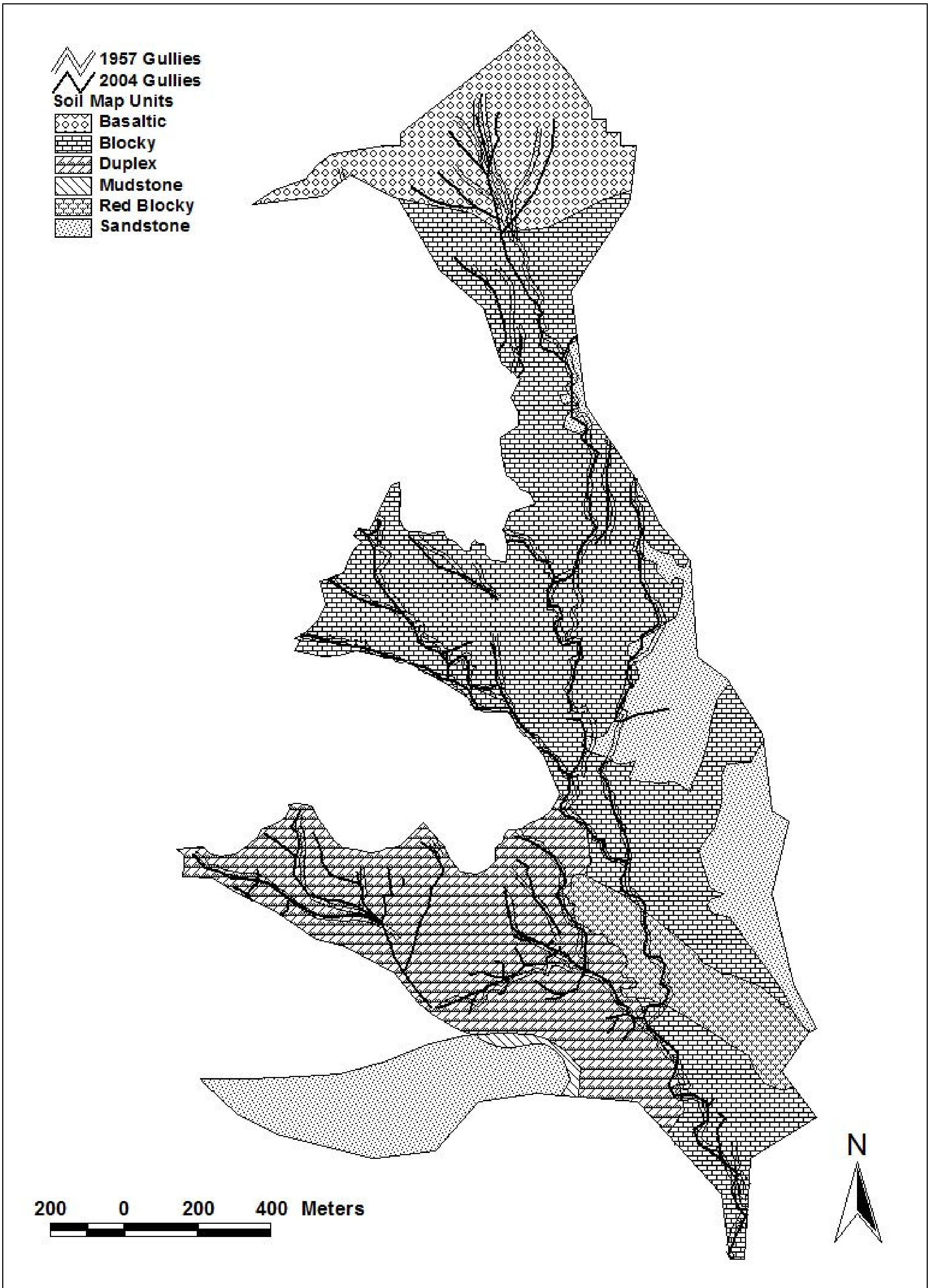
Fig. 5. Soil map of the Maphutseng area. 1: Basalt and sandstone rockland and lithosols., 2: Colluvial soils., 3: Berea soils and sandstone lithosols., 4: Gullied land., 5: Tsakholo with patches of Leribe soils., 6: Patsa soils., 7: Dolerite influenced soils., 8: Dolerite rockland and colluvium.

Appendix 1.3: Soil Map from Rydgren, 1986. Approximate study area is marked

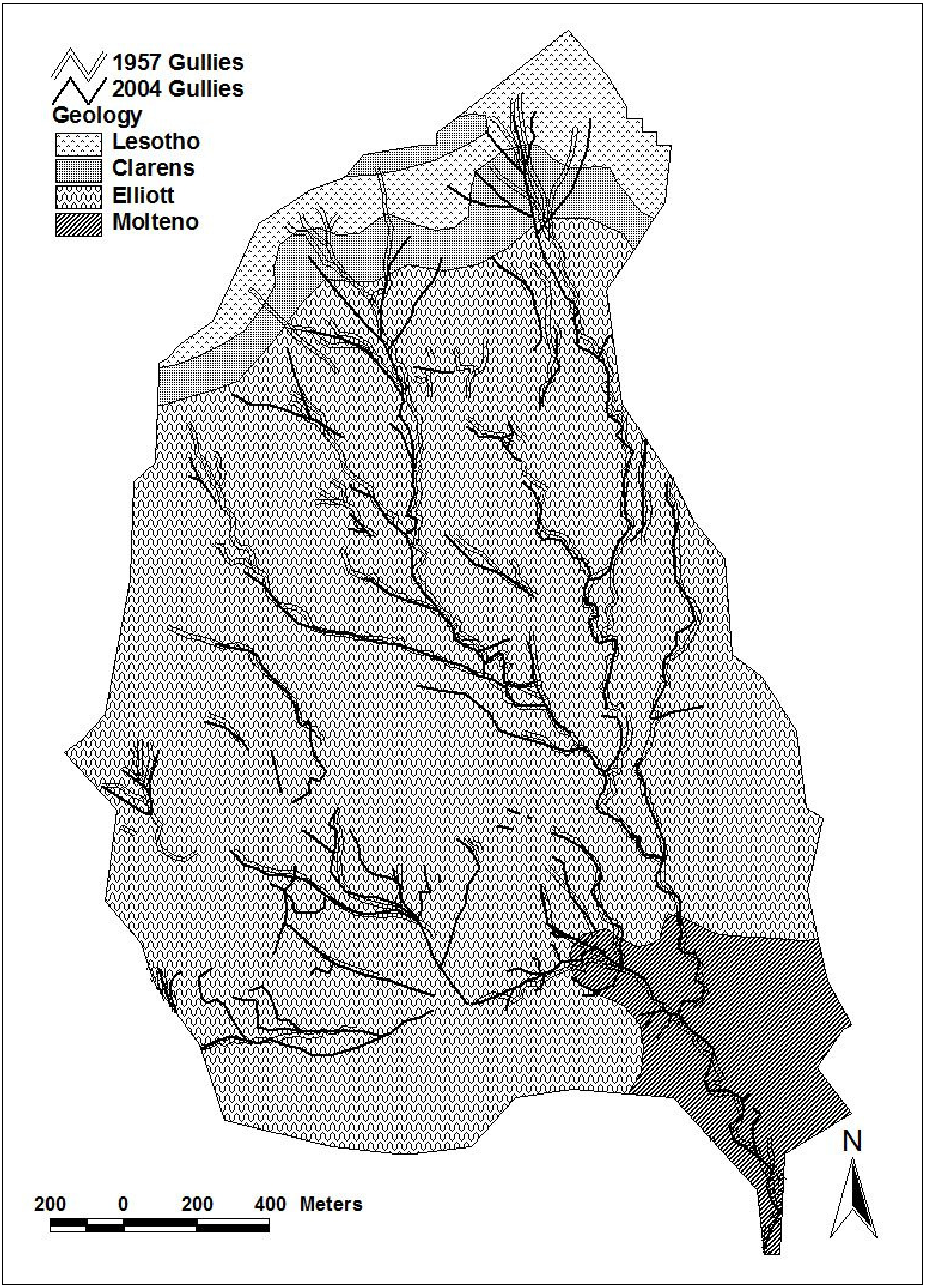
Appendix 1.4: 1957 Aerial Photograph



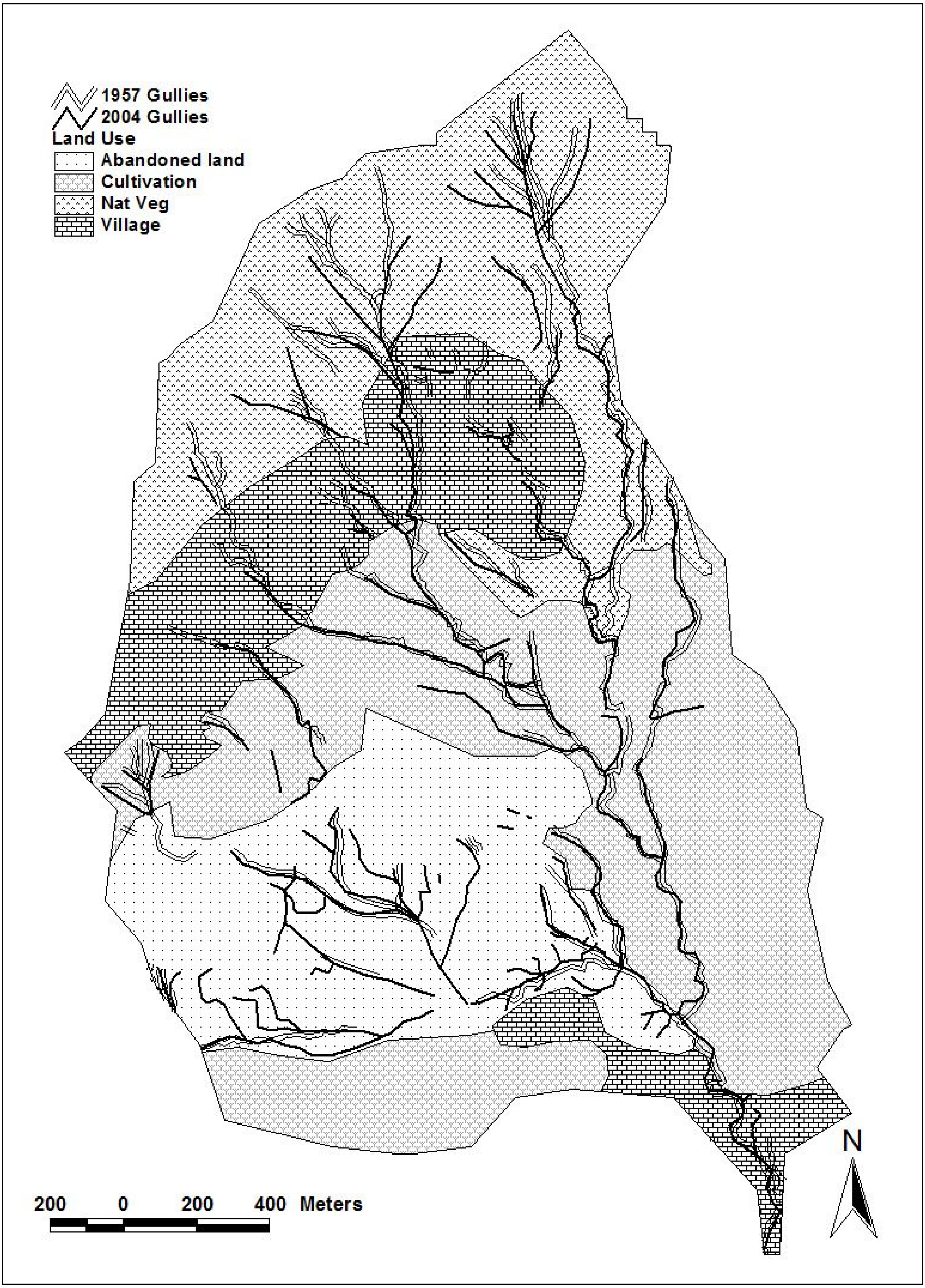
Appendix 1.5: 2004 Aerial Photograph



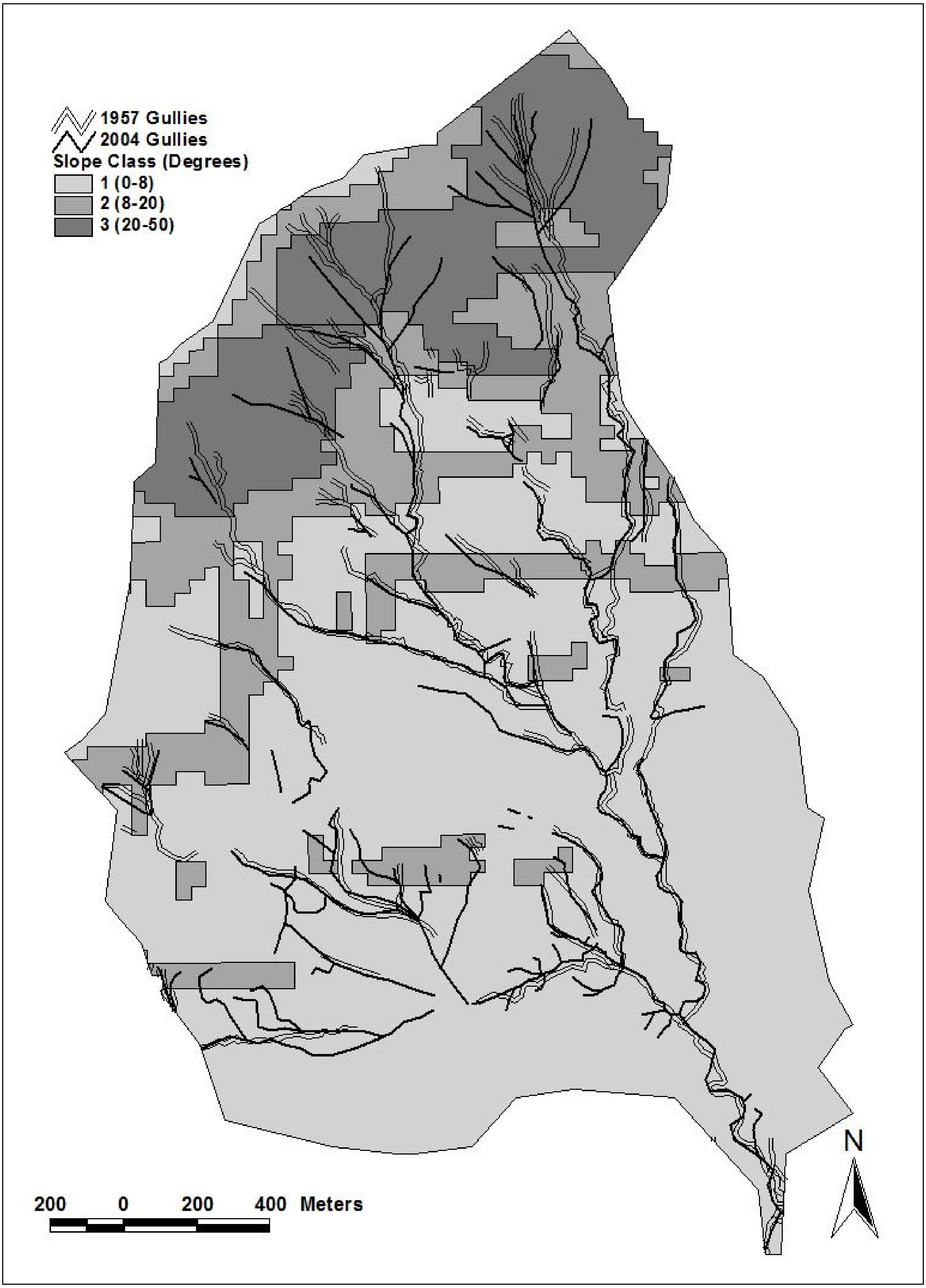
Appendix 1.6: Soil Map Units of the sub-catchment, showing the 1957 and 2004 gully extent



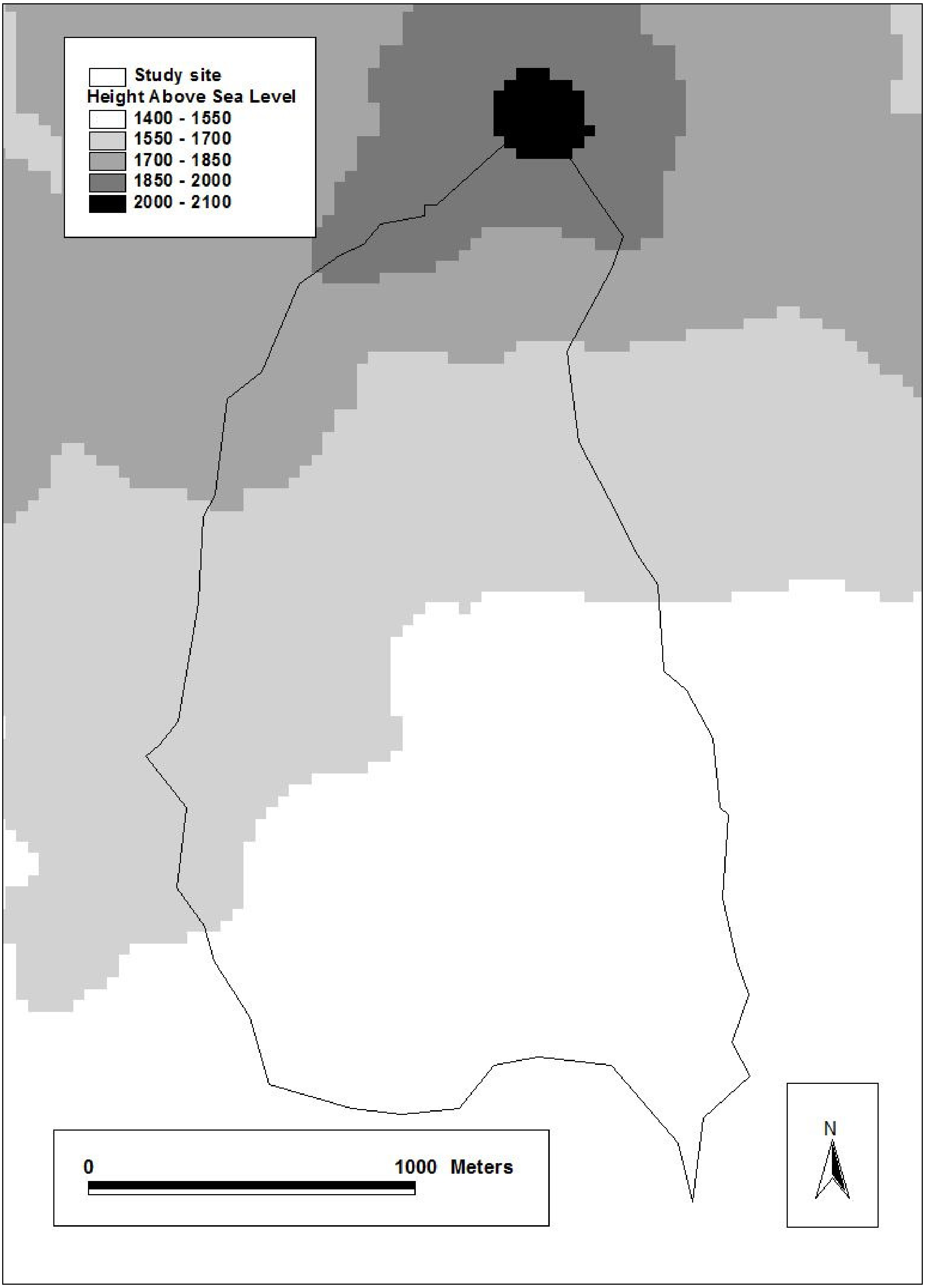
Appendix 1.7: Geological Map



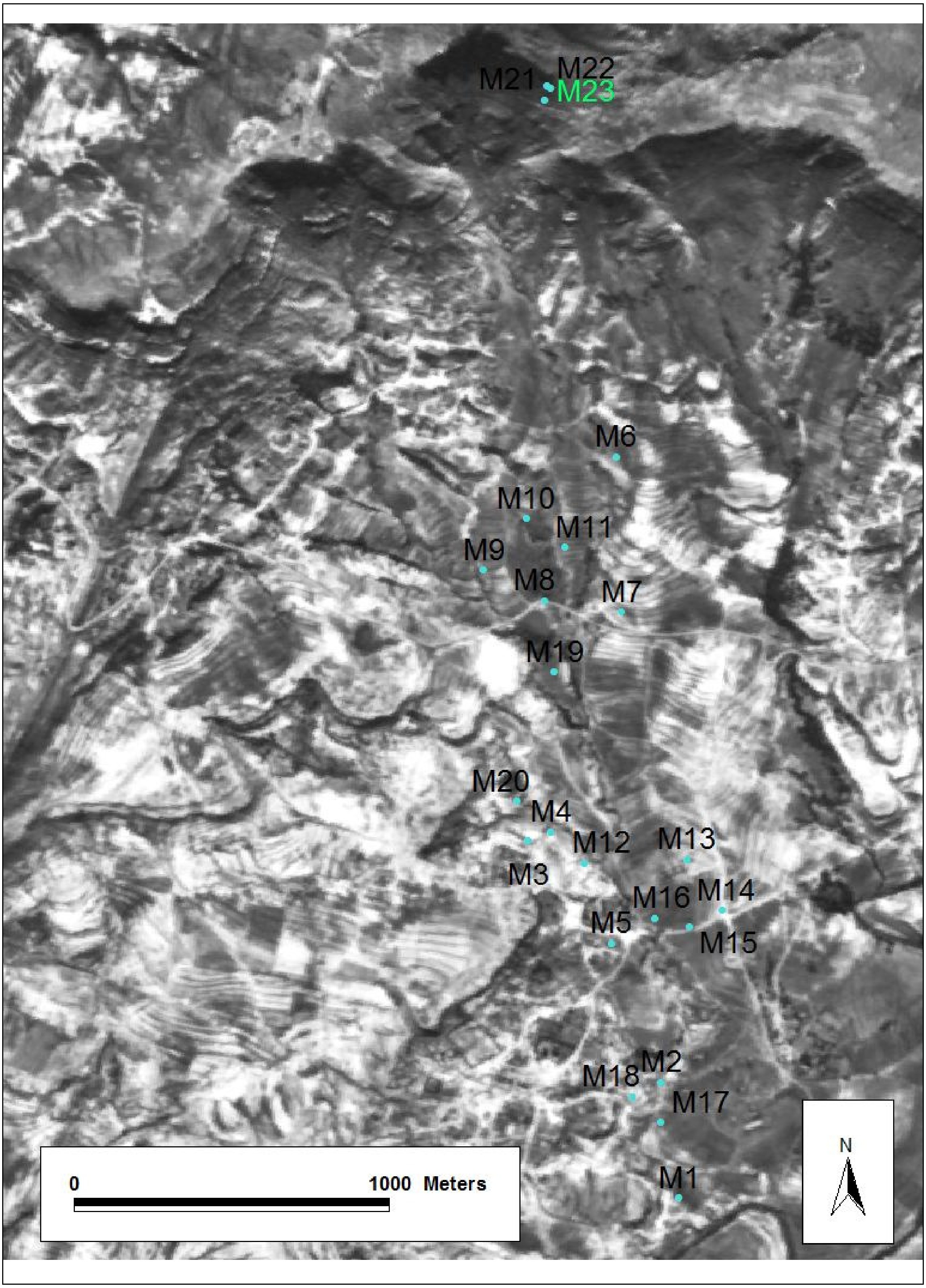
Appendix 1.8: Land Use Map



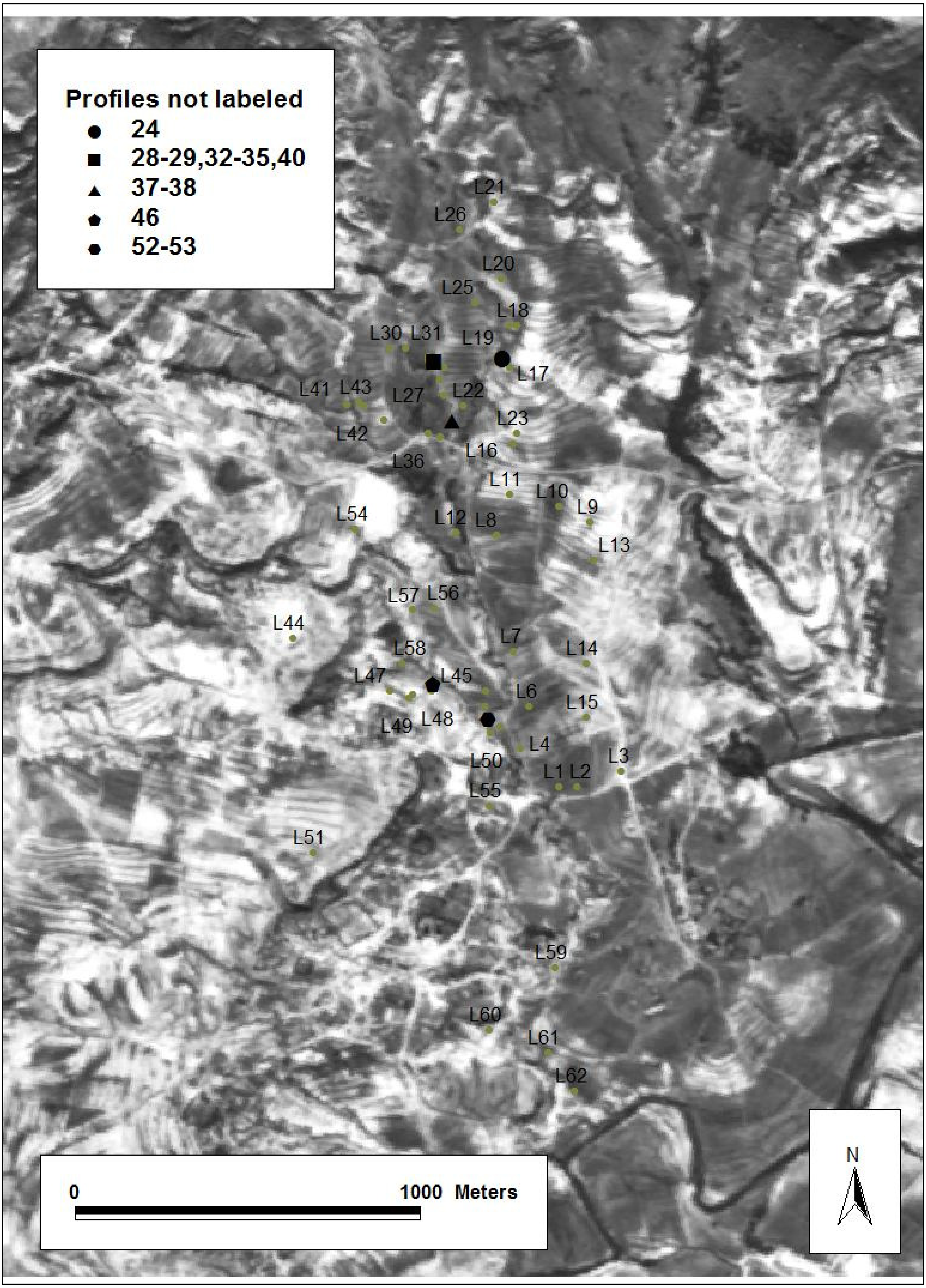
Appendix 1.9: Slope Class Map



Appendix 1.10: A DEM showing the heights above sea level for the study area. (ASTER GDEM, Undated; ASTER GDEM is a product of METI and NASA)



Appendix 1.11: Locations of the M-profiles



Appendix 1.12: Locations of the L profiles

Appendix 2: Soil data
Appendix 2.1.1: Profile descriptions of the modal profiles (M Profiles)

Profile nr: M1
Lat+Long: 30° 13' 4" / 27° 29' 16.3"
Altitude: 1476 m
Terrain Unit: Lower Midslope
Slope: 2 %
Aspect: South-west
Wetness Class: 1
Transitional Form: None

Soil form and family: Oakleaf caledon
WRB: Haplic Fluvisol (Sodic, Hypereutric)
Soil Map Unit: Sandy Alluvium
Vegetation / Land use: Barren
Parent Material: Origin binary, alluvium
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation : Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	100	Dry state; horizon undisturbed; dry colour: reddish brown 5YR5/4; moist colour: reddish brown 5YR4/4; texture: fine sandy loam; structure: weak fine subangular blocky; clear smooth transition.	Orthic
B1	400	Dry state; horizon undisturbed; dry colour: reddish brown 5YR4/4; moist colour: reddish brown 5YR4/3; structure: weak fine subangular blocky; few gravel 2-6mm; stoneline 10mm, single occurrence, lower part of horizon; abrupt smooth transition.	Neocutanic
B2	1200	Dry state; horizon undisturbed; dry colour: light reddish brown 5YR6/4; moist colour: reddish brown 5YR4/3; texture: loam; structure: weak fine subangular blocky.	Neocutanic

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Profile nr: M2
Lat+Long: 30° 12' 52.2" / 27° 29' 14.5"
Altitude: 1476 m
Terrain Unit: Midslope
Slope: 1%
Aspect: Level
Wetness Class: 6
Transitional Form: Sepane

Soil form and family: Bonheim windermere
WRB: Vertic Phaozems (Sodic)
Soil Map Unit: Melanic Blocky
Vegetation / Land use: Barren
Parent Material: Origin binary suspected
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation : Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	600	Dry state; dry colour: very dark grey 10YR3/1; moist colour: very dark grey 10YR3/1; texture: silty clay; structure: strong fine angular blocky; gradual smooth transition.	Melanic
B	1000+	Dry state; dry colour: reddish black 10R2.5/1; moist colour: very dark greyish brown 10YR3/2; texture: clay loam; common orange reduced iron oxide mottles; structure: moderate coarse angular blocky.	Pedocutanic

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Profile nr: M3
Lat+Long: 30° 12' 27.3" / 27° 29' 0.9"
Altitude: 1496 m
Terrain Unit: Midslope
Slope: 1 %
Aspect : North
Wetness Class: 2
Transitional Form: Estcourt
Soil form and family: Valsrivier zuney
WRB: Cutanic Luvisol (Hypereutric, Chromic)
Soil Map Unit: Duplex
Vegetation / Land use : Abandoned field/Disturbed land
Parent Material : Origin binary suspected
Underlying Material : Sedimentary rocks (unspecified)
Geological Group / Formation : Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	300	Dry state; horizon disturbed; dry colour: very pale brown 10yr7/3; moist colour: brown to dark brown 7.5YR4/2; texture: fine sandy loam; Orthic structure: weak fine subangular blocky; abrupt smooth transition.	Orthic
B	1100	Dry state; horizon undisturbed; dry colour: pink 5YR7/3; moist colour: dark reddish brown 5YR3/3; texture: clay loam; structure: moderate Pedocutanic coarse angular blocky; common clay cutans.	Pedocutanic

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Profile nr: M4
Lat+Long: 30° 12' 26.4" / 27° 29' 3.2"
Altitude : 1496 m
Terrain Unit: Midslope
Slope: 1 %
Aspect : North
Wetness Class: 7
Transitional Form:
Soil form and family: Estcourt nuweplaas
WRB: Solodic Planosol (Sodic)
Soil Map Unit: Duplex
Vegetation / Land use : Abandoned field/Disturbed land
Parent Material : Origin binary, aeolian
Underlying Materia : Sedimentary rocks (unspecified)
Geological Group / Formation : Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	150	Dry state; horizon disturbed; dry colour: greyish brown 10YR5/2; moist colour: very dark greyish brown 10YR3/2; texture: fine sandy loam; structure: weak fine subangular blocky; abrupt smooth transition	Orthic
E	400	Dry state; dry colour: light grey to grey 10YR6/1; moist colour: very dark grey 10YR3/1; texture: silty loam; structure: moderate coarse subangular blocky; abrupt smooth transition.	E-horizon
B	900+	Dry state; dry colour: grey 10YR5/1; moist colour: very dark greyish brown 10YR3/2; texture: clay loam; common yellow and black reduced iron oxide mottles; structure: moderate coarse prismatic; common clay cutans.	Prismacutanic

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Profile nr: M5

Lat + Long: 30° 12' 37.9" / 27° 29' 9.4"
Altitude: 1487 m
Terrain Unit: Midslope
Slope: 4 %
Aspect: East
Wetness Class: 6
Transitional Form: Klapmuts

Soil form and family: Estcourt nuweplaas
WRB: Solodic Planosol (Sodic)
Soil Map Unit: Duplex
Vegetation / Land use: Abandoned field/Disturbed land
Parent Material: Origin binary aeolian
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation: Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	370	Dry state; horizon disturbed; dry colour: pale brown 10YR6/3; moist colour: dark yellowish brown 10YR4/4; texture: fine sandy loam; structure: weak fine subangular blocky; diffuse smooth transition.	Orthic
E	450	Dry state; dry colour: light yellowish brown 10YR6/4; moist colour: dark yellowish brown 10YR4/4; texture: loam; structure: weak fine subangular blocky; abrupt smooth transition.	E-horizon
B	1000	Dry state; dry colour: yellowish red 5YR4/6; moist colour: yellowish red 5YR4/6; texture: clay; structure: moderate coarse angular blocky; common clay cutans.	Prismacutanic

---

Profile nr: M6

Lat+Long: 30° 11' 47.9" / 27° 29' 9.9"
Altitude: 1570 m
Terrain Unit: Upper Midslope
Slope: 8 %
Aspect: South
Wetness Class: 2
Transitional Form:

Soil form and family: Valsrivier goedemoed
WRB: Cutanic Luvisol (Hypereutric)
Soil Map Unit: Orthic Blocky
Vegetation / Land use: Agronomic cash crops
Parent Material: Origin binary suspected
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation: Elliott

Horizon	Depth (mm)	Description	Diagnostic horizon
A	100	Dry state; horizon disturbed; dry colour: brown to dark brown 7.5YR4/2; moist colour: dark brown 7.5YR3/2; texture: medium sand; structure: moderate medium subangular blocky; clear wavy transition.	Orthic
B	960	Dry state; dry colour: dark greyish brown 10YR4/2; moist colour: very dark brown 10YR2/2; texture: clay loam; structure: moderate coarse angular blocky; common clay cutans.	Pedocutanic

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Profile nr: M7

Lat+Long: 30° 12' 3.9" / 27° 29' 10.5"	**Soil form and family:** Glenrosa kilspindie
Altitude: 1538 m	**WRB:** Leptic Stagnic Cambisol (Sodic)
Terrain Unit: Upper Midslope	**Soil Map Unit:** Sandstone
Slope: 4 %	**Vegetation / Land use:** Agronomic cash crops
Aspect : South	**Parent Material:** Origin single
Wetness Class: 4	**Underlying Material:** Sandstone (unspecified)
Transitional Form:	**Geological Group / Formation:** Elliott

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	350	Dry state; horizon disturbed; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR5/6; texture: fine sandy loam; structure: weak fine subangular blocky; clear smooth transition.	Orthic
B	750	Dry state; dry colour: very pale brown 10YR7/4; moist colour: pale brown 10YR6/3; texture: fine sandy clay loam; common grey and white reduced iron oxide mottles; structure: weak fine subangular blocky; few flat stones 25-75mm.	Lithocutanic

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Profile nr: M8

Lat+Long: 30° 12' 2.7" / 27° 29' 2.6"	**Soil form and family:** Oakleaf ritchie
Altitude: 1543 m	**WRB:** Cutanic Luvisol (Hypereutric)
Terrain Unit: Upper Midslope	**Soil Map Unit**: Blocky
Slope: 4 %	**Vegetation / Land use:** Agronomic cash crops
Aspect: South	**Parent Material:** Origin binary suspected
Wetness Class: 2	**Underlying Material:** Sedimentary rocks (unspecified)
Transitional Form: Valsrivier	**Geological Group / Formation :** Elliott

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	150	Dry state; horizon disturbed; dry colour: reddish brown 5YR4/4; moist colour: dark brown 7.5YR3/2; texture: loam; structure: weak fine subangular blocky; gradual smooth transition.	Orthic
B1	450	Dry state; dry colour: brown to dark brown 7.5YR4/2; moist colour: dark brown 7.5YR3/2; texture: loam; structure: moderate fine subangular blocky; abrupt smooth transition.	Neocutanic
B2	1000+	Dry state; dry colour: dark brown 7.5YR3/2; moist colour: dark brown 7.5YR3/2; texture: clay loam; structure: moderate fine angular blocky.	Pedocutanic

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Profile nr: M9

Lat+Long: 30° 11' 59.6" / 27° 28' 56.3"
Altitude: 1543 m
Terrain Unit: Upper Midslope
Slope: 4 %
Aspect: South
Wetness Class: 3
Transitional Form:

Soil form and family: Valsrivier alice
WRB: Cutanic Luvisol (Hypereutric)
Soil Map Unit: Orthic Blocky
Vegetation / Land use: Agronomic cash crops
Parent Material: Origin binary suspected
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation: Elliott

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
A	150	Dry state; horizon disturbed; dry colour: brown 10YR5/3; moist colour: dark brown 7.5YR3/2; texture: loam; structure: weak fine subangular blocky; clear smooth transition.	Orthic
B	1000	Dry state; dry colour: brown to dark brown 7.5YR4/2; moist colour: dark brown 7.5YR3/2; texture: clay loam; structure: moderate fine angular blocky; common clay cutans.	Pedocutanic

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Profile nr: M10

Lat+Long: 30° 11' 59.6" / 27° 28' 56.3"
Altitude: 1549 m
Terrain Unit: Midslope
Slope: 4 %
Aspect: South-west
Wetness Class: 2
Transitional Form: Valsrivier

Soil form and family: Bonheim eureka
WRB: Vertic Phaozems (Sodic)
Soil Map Unit: Melanic Blocky
Vegetation / Land use: Grassveld, closed
Parent Material: Origin binary suspected
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation: Molteno

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon**
	50	Dry state; dry colour: brown 10YR5/3; moist colour: very dark greyish brown 10YR3/2; texture: loam; structure: weak fine subangular blocky; diffuse wavy transition.	Overburden
A	550	Dry state; dry colour: very dark greyish brown 10YR3/2; moist colour: black 10YR2/1; texture: loam; structure: moderate fine angular blocky; common clay cutans; few rounded gravel 2-6mm; gradual smooth transition.	Melanic
B	1000	Dry state; dry colour: brown to dark brown 7.5YR4/4; moist colour: dark brown 7.5YR3/2; texture: clay loam; structure: weak fine angular blocky; common clay cutans; common rounded gravel 2-6mm; gradual transition.	Pedocutanic

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Profile nr: M11

Lat+Long: 30° 11' 57.2" / 27° 29' 4.6'

Altitude: 1546 m

Terrain Unit: Upper Midslope

Slope: 9 %

Aspect: South

Wetness Class: 2

Transitional Form:

Soil form and family: Valsrivier slykspruit

WRB: Cutanic Luvisol (Hypereutric)

Soil Map Unit: Orthic Blocky

Vegetation / Land use: Grassveld, closed

Parent Material: Origin binary suspected

Underlying Material: Sedimentary rocks (unspecified)

Geological Group / Formation: Elliott

Horizon	Depth (mm)	Description	Diagnostic horizon
A	50	Dry state; dry colour: brown to dark brown 7.5YR4/4; moist colour: dark brown 7.5YR3/4; texture: fine sandy loam; structure: weak fine subangular blocky; few gravel 2-6mm; clear smooth transition	Orthic
B	900	Dry state; dry colour: dark brown 7.5YR3/4; moist colour: dark brown 7.5YR3/2; texture: clay loam; structure: moderate fine angular blocky; common coarse gravel 25-75mm.	Pedocutanic

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Profile nr: M12

Lat+Long: 30° 12' 29.6" / 27° 29' 6.6"

Altitude: 1494 m

Terrain Unit: Midslope

Slope: 4 %

Aspect: East

Wetness Class: 7

Transitional Form:

Soil form and family: Estcourt zastron

WRB: Solodic Planasol (Albic, Sodic)

Soil Map Unit: Duplex

Vegetation / Land use: Abandoned field/Disturbed land

Parent Material: Origin binary suspected

Underlying Material: Sedimentary rocks (unspecified)

Geological Group / Formation: Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	250	Dry state; dry colour: pale brown 10YR6/3; moist colour: brown to dark brown 10YR4/3; texture: loamy fine sand; structure: weak fine subangular blocky; aeolian ; clear smooth transition	Orthic
E	450	Dry state; dry colour: light grey 10YR7/2; moist colour: dark greyish brown 10YR4/2; texture: fine sandy loam; structure: moderate medium subangular blocky; abrupt smooth transition	E-horizon
B	1000+	Dry state; dry colour: pale brown 10YR6/3; moist colour: strong brown 7.5YR4/6; texture: fine sandy clay loam; common fine prominent orange reduced iron oxide mottles; structure: strong medium prismatic; common clay cutans.	Prismacutanic

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Profile nr: M13

Lat+Long: 30° 12' 29.2" / 27° 29' 17.1"
Altitude: 1489 m
Terrain Unit: Midslope
Slope: 4 %
Aspect: South
Wetness Class: 2
Transitional Form:

Soil form and family: Valsrivier zuney
WRB: Cutanic Luvisol (Hypereutric, Chromic)
Soil Map Unit: Red Blocky
Vegetation / Land use: Agronomic cash crops
Parent Material: Origin unknown
Underlying Material: Sandstone (unspecified)
Geological Group / Formation: Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	300	Dry state; horizon disturbed; dry colour: brown 10YR5/3; moist colour: dark brown 7.5YR3/2; texture: loam; structure: weak fine subangular blocky; clear wavy transition.	Orthic
B	1000	Dry state; dry colour: reddish brown 5YR4/3; moist colour: dark reddish brown 5YR3/3; texture: clay; structure: moderate coarse angular blocky; common clay cutans; very few gravel 6-25mm.	Pedocutanic

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Profile nr: M14

Lat+Long: 30° 12' 24.4" / 27° 29' 20.7"
Altitude: 1492 m
Terrain Unit: Midslope
Slope: 2 %
Aspect: South
Wetness Class: 2
Transitional Form:

Soil form and family: Swartland mtini
WRB: Cutanic Luvisol (Hypereutric, Chromic)
Soil Map Unit: Red Blocky
Vegetation / Land use: Agronomic cash crops
Parent Material: Origin unknown
Underlying Material: Sandstone (unspecified)
Geological Group / Formation: Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	250	Dry state; horizon disturbed; dry colour: strong brown 7.5YR5/6; moist colour: dark reddish brown 5YR3/3; texture: fine sandy loam; structure: weak fine subangular blocky; few mixed-shape stones 25-75mm; clear smooth	Orthic
B	600	Dry state; dry colour: reddish brown 5YR4/4; moist colour: dark reddish brown 5YR3/4; texture: clay loam; structure: strong coarse angular blocky; many clay cutans; common stones 25-75mm; few gravel 2-6mm; weathered remnants of stones multiple occurrence, lower part of horizon.	Pedocutanic

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Profile nr: M15

Lat+Long: 30° 12' 36.2" / 27° 29' 17.5"	**Soil form and family:** Valsrivier goedemoed
Altitude: 1486 m	**WRB:** Cutanic Luvisol (Hypereutric)
Terrain Unit: Midslope	**Soil map Unit:** Orthic Blocky
Slope: 1 %	**Vegetation / Land use:** Agronomic cash crops
Aspect: South	**Parent Material:** Origin binary suspected
Wetness Class: 4	**Underlying Material:** Sedimentary rocks (unspecified)
Transitional Form:	**Geological Group / Formation:** Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	250	Dry state; horizon disturbed; dry colour: brown to dark brown 7.5YR4/2; moist colour: dark brown 7.5YR3/2; texture: silty clay loam; structure: weak medium angular blocky; clear wavy transition.	Orthic
B	1000	Dry state; dry colour: brown to dark brown 7.5YR4/2; moist colour: black 7.5YR2.5/0; texture: silty clay; structure: moderate coarse angular blocky; many clay cutans.	Pedocutanic

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Profile nr: M16

Lat+Long: 30° 12' 36.2" / 27° 29' 17.5"	**Soil form and family:** Oakleaf cooper
Altitude: 1487 m	**WRB:** Cutanic Luvisol (Hypereutric)
Terrain Unit: Midslope	**Soil Map Unit:** Orthic Blocky
Slope: 1 %	**Vegetation / Land use:** Agronomic cash crops
Aspect: South	**Parent Material:** Origin binary suspected
Wetness Class: 4	**Underlying Material:** Sedimentary rocks (unspecified)
Transitional Form: Valsrivier	**Geological Group / Formation:** Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	100	Dry state; dry colour: dark greyish brown 10YR4/2; moist colour: black 10YR2/1; texture: loam; structure: weak medium angular blocky; gradual smooth transition.	Orthic
AB	550	Dry state; dry colour: dark greyish brown 10YR4/2; moist colour: black 10YR2/1; texture: loam; structure: weak medium angular blocky; common clay cutans; clear smooth transition.	Neocutanic
B	1000	Dry state; dry colour: dark grey 10YR4/1; moist colour: very dark grey 7.5YR3/0; texture: clay loam; structure: moderate medium angular blocky; very few gravel 2-6mm	Pedocutanic

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Profile nr: M17

Lat+Long: 30° 12' 56.2" / 27° 29' 14.5"
Altitude: 1472 m
Terrain Unit: Midslope
Slope: 1 %
Aspect: South-west
Wetness Class: 3
Transitional Form:

Soil form and family: Bonheim windermere
WRB: Vertic Phaozems (Sodic)
Soil Map Unit: Melanic Blocky
Vegetation / Land use: Grassveld, sparse
Parent Material: Origin binary suspected
Underlying Material: Sedimentary rocks (unspecified)
Geological Group / Formation: Molteno

Horizon	Depth (mm)	Description	Diagnostic horizon
A	100	Dry state; dry colour: dark brown 7.5YR3/2; moist colour: very dusky red 10R2.5/2; texture: silty clay loam; structure: moderate medium angular blocky; medium cracks; clear smooth transition.	Melanic
B	900+	Dry state; dry colour: very dark brown 7.52/2; moist colour very dark brown 7.5YR2/2; texture: silty clay loam; structure: strong coarse angular blocky; medium cracks; common cutans.	Pedocutanic

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Profile nr: M23

Lat+Long: 30° 11' 9.8" / 27° 29' 2.8"
Altitude: 1940 m
Terrain Unit: Scarp
Slope: 26 %
Aspect: South
Wetness Class: 2
Transitional Form:

Soil form and family: Milkwood effingham
WRB: Mollic Leptosols (Sodic, Eutric)
Soil Map Unit: Basaltic
Vegetation / Land use : Grassveld, open
Parent Material: Origin single
Underlying Material: Igneous rocks (Basalt)
Geological Group / Formation: Lesotho

Horizon	Depth (mm)	Description	Diagnostic horizon
A	450	Dry state; dry colour: very dark grey 10YR3/1; moist colour: black 10YR2/1; texture: loam; structure: strong medium granular.	Melanic

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Appendix 2.1.2: Soil Colour values

Sample Number	Colour				
	Munsell		Numerical value*		
	Dry	Moist	Dry	Moist	Moist vs Dry
M1A	5YR5/4	5YR4/4	12.4	8.55	4.00
M1B	5YR6/4	5YR4/3	8.55	8.25	1.00
M2A	10YR3/1	10YR3/1	4.03	4.03	0.00
M2B	2.5YR5/1	10YR3/2	12.0	4.18	8.09
M3A	10YR7/3	7.5YR4/2	20.1	8.07	12.0
M3B	5YR4/4	5YR3/3	8.55	4.48	4.12
M4A	10YR5/2	10YR3/2	12.1	4.18	8.00
M4E	10YR6/1	10YR3/1	16.0	4.03	12.0
M4B	10YR5/1	10YR3/2	12.0	4.18	8.06
M5A	10YR6/3	10YR4/4	16.1	8.59	8.06
M5E	10YR6/4	10YR4/4	16.3	8.59	8.00
M5B	5YR4/6	5YR4/6	9.44	9.44	0.00
M6A	7.5YR4/2	7.5YR3/1	8.07	4.01	4.12
M6B	10YR4/2	10YR2/2	8.09	1.20	8.00
M7A	7.5YR5/6	7.5YR5/6	13.0	13.0	0.00
M7B	10YR7/4	10YR6/3	20.2	16.1	4.12
M8A	7.5YR4/4	7.5YR3/2	8.57	4.15	4.47
M8B1	7.5YR4/2	7.5YR3/2	8.07	4.15	4.00
M8B2	7.5YR3/1	7.5YR3/2	4.01	4.15	1.00
M9A	10YR5/3	7.5YR3/2	12.2	4.15	8.07
M9B	7.5YR4/1	7.5YR3/1	8.01	4.01	4.00
M10A	10YR5/3	10YR3/2	12.2	4.18	8.06
M10B1	10YR3/2	10YR2/1	4.18	0.47	4.12
M10B2	7.5YR4/3	7.5YR3/2	8.26	4.15	4.12
M11A	7.5YR4/4	7.5YR3/3	8.57	4.50	4.12
M11B	7.5YR3/2	7.5YR3/1	4.15	4.01	1.00
M12A	10YR6/3	10YR4/3	16.1	8.29	8.00
M12E	10YR7/2	10YR4/2	20.0	8.09	12.0
M12B	10YR6/3	7.5YR4/3	16.1	8.26	8.01
M13A	10YR5/3	7.5YR3/2	12.2	4.15	8.07
M13B	5YR4/3	5YR3/3	8.25	4.48	4.00
M14A	7.5YR5/6	5YR3/3	13.0	4.48	8.57
M14B	5YR4/4	5YR3/4	8.55	5.01	4.00
M15A	7.5YR4/1	7.5YR3/1	8.01	4.01	4.00
M15B	7.5YR4/1	7.5YR2.5/1	8.01	2.02	6.00
M16A	10YR4/2	10YR2/1	8.09	0.47	8.06
M16B	10YR4/1	7.5YR3/1	8.01	4.01	4.00
M17A	7.5YR3/2	7.5YR2.5/2	4.15	2.28	2.00
M17B	7.5YR3/1	7.5YR2.5/1	4.01	2.02	2.00
M18	5Y7/2	5Y5/3	20.0	12.2	8.06
M19	5YR5/4	5YR4/3	12.4	8.25	4.12
M20	5YR6/4	5YR4/4	16.3	8.55	8.00
M21	10YR3/2	10YR2/2	4.18	1.20	4.00
M22	10YR4/6	7.5YR2.5/3	9.50	2.88	6.74
M23	10YR3/1	10YR2/1	4.03	0.47	4.00

* Calculated value from Melville and Atkinson (1985), with reference colour: 10YR2/1

Appendix 2.1.3: Particle size analysis

Sample Number	Particle Size Analysis Coarse sand 500-2000µm	Medium sand 250-500µm	Fine sand 125-250µm	Very fine sand 53-125µm	Silt 2-53µm	Clay <2µm
M1A	1.1	4.7	30.9	33.4	18.7	11.2
M1B	0.8	3.6	20.7	25.2	37.7	12.0
M2A	0.4	0.0	0.00	3.71	48.5	47.3
M2B	1.1	0.4	2.29	23.1	44.6	28.5
M3A	0.8	7.2	34.9	26.7	23.6	6.79
M3B	0.2	4.0	15.6	13.6	35.1	31.5
M4A	0.2	5.4	32.8	24.7	28.4	8.53
M4E	0.0	1.6	13.8	16.4	51.7	16.5
M4B	0.7	2.1	12.7	13.5	38.7	32.2
M5A	0.3	3.0	31.7	32.8	26.1	6.07
M5E	0.2	1.7	19.1	21.4	37.6	20.0
M5B	0.4	0.8	9.12	17.2	29.6	42.9
M6A	0.6	1.1	9.77	30.0	38.6	19.9
M6B	0.6	0.5	6.53	22.5	41.3	28.6
M7A	0.3	0.9	34.6	28.8	16.9	18.6
M7B	0.3	0.4	19.4	33.7	22.3	23.8
M8A	0.6	0.8	11.7	36.1	30.5	20.4
M8B1	0.3	0.6	11.5	34.2	32.6	20.9
M8B2	0.5	0.8	8.01	25.6	35.0	30.2
M9A	1.8	1.4	10.5	30.4	39.1	16.8
M9B	0.8	0.8	5.22	19.3	43.6	30.3
M10A	5.5	2.5	8.66	24.8	39.2	19.4
M10B1	4.8	2.1	9.15	23.3	33.6	27.0
M10B2	7.3	3.1	11.4	23.8	24.4	30.1
M11A	7.8	3.2	16.6	32.6	23.1	16.7
M11B	6.4	3.0	7.71	21.2	32.3	29.3
M12A	0.7	4.2	37.6	31.6	19.0	6.80
M12E	0.2	2.8	29.4	28.5	32.2	6.78
M12B	0.8	2.5	24.0	23.8	24.1	24.8
M13A	0.4	0.5	6.83	28.0	44.7	19.5
M13B	0.5	0.5	8.62	24.5	23.9	42.1
M14A	0.8	3.0	20.9	29.4	26.6	19.2
M14B	3.4	3.4	14.1	16.9	24.4	37.8
M15A	0.6	0.1	1.26	9.59	55.3	33.1
M15B	0.4	0.0	1.00	7.17	50.6	40.9
M16A	0.9	1.8	14.5	31.6	34.8	16.4
M16B	1.6	1.4	10.2	24.3	34.2	28.3
M17A	0.4	0.2	2.0	14.2	47.3	35.9
M17B	0.2	1.9	5.25	8.65	50.8	33.2
M18	0.3	0.0	2.26	19.91	61.9	15.7
M19	1.7	0.5	3.64	25.3	54.0	15.0
M20	0.8	0.4	5.37	18.8	59.1	15.5
M21	18.2	6.4	10.2	19.6	32.9	12.8
M22	23.0	9.0	11.5	17.1	27.7	11.6
M23	12.4	3.9	7.03	16.2	42.9	17.5

Appendix 2.1.4: Some chemical analyses

Sample Number	Total N %	Total C %	pH KCl	pH Water	SAR	EC mS/m	Fe_{CBD} %	AL_{CBD} %	Mn_{CBD} ppm
M1A	0.1	0.2	5.3	6.8	0.2	11.7	0.4	0.1	255
M1B			6.9	8.5	1.3	23.3	0.4	0.1	170
M2A	0.2	1.8	5.3	6.7		41.4	0.8	0.1	265
M2B			6.2	7.8	0.9	26.3	0.6	0.0	205
M3A	0.1	0.4	5.0	6.3	0.7	12.3	0.4	0.1	85
M3B			4.4	6.4	0.9	10.7	0.7	0.1	350
M4A	0.1	0.6	5.7	6.8	0.2	22.7	0.3	0.0	180
M4E			5.3	6.8		23.4			
M4B			5.5	7.2	1.6	11.3			
M5A	0.1	0.5	5.0	6.2	0.2	23.3	0.3	0.0	30
M5E			4.3	6.1	1.8	23.4			
M5B			4.7	6.2	3.1	20.0	1.3	0.2	215
M6A	0.1	1.2	5.0	6.5	0.3	17.5	0.7	0.1	155
M6B			5.4	6.9	0.4	16.6			
M7A	0.0	0.5	4.0	5.4	0.5	14.4	0.7	0.2	155
M7B			4.1	5.5	1.6	13.7	0.9	0.2	150
M8A	0.0	1.1	4.9	6.1	0.4	18.8	0.9	0.1	390
M8B1			4.9	6.1	0.2	18.3			
M8B2			4.6	5.9	0.5	10.2			
M9A	0.0	0.8	5.6	6.8	0.2	17.1	0.7	0.1	210
M9B			4.9	6.3	0.8	8.00			
M10A	0.2	3.3	4.9	6.0	0.1	20.2	1.0	0.1	240
M10B1			5.4	7.0	0.2	11.2			
M10B2			5.7	7.3	0.3	11.3	1.3	0.2	200
M11A	0.0	0.8	5.1	6.8	0.4	17.5	0.8	0.1	55
M11B			5.8	7.6	0.9	30.9			
M12A	0.0	0.3	5.2	6.2	0.4	13.5	0.3	0.1	220
M12E			5.6	7.3	2.6	25.7			
M12B			6.1	8.0	6.9	31.0			
M13A	0.0	1.0	4.7	5.9	0.3	19.3	0.8	0.1	485
M13B			4.9	6.4	0.6	11.7	1.2	0.2	240
M14A	0.0	0.6	4.7	6.1	0.3	18.1	0.9	0.1	225
M14B			4.6	6.2	0.5	15.2	1.7	0.2	425
M15A	0.0	2.0	5.0	6.1	0.3	23.4	1.1	0.1	50
M15B			4.9	6.3	0.5	16.4			
M16A	0.0	1.2	5.4	6.7	0.2	20.0	0.5	0.1	105
M16B			5.5	6.8	0.3	26.1			
M17A	0.1	2.8	4.8	6.1	0.2	21.2	1.2	0.2	50
M17B			5.1	6.5		20.0			
M18	0.0	0.1	6.5	8.3	1.3	20.4	0.2	0.1	340
M19	0.0	0.1	7.4	8.7	0.6	17.9	0.1	0.1	95
M20	0.1	0.7	7.8	9.1	5.3	33.1	0.6	0.1	410
M21	0.3	4.8	4.7	6.5	0.2	15.0	0.4	0.1	530
M22	0.3	7.1	4.9	7.7	0.3	17.9	0.3	0.1	235
M23	0.1	4.9	5.6	6.9	0.2	29.1	0.5	0.2	495

Appendix 2.1.5: Exchangeable Cation Analyses

Sample Number	Exchangeable Cations									ECEC/Clay	
	Ca	Mg	K	Na	ECEC	ECaP	EMgP	ESP	Ca:Mg	Total	C_{adj}*
		cmolc/kg				%	%	%		cmolc/kg	
M1A	3.9	1.5	0.2	0.1	5.6	68.8	26.0	0.9	2.6	50	47
M1B	8.5	2.5	0.1	0.2	11.3	74.8	22.3	1.7	3.4	94	
M2A[a]	20.4	6.1	0.4	0.3	27.1	75.3	22.4	1.0	3.4	57	
M2B	14.5	4.0	0.3	0.2	19.0	76.5	20.8	1.2	3.7	67	
M3A	2.4	0.7	0.3	0.1	3.4	70.3	19.8	1.7	3.5	50	42
M3B	5.7	2.4	0.2	0.1	8.8	64.9	27.8	1.7	2.3	28	
M4A	5.1	0.7	0.2	0.0	6.1	83.8	11.9	0.7	7.0	71	61
M4E[a]	5.3	0.7	0.1	0.1	6.2	84.8	11.1	2.1	7.7	96	
M4B	9.2	1.7	0.3	0.3	11.5	80.1	15.1	2.5	5.3	36	
M5A	2.2	0.7	0.3	0.0	3.2	67.9	20.5	1.2	3.3	53	40
M5E	3.3	1.7	0.1	0.2	5.5	61.0	31.0	3.3	2.0	27	
M5B	7.3	4.1	0.4	0.6	12.4	58.9	33.0	4.8	1.8	29	
M6A	10.0	3.1	0.2	0.1	13.4	74.7	23.2	0.5	3.2	67	58
M6B	15.3	3.8	0.2	0.1	19.4	78.9	19.7	0.5	4.0	68	
M7A	2.4	0.8	0.2	0.1	4.5	53.8	17.7	1.1	3.0	24	21
M7B	4.8	2.1	0.1	0.2	9.1	53.0	23.2	2.3	2.3	38	
M8A	6.3	2.3	0.5	0.1	9.2	68.5	25.2	0.7	2.7	45	38
M8B1	6.4	2.2	0.3	0.1	9.0	71.7	24.7	0.8	2.9	43	
M8B2	8.7	3.2	0.2	0.1	12.2	70.9	26.2	1.1	2.7	40	
M9A	9.1	1.8	0.3	0.1	11.2	80.5	16.1	0.6	5.0	67	60
M9B	9.6	2.8	0.3	0.2	12.9	74.7	21.4	1.6	3.5	43	
M10A	10.6	5.6	0.8	0.1	17.1	62.1	32.9	0.3	1.9	88	63
M10B1	13.1	6.9	0.2	0.1	20.3	64.6	34.1	0.5	1.9	75	
M10B2	13.1	6.4	0.2	0.1	19.8	66.0	32.5	0.7	2.0	66	
M11A	7.8	3.5	0.2	0.1	11.6	67.2	30.4	0.7	2.2	70	63
M11B	20.2	8.1	0.3	0.4	28.9	69.8	28.1	1.2	2.5	99	
M12A	2.5	0.7	0.2	0.0	3.4	73.4	20.2	1.4	3.6	50	
M12E	2.4	0.5	0.0	0.1	3.1	79.7	14.8	3.9	5.4	45	45
M12B	7.5	1.9	0.2	1.0	10.5	70.7	17.8	9.3	4.0	42	
M13A	5.9	2.3	0.3	0.1	8.6	68.6	26.8	0.8	2.6	44	37
M13B	8.7	4.2	0.4	0.1	13.5	64.6	31.4	1.1	2.1	32	
M14A	4.9	2.8	0.4	0.0	8.1	59.9	34.4	0.6	1.7	42	38
M14B	10.0	5.6	0.3	0.1	16.0	62.3	35.2	0.9	1.8	42	
M15A	10.8	4.5	0.6	0.1	16.0	67.6	27.8	0.6	2.4	48	39
M15B	11.4	5.3	0.3	0.2	17.2	66.3	30.7	0.9	2.2	42	
M16A	7.2	3.2	0.3	0.1	10.8	66.4	29.9	0.6	2.2	66	55
M16B	9.4	4.8	0.3	0.1	14.6	64.4	32.8	0.6	2.0	52	
M17A	7.3	10.1	0.2	0.1	17.7	41.4	57.0	0.4	0.7	49	38
M17B[a]	8.2	8.8	0.2	0.3	17.4	47.1	50.3	1.5	0.9	52	
M18	10.9	4.0	0.3	0.2	15.4	70.9	25.9	1.3	2.7	98	97
M19	15.7	3.7	0.0	0.2	19.6	79.9	19.0	1.0	4.2	131	130
M20	9.7	1.3	0.2	0.4	11.6	83.6	10.9	3.3	7.7	75	68
M21	15.5	6.8	0.4	0.1	22.8	68.1	29.9	0.3	2.3	178	122
M22	20.8	8.6	0.1	0.3	29.8	69.9	28.9	1.1	2.4	257	165
M23	20.9	8.9	0.2	0.2	30.1	69.3	29.4	0.5	2.4	172	130

*C_{adj} = Carbon adjusted ECEC/Clay

[a]Values closely estimated as no Ca and Mg saturated paste determinations could be done.

Appendix 2.1.6: Determinant Variables

Sample Number	Infiltration	%WSA	WD Fine silt	WD Clay	WD Silt+Clay	Dispersion Ratio
	mm/h			%		
M1A	89	32.4	6.2	2.5	8.7	22.2
M1B		27.4	8.7	3.7	12.5	31.1
M2A	71	89.9	21.2	7.5	28.7	15.8
M2B		61.8	17.5	5.0	22.4	17.5
M3A	83	50.0	15.0	3.7	18.7	55.1
M3B		48.7	18.7	8.7	27.4	27.7
M4A	55	50.8	8.7	2.5	11.2	29.2
M4E		39.6	23.7	5.0	28.7	30.3
M4B		79.5	23.7	11.2	34.9	34.8
M5A	77	62.4	11.2	2.5	13.7	41.1
M5E		39.2	17.5	5.0	22.4	24.9
M5B		78.9	13.7	6.2	19.9	14.5
M6A	108	55.8	11.2	1.2	12.5	6.3
M6B		74.2	13.7	3.7	17.5	13.1
M7A	101	45.0	7.5	1.2	8.7	6.7
M7B		65.1	8.7	2.5	11.2	10.5
M8A	131	44.6	8.7	2.5	11.2	12.3
M8B1		59.1	12.5	2.5	15.0	12.0
M8B2		73.2	7.5	2.5	10.0	8.3
M9A	78	35.0	12.5	3.7	16.2	22.2
M9B		69.1	13.7	3.7	17.5	12.3
M10A	194	94.0	7.5	2.5	10.0	12.8
M10B1		91.5	6.2	1.2	7.5	4.6
M10B2		90.0	6.2	1.2	7.5	4.1
M11A	101	81.4	6.2	1.2	7.5	7.5
M11B		78.1	8.7	2.5	11.2	8.5
M12A	56	25.2	5.0	2.5	7.5	36.7
M12E		17.7	12.5	3.7	16.2	55.2
M12B		61.1	11.2	17.5	28.7	70.4
M13A	55	56.5	15.0	3.7	18.7	19.2
M13B		71.8	11.2	2.5	13.7	5.9
M14A	102	30.9	8.7	1.2	10.0	6.5
M14B		92.2	8.7	1.2	10.0	3.3
M15A	32	44.0	26.2	5.0	31.2	15.0
M15B		84.0	21.2	5.0	26.2	12.2
M16A	94	35.6	10.0	2.5	12.5	15.2
M16B		67.1	12.5	2.5	15.0	8.8
M17A	108	90.7	13.7	1.2	15.0	3.5
M17B		86.3	16.2	2.5	18.7	7.5
M18	99	94.8	10.0	0.0	10.0	0.0
M19	88	89.7	8.7	1.2	10.0	8.3
M20	9	85.7	11.2	2.5	13.7	16.1
M21	202	97.7	6.2	0.0	6.2	0.0
M22	304	88.1				
M23	439	94.6	3.7	0.0	3.7	0.0

Appendix 2.2: Profile descriptions of the survey profiles (L profiles)

Appendix 2.2.1: Key to abbreviations used in profile descriptions

Land Form

Symbol	Description
LL	Level land <10% Plateau
SH	Sloping land 10-30% medium gradient hill
SM	Sloping land 10-30% medium gradient mountain
SE	Sloping land 10-30% medium gradient escarpment zone

Slope Shape

Symbol	Description
S	Straight
C	Concave
V	Convex

First letter indicates the primary and the second letter indicates the secondary shape

Slope Position

Symbol	Description
LS	Lower slope
MS	Mid slope
US	Upper slope

Human Influence

Symbol	Description
PL	Plough Cultivation
C	Contour
WC	Water Channel
FP	Foot Path

Vegetation

Symbol	Description
G	Grass
W	Weeds
N	None

The number indicates percentage cover

Parent Material

Symbol	Description
Bnry sus	Suspected Binary Unconsolidated
Bnry	Binary Unconsolidated
SS	Sandstone

Wetness Class

Scale of 1-10 with 10 being wettest

Structure

Symbol	Description
Fa	Fine Angular
Ca	Coarse Angular
Sa	Subangular
Pr	Prismatic
Sl	Stone Line

Sand Grade

Symbol	Description
f	Fine
m	Medium
c	Coarse

Coarse Fragments

Symbol	Description	Size
f	Fine Gravel	2-25mm
g	Coarse Gravel	25-75mm
k	Stones	75-250mm

Numerical number indicates occurrence with 1=10%, eg. 5 = 50%

Depth Code

Symbol	Depth (mm)
1	0-150
2	150-250
3	250-350
4	350-450
5	450-550
6	550-750
7	750-950
8	950-1150
9	1150-1350
0	1350-1550

First number shows depth of first (top) horizon
Second number shows depth of second (sub) horizon
Third number shows depth of third (deep) horizon

Soil Form

Abbreviation according to Soil Classification Working Group, 1991

Appendix 2.2.1: Profile descriptions of 62 survey profile pits – terrain features

Profile	Depth Code	Soil Form and Family	Land form	Slope Shape	Slope Position	Aspect	Terrain information Slope Gradient (Degrees)	Slope Length (m)	Human Influence	Vegetation	Parent Material	Transitional Form	Wetness class
L1	249	Bo2210	LL	SS	MS	S	2	10	PL, C	N	Bnry sus	Va	1
L2	38	Va1121	LL	SS	MS	W	3	20	PL	W	Bnry sus		1
L3	258	Va1211	LL	VS	MS	W	3	20	PL, C	G+W	Bnry		1
L4	359	Du1110	LL	LC	MS	S	5	15	C	W+G 50	Bnry	Va	1
L5	348	Wb1000	LL	CL	MS	W	8	5	Check dam	G 70	Bnry		
L6	178	Va1121	LL	CS	MS	W	7	4	PL, C	W 60	Bnry sus		1
L7	268	Va1121	LL	SS	MS	S	1	20	PL, C	W 60	Bnry sus		1
L8	257	Va1111	LL	VS	MS	S	5	4	PL, C	N	Bnry		1
L9	29	Se1110	SH	SS	MS	S	7	5	PL, C	W 20	Bnry sus		3
L10	370	Ll1000	SH	SS	MS	S	7	10	PL, C	W 50	Bnry sus		6
L11	19	Va1121	SH	SS	MS	S	7	10	PL, C	W 40	Bnry sus	Oa/deep Se	2
L12	246	Oa1110	SH	SS	MS	S	2	10	PL, C	W 60	Bnry	Du/Va	2
L13	13	Gs1111	SH	SS	MS	S	1	5	PL, C	W 30	SS	Sw/Ms	1
L14	30	Va1121	SH	SS	MS	S	7	25	PL, C	W 60	Bnry sus		1
L15	30	Va1221	LL	VS	MS	S	2	30	PL, C	G+W 80	Bnry sus		1
L16	23	Gs1111	SM	CS	MS	S	4	7	PL, C	W 40	SS		3
L17	18	Ss1100	SM	VS	MS	S	3	20	PL, C	W 10	Bnry sus	Va	6
L18	280	Va1211	SM	VS	US	S	2	10	PL, C	W 30	Bnry sus	Oa	1
L19	29	Va1121	SM	SC	US	S	4	40	PL, C	W 50	Bnry	Ss/ deep Se	3
L20	158	Va1121	SM	SS	US	S	6	30	PL, C	W 50	Bnry sus		1
L21	29	Oa1210	SM	CS	US	S	4	15		G 100	Bnry	Oa	1
L22	149	Va1122	SM	SV	MS	S	4	20	PL, C	W 20	Bnry sus	Au	1
L23	36	Oa1110	SM	VS	MS	SW	4	13	WC	G 80	SS	Va	1
L24	356	Va1121	SM	SV	MS	S	3	10	C	G 60	Bnry sus	Sw	1
L25	357	Va1121	SM	VV	US	S	3	15	PL, C	W 30	Bnry sus	Gs	6
L26	268	Va1121	SM	SV	US	S	5			G 90	Bnry		3

Appendix 2.2.2: Continued

Profile	Depth	Soil					Terrain information						
	Code	Form and Family	Land form	Slope Shape	Slope Position	Aspect	Slope Gradient (Degrees)	Slope Length (m)	Human Influence	Vegetation	Parent Material	Transitional Form	Wetness class
L27	29	Va1111	SM	SC	MS	SW	12	10	FP	G 90	Bnry		1
L28	28	Du2110	SM	CC	MS	S	4		FP	G 100	Bnry	Oa/Va	1
L29	37	Va2121	SM	VC	MS	SE	18	2	FP	G 80	Bnry		3
L30	35	Bo3210	SM	CV	US	S	7			G+W 70	Bnry sus	Sw/Oa	2
L31	28	Va1111	SM	CC	US	E	9	20		G 90	Bnry sus	Oa	2
L32	290	Du1210	SM	CC	MS	S	3	2		G+W 80	Bnry	Tu	1
L33	270	Tu1110	SM	CC	MS	W	4	2		G 70	Bnry	We	3
L34	260	Va1111	SM	CC	MS	S	9			G 85	Bnry sus	Oa	1
L35	346	Se1110	SM	VV	MS	S	7			G+W 40	Bnry		3
L36	39	Va1112	SM	CC	MS	S	1	5	PL, C	W 20	Bnry		2
L37	36	Du1110	SM	CV	MS	S	7	4		G 95	Bnry	Va	2
L38	169	Va1121	SM	CC	MS	S	2	40		G 97	Bnry sus	Ss	3
L39	39	Va1111	SM	CC	MS	SW	6	15		G 90	Bnry		1
L40	28	Va1121	SM	CC	MS	S	4	30	PL, C	W 40	Bnry	Ss	2
L41	279	Va2122	SM	CC	MS	S	12	4	PL, C	W 40	Bnry		1
L42	370	Du1210	SM	CC	MS	S	5		Gully	G 100	Bnry sus	Se	6
L43	149	Va2121	SM	SS	MS	S	2	15	PL, C	W 40	Bnry sus	Va	3
L44	14	Va1111	SM	VV	MS	NE	3	30	PL, C	W 40	Bnry sus	Oa	2
L45	159	Du1110	SM	VC	MS	E		40	WC	G 60	Bnry	Va/deep Se	6
L46	258	Du1210	SM	CS	MS	E	2	20	PL, C	W 50	Bnry sus		6
L47	158	Es2200	SM	CC	MS	N	3	2	PL/FP	W 35	Bnry sus	Ss	6
L48	360	Va2221	SE	SC	MS	N	4	17	WC	G+W 40	Bnry sus	Diep Se	2
L49	228	Es1200	S	CS	MS	NE	3	0.5	PL, C	G 40	Bnry	Ss	7
L50	138	Es1200	SE	CV	MS	NE	2	3	PL, C	W 5	Bnry sus	Ss	6
L51	4	Ms1100	LL	SS		NW	3	30	PL, C	N	SS	Gs	2
L52	380	Va1211	SM	SC	MS	SE	2	30	PL, C	W 70	Bnry	Oa/deep Se	2
L53	134	Km1220	SM	VV	MS	SE	2	17	PL, C	W 60	Bnry		6

Appendix 2.2.2: Continued

Profile	Depth Code	Soil Form and Family	Land form	Slope Shape	Slope Position	Aspect	Terrain information Slope Gradient (Degrees)	Slope Length (m)	Human Influence	Vegetation	Parent Material	Transitional Form	Wetness class
L54	260	Tu2110	SE	CV	MS	E	8	20	PL, C	W 60	Bnry	Buried Se	2
L55	25	Es2200	SE	CS	LS	E	5	7	PL	W 60	Bnry		6
L56	17	Se1110	SM	CS	MS	S	4	7	PL, C	G+W 50	Bnry sus	Tu	2
L57		Es			MS	S							6
L58		Es			MS	SE							6
L59	58	Bo1110	LL	S	LS	S	2			W 20	Bnry	Tu	3
L60	3	Tu2110			LS	E							
L61	3	Va1111			LS	S						Oa	
L62	269	Oa1210			LS	S							

Appendix 2.2.3: Profile descriptions of 62 survey profile pits – horizon descriptions

Profile	Depth Code	Soil Form and Family	Colour			Structure			Sand grade			Coarse Fragments		
			Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep
L1	249	Bo2210	7.5YR3/2 (m)	5YR3/2 (m)	2.5YR3/2 (m)	Fa	Ca	Ca	f	f	f			
L2	38	Va1121	7.5YR3/2 (m)	5YR3/2 (m)		Sa	Ca		f	f				
L3	258	Va1211	7.5YR5/8 (m)	5YR4/4 (m)	5YR 4/6 (m)	Sa	Fa	Ca	f	f	c		5k	
L4	359	Du1110	10YR4/4 (m)	7.5YR4/4 (m)	7.5YR 3/2 (m)	Fa	Ca	Ca	f	f	f	4f		
L5	348	Wb1000	10YR4/4		10YR5/4	Sa	SL	Sa			c		8k	3f
L6	178	Va1121	7.5YR4/4	7.5YR3/2	7.5YR5/6	Sa	Ca	Ca	f	f	f			
L7	268	Va1121	7.5YR5/4	7.5YR5/4	5YR5/4	Sa	Ca	Sa	f	f	f			1k
L8	257	Va1111	7.5YR4/4	7.5YR3/3	5YR3/1	Sa	Fa	Fa	f	f	f		1f	3f
L9	29	Se1110	10YR7/8	5YR4/6		Sa	Sa		f	f		1f		
L10	370	Ll1000	10YR4/1	10YR4/1	10YR3/2	Sa	Sa	Sa	f	f	f			
L11	19	Va1121	7.5YR5/6	7.5YR4/5 (m)		Sa	Ca		f	f			1f	
L12	246	Oa1110	7.5YR5/4	10YR5/8	10YR5/3	Sa	Sa	Sa	c	c	c	4f	2f	1f
L13	13	Gs1111	10YR6/4	7.5YR6/8 (m)		Sa	Sa		f	f		1f		
L14	30	Va1121	7.5YR5/6	7.5YR4/4		Sa	Ca		f	f		1f	1f	
L15	30	Va1221	7.5YR5/4	5YR4/8		Sa	Ca		f	f		1f	1f	
L16	23	Gs1111	10YR6/6	10YR5/8		Sa	Rock		f	f				
L17	18	Ss1100	10YR4/4	10YR4/4		Sa	Pr		f	f		1f		
L18	280	Va1211	5YR4/2	5YR3/3	5YR 6/3	Sa	Fa	Fa	f	f	f			
L19	29	Va1121	7.5YR4/2	10YR3/1		Sa	Ca		f	f		1f		
L20	158	Va1121	10YR4/3	10YR3/3	10YR4/4	Sa	Ca	Ca	f	f	f			
L21	29	Oa1210	5YR6/4	5YR4/4 (m)		Sa	Sa		f	f		1f	1f	
L22	149	Va1122	7.5YR5/4	7.5YR5/6 (m)	7.5YR5/6 (m)	Sa	Ca	Ca	f	f	f	2f	1f	
L23	36	Oa1110	7.5YR6/6	7.5YR5/6		Sa	Sa		m	m		1f	1f	
L24	356	Va1121	10YR4/3	7.5YR5/2	7.5YR5/6	Sa	Ca	Sa	f	f	f	1f	1f	1f
L25	357	Va1121	10YR5/6	7.5YR4/4	7.5YR 4/4	Sa	Ca	Ca	mixed	mixed	mixed	1f	5f+1g	4f+2g+2k
L26	268	Va1121	10YR5/6	7.5YR4/4	7.5YR 4/4	Sa	Ca	Ca	f	f	f	1f	1f	5f

Appendix 2.2.3: Continued

Profile	Depth Code	Soil Form and Family	Colour			Structure			Sand grade			Coarse Fragments		
			Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep
L27	29	Va1111	10YR3/3	10YR3/2		Sa	Fa		f	f		1f	3f	
L28	28	Du2110	7.5YR5/4	5YR5/4(m)		Sa	Sa		f	f		1f	1f	
L29	37	Va2121	10YR5/2	10YR4/3		Sa	Ca		c/m	f		2f	3f+1g	
L30	35	Bo3210	7.5YR3/2	7.5YR5/4 (m)		Ca	Ca		c	c		3f	4f	
L31	28	Va1111	7.5YR5/2	7.5YR4/2		Sa	Fa		m	m		3f	3f	
L32	290	Du1210	10YR4/3	10YR4/3	5YR 4/8	Sa	Fa	Ca	c	c	c	4f	2f	2f
L33	270	Tu1110	10YR5/6	10YR4/4	2.5YR5/4	Sa	Sa	Sa	c	c	c	3f+1g	3f+1g	1f
L34	260	Va1111	7.5YR4/4	7.5YR5/6	7.5YR 5/6	Sa	Fa	Ca	c	c	c		1f	0.5f
L35	346	Se1110	7.5YR4/4	7.5YR3/3	7.5YR3/3	Sa	Fa	Fa	c	c	c	5f+3g+1r	1f	3f
L36	39	Va1112	7.5YR5/2	7.5YR4/4		Sa	Fa		f	c+f		1g	0.5f	
L37	36	Du1110	7.5YR4/4 (m)	7.5YR4/4 (k)	5YR3/4	Sa	Fa	Fa	f	c	m	1f	3f	1k
L38	169	Va1121	7.5YR4/2	7.5YR3/2 (m)	7.5YR3/2 (m)	Ca	Ca	Ca	c	c	c		1m	
L39	39	Va1111	7.5YR5/6	10YR3/3		Sa	Fa		m	g/m		1f	1f+1m	
L40	28	Va1121	7.5YR5/6	7.5YR3/2 (m)		Sa	Ca		m	f				
L41	279	Va2122	7.5YR5/2	7.5YR4/2	5YR4/8	Sa	Ca	Ca	f	f	m			
L42	370	Du1210	5YR5/6	7.5YR5/6 (m)	7.5YR 3/2 (m)	Sa	Ca	Ca	c	m/c	c	1f	1f+1m	1f
L43	149	Va2121	7.5YR5/2	7.5YR4/2	10YR3/3	Sa	Fa	Ca	m/c	c/m	m/c		1f+1m	
L44	14	Va1111	7.5YR6/4	7.5YR4/4 (m)		Sa	Sa		m/c	m/c				
L45	159	Du1110	7.5YR6/2	7.5YR4/4 (m)	10YR5/3 (m)	Sa	Fa	Ca	m	m				
L46	258	Du1210	10YR5/2	7.5YR5/2	10YR7/1	Sa	Fa	Ca	c	m	f	1f	1f	
L47	158	Es2200	7.5YR7/6	7.5YR 7/3	10YR3/2	Sa	Sa	Pr	m	m	f			
L48	360	Va2221	7.5YR6/4	5YR6/4	2.5YR5/4	Sa	Fa	Ca	m	m	m	1f	1f	1f
L49	228	Es1200	7.5YR6/2	7.5YR6/2	5YR3/1	Sa	Sa	Pr	m	m	f	1f		
L50	138	Es1200	10YR5/3	7.5YR7/6	5YR5/6	Sa	Pr	Pr	m/c	m	m/c	1f		
L51	4	Ms1100	5YR6/4			Sa			m/f					
L52	380	Va1211	5YR6/4	5YR5/6	10YR4/3	Sa	Fa	Fa	m	m	c	1f		2f
L53	134	Km1220	5YR5/2	5YR6/2	5YR6/6	Sa	Sa	Ca	m	m	f			

Appendix 2.2.3: Continued

Profile	Depth Code	Soil Form and Family	Colour			Structure			Sand grade			Coarse Fragments		
			Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep	Top	Sub	Deep
L54	260	Tu2110	7.5YR6/4	7.5YR4/2		Sa	Ca		f	f	f			
L55	25	Es2200	10YR5/4 (m)	10YR5/4 (m)	5YR5/6 (m)	Sa	Sa	Pr	m	m	c			
L56	17	Se1110	5YR3/4 (m)	5YR4/4 (m)		Sa	Fa		m	c		1f	2f	
L57		Es				Sa	Pr							
L58		Es				Sa	Pr							
L59	58	Bo1110	5YR2.5/2	7.5YR4/2		Fa	Fa		f	f				
L60	3	Tu2110				Sa	Sa							
L61	3	Va1111				Sa	Sa							
L62	269	Oa1210				Sa	Sa							

Appendix 2.2.4: Profile descriptions of 62 survey profile pits - analytical information

Profile	Depth Code	Soil Form and Family	Clay Percentage			pH water		pH KCl		EC mS/m	
			Top	Sub	Deep	Top	Sub	Top	Sub	Top	Sub
L1	249	Bo2210	40	40	40	6.63	6.84	5.35	5.46	4.6	3.0
L2	38	Va1121	40	40		6.13	6.48	5.02	5.04	3.1	4.8
L3	258	Va1211	20	40	40	6.01	6.83	4.63	5.06	2.0	4.7
L4	359	Du1110	20	20	40	7	7.27	5.48	5.89	3.9	3.3
L5	348	Wb1000	5			7.1	7.38	5.66	6.00	3.6	2.6
L6	178	Va1121	20	20	25	6.71	6.68	5.53	5.3	6.6	3.4
L7	268	Va1121	12	30	25	6.66	6.89	5.35	5.75	2.7	3.9
L8	257	Va1111	15	40	35	6.13	6.3	4.86	4.79	2.6	4.2
L9	29	Se1110	5	28		5.52	5.94	4.27	4.39	2.9	5.7
L10	370	Ll1000	25	35	25	6.57	6.82	5.41	5.54	3.1	2.4
L11	19	Va1121	15	25		5.69	6.43	4.43	4.63	2.7	4.7
L12	246	Oa1110	20	20	20	6.97	6.9	5.69	5.55	5.8	4.9
L13	13	Gs1111	7	25		6.02		4.39		3.4	
L14	30	Va1121	5	27		6.01	6.26	4.73	4.77	2.2	2.7
L15	30	Va1221	10	30		6.29	6.39	4.9	4.63	3.7	4.6
L16	23	Gs1111	8	20		5.39		4.13		2.7	
L17	18	Ss1100	25	25		6.81	7.10	5.56	5.88	6.4	5.4
L18	280	Va1211	20	20	20	6.06	6.04	4.66	4.40	2.0	2.6
L19	29	Va1121	20	30		6.54	6.74	5.32	5.32	5.2	4.2
L20	158	Va1121	25	25	25	6.4	6.66	5.19	5.39	3.9	4.6
L21	29	Oa1210	20	20		6.37	6.53	5.35	5.18	7.7	4.7
L22	149	Va1122	25	16	25	6.61	8.00	5.2	7.11	4.6	7.5
L23	36	Oa1110	7	12		6.25		4.87		4.9	
L24	356	Va1121	23	20	15	6.29	6.46	5.02	5.11	3.7	3.8
L25	357	Va1121	20	25	25	6.3	6.62	4.98	5.10	3.0	15.5
L26	268	Va1121	25	35	35	6.22	6.56	5.02	5.37	7.0	4.3
L27	29	Va1111	20	20		6.24	6.38	5.04	5.23	10.9	6.2
L28	28	Du2110	22	22		6.45	6.71	5.00	5.21	6.3	3.5
L29	37	Va2121	17	23		6.95	7.29	5.45	5.84	7.3	5.6
L30	35	Bo3210	25	25		6.8	7.05	5.28	5.36	6.5	3.9
L31	28	Va1111	20	25		6.31	6.62	5.1	5.42	6.9	9.1
L32	290	Du1210	15	20	30	6.73	7.15	5.31	5.77	5.0	11.4
L33	270	Tu1110	18	18-28	30	6.48	6.52	4.90	4.90	8.1	5.8
L34	260	Va1111	25	25	18	6.56	6.79	5.09	5.28	6.2	4.9
L35	346	Se1110	15	25	25	6.41	6.91	5.08	5.25	8.8	6.7
L36	39	Va1112	15	30		6.02	5.75	4.94	4.74	5.7	8.1
L37	36	Du1110	40	20	15	6.16	6.46	4.78	4.92	6.5	5.2
L38	169	Va1121	33	33	40	6.39	6.57	4.92	4.57	5.5	2.7
L39	39	Va1111	18	40		6.45	6.44	4.91	5.29	8.7	3.0
L40	28	Va1121	15	40		6.1	6.48	4.80	4.99	2.1	3.3
L41	279	Va2122	25	40	40	7.02	6.46	5.81	5.10	7.0	4.2
L42	370	Du1210	27	25	33	6.6	6.77	5.33	5.55	4.0	2.5
L43	149	Va2121	15	23	30	6.81	6.62	5.48	5.41	4.9	5.4
L44	14	Va1111	12	15		5.45	5.93	4.58	4.76	12.6	1.9
L45	159	Du1110	10	15	30	6.4	6.7	5.37	5.21	4.0	2.7
L46	258	Du1210	15	18	40	6.69	7.16	5.72	6.33	4.8	4.9
L47	158	Es2200	8	32	23	6.36	6.16	5.4	4.91	6.2	2.9
L48	360	Va2221	7	20	15	6.00	6.41	4.91	4.68	2.0	2.8
L49	228	Es1200	7	7	45	6.38	6.97	5.43	5.89	3.7	6.8

Appendix 2.2.4: Continued

Profile	Depth Code	Soil Form and Family	Clay Percentage			pH water		pH KCl		EC mS/m	
			Top	Sub	Deep	Top	Sub	Top	Sub	Top	Sub
L50	138	Es1200	30	35	35	6.31	6.71	5.54	5.39	14.6	6.8
L51	4	Ms1100	7			6.09		4.86		5.0	0.0
L52	380	Va1211	7	12	30	6.60	6.65	5.64	5.59	4.4	2.9
L53	134	Km1220	7	7	40	6.22	6.49	5.24	5.31	5.0	2.7
L54	260	Tu2110	12	30		6.63	7.12	5.51	5.85	4.1	3.0
L55	25	Es2200	5	45		5.23	7.12	4.25	5.65	3.9	7.5
L56	17	Se1110	15	38		6.35	6.87	5.08	5.07	5.8	2.4
L57		Es								0.0	0.0
L58		Es				5.36	6.40	4.45	5.07	11.2	2.7
L59	58	Bo1110	35	35		6.50	6.92	5.35	5.58	6.4	4.4
L60	3	Tu2110									
L61	3	Va1111									
L62	269	Oa1210	12								

Appendix 3: Analytical methods

Appendix 3.1: Infiltrability Index

A rapid laboratory method was used to estimate the infiltrability and inherent crusting tendency of the pedoderm samples. This method was developed by Mills and Fey (2004) and modified slightly by Medinski (2007). The method followed was the one used by Medinski. The following description of the method has largely been duplicated from that publication.

A 16 g of air-dried soil was agitated vigorously with 80 ml of distilled water in a 120 ml cylinder on a reciprocal shaker at 150 rpm for 5 minutes. Two replicas of each soil sample consisting of 5 g of soil packed into 10 ml plastic syringes were used. A 1 mm layer of cotton wool was placed at the base of the syringes before adding the dry soil. The syringes were then placed in distilled water to allow water to move up into the syringe and saturate the soil. The agitated soil suspension was left to settle for 5 minutes after which a 21 ml aliquot was carefully taken from the settled suspension using a pipette immersed to a depth of 15 cm to prevent disturbance of the settled sediment. From this 21 ml aliquot, 7ml was then taken and pipetted gently into a syringe, while the base of the syringes was blocked by finger pressure to prevent premature drainage. The syringes were then placed in a rack above a beaker on a digital balance and the bases of the syringes were released to allow drainage into the beaker. The rate of water release from the syringes was recorded as the mass increase of the receiving beakers over time.

Appendix 3.2: Water dispersible silt and clay

The water dispersible silt and clay was determined with the double pipette method (Soil Classification Working Group, 1991), but with a few minor adjustments. The method is described by Medinski (2007), and this description has also largely been duplicated from that publication.

Thirty gram of soil was weighed into a beaker, after which 150 ml of distilled H_2O was added to make a 1:5 soil:water suspension. The beaker was then put onto a shaker for 5 min. The soil suspension was subsequently decanted into a 1 L glass cylinder and made up to 1 L with distilled water. The solution was thoroughly mixed with a rod for 1 minute and then left to stand to allow the dispersed particles to settle. An aliquot of 25 ml was pipetted at the prescribed time from a 10 cm depth into a porcelain dish of recorded weight for fine silt + clay determination. The water was evaporated from the dish by placing it in a water bath. The porcelain dishes were finally put into an oven at 100ºC to ensure complete drying. The weight of sample was recorded. Another 25 ml aliquot was taken from the same cylinder for clay determination, at the prescribed time and treated in the same way as the first aliquot.

The fine silt and clay content were calculated using the following formulas:

Percent fine silt + clay (SC) = A x 1000 x 100 / E x 25,

Percent clay (C) = B x 1000 x 100 / E x 25,

Percent Fine Silt = SC – C,

Where:

A – mass(g) of pipetteted fine silt plus clay
B – mass(g) of pipetteted clay
E – mass of dry total soil sample

Appendix 3.3: Aggregate stability

The percentage water stable aggregates (%WSA) were determined at the University of Pretoria with a method based on the wet sieving method of Kemper and Rosenau (1986).

Four grams soil in the 1-2mm aggregate size fraction was placed on a 250µm sieve and wetted by submergence in tap water for two minutes. Then the sieve (with the soil on) was moved up and down in the water at 35 oscillations per minute for three minutes, with an amplitude of 2cm. The fraction of aggregates larger than 250µm was transferred to pre-weighed beakers, and dried overnight in an oven at 105°C and weighed. This gave the weight of the stable aggregates (SA).

The stable aggregates were dispersed by mixing it with a Calgon solution it in a Vortex mixer, until all the aggregates were dispersed. The dispersed soil was again passed through a 250µm sieve and dried overnight in a 105°C oven. The mass of sand larger than 250µm (S) in the sample was determined when this dry sample was weighed.

The %WSA is determined with the following equation

$$\%WSA = \frac{SA - S}{4g - S} \times 100$$

Appendix 4: Gully parameters

Appendix 4.1: Gully length and density for the map units of the erosion factors for 1957 and 2004

Area			2004			1957		
	Size		Gully Length		Gully	Gully Length		Gully
		% of total area		% of total length	Density		% of total length	Density
	(ha)	(%)	(m)	(%)	(km/km^2)	(m)	(%)	(km/km^2)
Geology								
Lesotho	21.4	6	386.5	2	1.8	715.6	3	3.3
Clarens	19.5	5	1047.1	4	5.4	1306.1	6	6.7
Elliott	300.1	81	20070.2	84	6.7	17418.4	81	5.8
Molteno	29.1	8	2342.6	10	8.0	2077.8	10	7.1
Land Use								
Abandoned Land	79.0	21	8505.8	36	10.8	4378.8	20	5.5
Cultivation	128.4	34	6728.6	28	5.2	6397.7	30	5.0
Natural Vegetation	95.6	26	5681.1	24	5.9	6685.3	31	7.0
Village	67.1	18	2930.9	12	4.4	4056.1	19	6.0
Slope Class								
1 (0-8°)	242.9	66	16699.1	70	6.9	13245.8	62	5.5
2 (8-20°)	72.6	20	4400.3	19	6.1	4902.3	23	6.8
3 (20-50°)	54.5	15	2747.0	12	5.0	3369.9	16	6.2
Whole Catchment	370.1	100	23846.4	100	6.4	21517.9	100	5.8
Soils								
Basaltic	21.2	11	1278.5	9	6.0	1140.3	9	5.4
Blocky	84.1	44	7046.1	48	8.4	7568.9	59	9.0
Duplex	41.2	22	5616.3	38	13.6	3476.9	27	8.4
Red Blocky	10.2	5	274.3	2	2.7	259.5	2	2.5
Sandstone	33.9	18	480.7	3	1.4	492.3	4	1.5
Mudstone	0.9	0.4	0.0	0	0.0	0.0	0	0.0
Whole Soil Area	191.5	100.	14696.0	100	7.7	12938.0	100	6.8

Appendix 4.2: Gully extension on the different map units

Area	Gully extension				
	Length	Density	Density/year	% extension from 1957	% of total extension
	(m)	(km/km^2)	(m/km^2/year)	(%)	(%)
Geology					
Lesotho	-329.1	-1.5	-32.71	-46	-14
Clarens	-259.0	-1.3	-28.29	-20	-11
Elliott	2651.8	0.9	18.80	15	114
Molteno	264.8	0.9	19.35	13	11
Land Use					
Abandoned Land	4127.0	5.2	111.20	94	177
Cultivation	330.9	0.3	5.48	5	14
Natural Vegetation	-1004.2	-1.1	-22.34	-15	-43
Village	-1125.2	-1.7	-35.67	-28	-48
Slope Class					
1 (0-8°)	3453.4	1.4	30.25	26	148
2 (8-20°)	-502.0	-0.7	-14.72	-10	-22
3 (20-50°)	-622.9	-1.1	-24.31	-19	-27
Whole Catchment	2328.5	0.6	13.39	11	100
Soils					
Basaltic	138.2	0.7	13.85	12	8
Blocky	-522.9	-0.6	-13.22	-7	-30
Duplex	2139.4	5.2	110.54	62	122
Red Blocky	14.8	0.1	3.07	6	0.8
Sandstone	-11.6	0.0	-0.73	-2	-0.7
Mudstone	0.0	0.0	0.00	***	0.0
Whole Soil Area	1757.9	0.9	19.53	14	100

Appendix 4.3: Gully heads on the map units of the erosion factors for 1957 and 2004

Area	2004 Gully Heads (#)	2004 Gully heads per km^2	2004 Discon-tinuous Gully heads (#)	2004 Discon-tinuous Gully Heads (%)	2004 Gully Heads at Bedrock (#)	2004 Gully Heads at Bedrock (%)	2004 Slope Class	1957 Gully Heads (#)	1957 Gully heads per km^2	1957 Discon-tinuous Gully heads (#)	1957 Discon-tinuous Gully Heads (%)	1957 Gully Heads at Bedrock (#)	1957 Gully Heads at Bedrock (%)	1957 Slope Class
Geology														
Lesotho	5	23	0	0	5	100	5.60	9	42	0	0	9	100	4.11
Clarens	5	26	1	20	5	100	6.20	2	10	0	0	2	100	4.00
Elliott	59	20	20	34	23	39	2.29	47	16	18	38	22	47	3.02
Molteno	7	24	0	0	0	0	1.00	2	7	0	0	0	0	1.00
Land Use														
Abandoned Land	34	43	5	15	12	35	1.71	12	15	3	25	11	92	2.08
Cultivation	12	9	5	42	4	33	2.00	9	7	2	22	5	56	2.00
Natural Vegetation	17	18	5	29	15	88	5.65	23	24	6	26	14	61	4.65
Village	13	19	6	46	2	15	1.77	16	24	7	44	3	19	2.44
Slope Class														
1 (0-8°)	44	18	11	25	8	18	1.49	23	9	7	30	12	52	1.70
2 (8-20°)	17	23	7	41	11	65	2.65	21	29	6	29	14	67	2.57
3 (20-50°)	14	26	3	21	14	100	6.36	16	29	5	31	7	44	6.00
Whole Catchment	76	21	21	28	33	43	2.65	60	16	18	30	33	55	3.15
Soils														
Basaltic	6	28	0	0	6	100	5.50	6	28	0	0	6	100	5.17
Blocky	9	11	3	33	1	11	2.00	8	10	5	63	2	25	2.38
Duplex	26	63	2	8	10	39	1.62	9	22	3	33	8	89	2.11
Red Blocky	0	0	0	***	0	***	***	0	0	0	***	0	***	***
Sandstone	1	3	0	0	0	0	1.00	0	0	0	***	0	***	***
Whole Soil Area	42	22	5	12	17	41	2.24	23	12	8	35	16	70	3.00

Appendix 4.4: Gully head increase on the different map units

Area	Gully Head Increase (#)	Gully Head Increase (%)	New Heads per km^2	New Discontinuous Gully Heads (#)	New Discontinuous Gully Heads (%)	Gully Heads extended unto Bedrock (#)	Gully Heads extended unto Bedrock (%)
Geology							
Lesotho	-4	-44	-19	0	***	-4	-44
Clarens	3	150	15	1	***	3	150
Elliott	12	25	4	2	11	1	5
Molteno	5	250	17	0	***	0	0
Land Use							
Abandoned Land	22	183	28	2	67	1	9
Cultivation	3	33	2	3	150	-1	-20
Natural Vegetation	-6	-26	-6	-1	-17	1	7
Village	-3	-19	-4	-1	-14	-1	-33
Slope Class							
1 (0-8°)	21	91	9	4	57	-4	-33
2 (8-20°)	-4	-19	-6	1	17	-3	-21
3 (20-50°)	-2	-13	-4	-2	-40	7	100
Whole Catchment	16	27	4	3	17	0	0
Soils							
Basaltic	0	0	0	0	***	0	0
Blocky	1	13	1	-2	-40	-1	-50
Duplex	17	189	41	-1	-33	2	25
Red Blocky	0	***	0	0	***	0	***
Sandstone	1	***	3	0	***	0	***
Whole Soil Area	19	83	10	-3	-38	1	6

Appendix 5: Statistical data

Appendix 5.1: R^2 values for the correlations of soil factors with %WD Clay, with a Pearson's P value of <0.01.

Soil Property	Sign of Correlation	Linear R^2-value	Best Fit Shape	Best Fit R^2-value
Exchangeable Ca	(-)	0.19	logarithmic	0.26
Medium sand	(+)	0.23	2nd order polinomial	0.24
Ca:Na	(-)	0.24	logarithmic	0.34
Clay	(-)	0.25	2nd order polinomial	0.36
Mg:Na	(-)	0.27	logarithmic	0.56
Exchangeable (Ca+Mg)	(-)	0.29	power	0.35
ECEC	(-)	0.29	power	0.37
(Ca+Mg)/Na	(-)	0.29	logarithmic	0.42
Al%	(-)	0.31	exponential	0.54
EMgP	(-)	0.32	power	0.45
Fine sand	(+)	0.34	2nd order polinomial	0.34
Ca:Mg	(+)	0.34	power	0.45
Exchangeable Mg	(-)	0.36	power	0.52
SAR	(+)	0.38	2nd order polinomial	0.37
ESP	(+)	0.45	logarithmic	0.43
Colour	(+)	0.49	2nd order polinomial	0.51
"Free" Fe%	(-)	0.53	power	0.63
"Free" Fe+Al%	(-)	0.53	exponential	0.65

Appendix 6: Calculations of soil properties

Exchangeable Cations

$Cation_{ex} = Cation_{NH4OAc} - Cation_{sat\ paste}$ (cmolc/kg)

Effective CEC

$ECEC = Ca_{ex}+Mg_{ex}+K_{ex}+Mg_{ex}$+Titrateable acidity

ECEC/Clay

ECEC/Clay = ECEC / Clay% X 100

Carbon adjusted ECEC/Clay

$ECEC/Clay_{Cadj}$ = (ECEC-(C%X1.5))/Clay%X100

Exchangeable Sodium Percentage*

ESP = Na_{ex}/ECEC X 100

* the same for all the other cations

Sodium Adsorption Ratio

$$SAR = \frac{Na_{Satpaste}}{\sqrt{\frac{Ca_{Satpaste} + Mg_{Satpaste}}{2}}}$$

Dispersion ratio

Dispersion ratio = water dispersible clay% / total clay% X 100

Fe/Clay

Fe/Clay = Fe_{CBD}/Clay%

Fe/(Clay+Silt)

Fe/(Clay+Silt)= Fe_{CBD}/(Clay%+Silt%)

Clay accumulation index

Clay accumulation index = Clay % (B Horizon) / Clay% (A horizon)