EROSION DYNAMICS AT THE CATCHMENT LEVEL: SPATIAL AND TEMPORAL VARIATIONS OF SEDIMENT MOBILIZATION, STORAGE AND DELIVERY

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ABSTRACT

Soil material exported from river catchments by soil erosion is a key issue in environmental sustainability. Although soil erosion processes have been thoroughly investigated, their dynamics, specifically the continuity of erosion processes and sediment source locality, are less studied. The aim of this investigation was to evaluate the changes in the fluxes and characteristics of sediments during their downslope and downstream transport. The study was conducted in a 1000 ha catchment of the Drakensberg foothills, South Africa. Sediment fluxes were monitored at nested scales during the 2009-2011 rainy seasons using 1×1m and 2×5 m erosion plots and H-flumes coupled to automatic samplers from 23 ha, 100 ha catchments. In addition, soil texture, colour and total organic carbon and nitrogen contents in sediments exported from the nested scales and a 1000 ha catchment were compared to in-situ surface and sub-surface soil horizons in a 23 ha catchment river bank and hillslope soils and fluvial sediments. There was a sharp increase of sediment fluxes with increasing slope length (846±201 $gm^{-1}y^{-1}$ for 1 m^2 *vs* 6820±1714 $gm^{-1}y^{-1}$ for 10 m^2), revealing a limited contribution of splash erosion compared to rain-impacted flow erosion. Sediment fluxes decreased to 500±100 $gm^{-1}y^{-1}$ and 100±10 $gm^{-1}y^{-1}$ at the 23 ha and 100 ha catchments respectively, indicating the occurrence of sedimentation during sediment downslope and downstream transport. A principal component analysis (PCA) suggested that rain impacted flow erosion efficiency at the 10 m^2 scale was significantly correlated with soil bulk density, clay content and antecedent rainfall ($P<0.05$). Moreover, strong correlations existed between runoff, sediment concentration and soil loss and selected soil surface and environmental variables at the plot scales. Correlations became weaker at the catchment scales due to increasing landscape heterogeneity and the complexity of soil erosion dynamics. An additional PCA suggested that stream bank erosion contributed to 63% of the soil loss from the 23 ha catchment. During their downstream transport, sediments were discriminated by the second PCA axis, which correlated with the clay and fine silt content, 100 ha sediments showed negative coordinates to this axis while 1000 ha catchment sediment had positive coordinates.

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PREFACE

The work presented in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from February 2010 to August 2011, under the supervision of Dr. V. A. M. Chaplot.

This study represents original work by the author and has not been submitted in any form for any degree or diploma to any other tertiary institution. The use of the work of others has been accordingly acknowledged in the text.

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Signature (Student) Date

Mr. E.G.M. Oakes

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Signature (Supervisor) Date

Prof. V. A. M. Chaplot

PLAGIARISM DECLARATION

I, ………………………………… declare that

1. The research reported in this dissertation, except where otherwise indicated, is my original work.
2. This dissertation has not been submitted for any degree or examination at any other university.
3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
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1. INTRODUCTION

The soil resource provides numerous services for the continued existence of virtually all terrestrial organisms. The subsurface soil environment is the location of the occurrence of interactions between the chemically reactive clay fraction of the soil particle size distribution and the soil biology, such as plant roots and microorganisms, for example bacteria (Brady and Weil, 2008). These ongoing interactions, in turn, aid in the cycling of nutrients and organic matter, which improve overall soil quality (Brady and Weil, 2008). In the context of hydrological processes, soils serve as a partitioning point for runoff and infiltration and as subsurface reservoirs supplying terrestrial fluvial systems with water (Hillel, 2003). From an agricultural perspective, soil aids in providing a medium for the growth of crops, facilitating increased per capita food production (Brady and Weil, 2008), while in an environmental context, soils are a sink for carbon and aid in the purification of waste material (Hooda and Alloway, 1997).

Water movements within landscapes and the movement of soil material therein is one of the main mechanisms of soil evolution (Paton *et al*., 1995). This process is termed soil erosion by water and the acceleration thereof in all climates, particularly in response to anthropogenic modification of landscapes, is a serious threat to natural ecosystem functionality (Lal, 1999, Chaplot and Le Bissonnais, 2003; Podwojewski *et al*., 2008). Soil erosion depletes an affected area of soil and its constituent nutrients, resulting in depressed biodiversity, land productivity and per capita food production and the mitigation of rising environmental threats such as water scarcity and climate change (Gregorich *et al*., 1998; Lal, 1999; Dawson and Smith, 2007). Furthermore, fluvial systems and terrestrial reservoirs undergo significant siltation resulting in reduced storage capacity (Li *et al*., 2003). In addition, eroded sediments entering terrestrial water bodies may contain chemicals which may cause imbalances in the chemistry of terrestrial waters, leading to crises such as eutrophication. However, soil water erosion may be beneficial to ecosystems because eroded soil material is concentrated to some limited areas of the landscape, generally the lowlands. Soil erosion may also provide a sink for potential sources of atmospheric carbon (Chaplot *et al*., 2009).

Internationally, many tons of soil are lost annually due to soil erosion by water. This has tremendous negative impacts on land productivity and social integrity. Excessive soil erosion exacerbates poverty, particularly in parts of the world where millions of people make a direct living off the land by way of subsistence agriculture (i.e. Africa and Asia). Soil erosion has been highlighted as a significant area of concern regarding food security and environmental integrity (Lal, 1999; UNEP, 2007). In the light of the detrimental impacts of soil erosion, concerted efforts have been focused on understanding soil erosion processes and their dynamics in order to facilitate mitigation strategies to protect the environment from the *in-situ* and *ex-situ* impacts of soil erosion.

Conventional methods employed in soil erosion research to assess soil erosion dynamics within landscapes include, among others, the use of runoff-plots of different sizes, both under natural or artificial rain, the monitoring of catchment soil loss using flumes or weirs and natural or artificial tracers (Wishmeir and Smith, 1978; Poesen *et al*., 2003; Walling *et al*., 2006). Numerous studies have used micro plots (±1×1m) (Le Bissonnais *et al*., 1998; Fox and Bryan, 1999; Stomph *et al*., 2002; Chaplot and Le Bissonnais, 2003; Dlamini *et al*. 2010; Podwojewski *et al*., 2011) to evaluate the contribution of local erosion mechanisms (mainly splash and rain-impacted flow) on soil displacement from its initial place. Several mechanism-based studies have been performed to link soil water erosion to environmental factors of control. Podwojewski *et al*. (2011), under relatively similar conditions in South Africa, assessed the vegetation cover thresholds for decreased soil infiltration and increased soil erosion. Other microplot studies have considered various erosion-controlling factors such as slope gradient (Fox and Bryan, 1999) or specific soil constituents such as organic carbon (Boix-Fayos *et al*., 2009). Microplots have been extensively used as well for assessing the spatial variations of soil erosion. Under sloping lands and clayey soil conditions, Dlamini *et al* (2010) in a 350 m long rangeland hillslope of the Drakensberg foothills of South Africa found soil losses to vary between 3 and 13 ton ha^{-1} y^{-1}, the highest rate being found on bare and crusted soils. Although microplots have allowed some interrill erosion processes and factors of control to be better understood and quantified, they do not allow a complete assessment of soil erosion dynamics at the landscape level. While they allow point scale interrill mechanisms such as splash and to some extent rain-impacted flow (Kinnel, 2004) to be evaluated, other sheet or linear erosion and sedimentation processes that require a greater surface area to be operative are not accessed. Longer plots (Wischmeier and Smith, 1978) aid in avoiding some of these limitations by including more erosion mechanisms such as flow detachment and flow transport, however, they do not account for the entire range of catchment-scale erosion processes.

H-flumes or weirs allow the impact of the different detachment, transport, and sedimentation mechanisms on catchment exports to be assessed (Verbist *et al*., 2010). The different studies available reveal that the sediment yields from catchments represent a minute portion only of those estimated from microplots or plots (Roehl, 1962; Walling, 1983; Le Bissonnais *et al*., 1998; Verstraeten and Poesen 2001; Cammeraat, 2004; Beven *et al*., 2005; de Vente *et al*., 2006; Parsons *et al*., 2006; Walling *et al*., 2006). Expressed as a percentage of total soil displacement, catchment yields of sediments were shown to range between 1% in 166 to 234 km^2 in catchments in southern England (Walling *et al*., 2006) and 2% for a 60 ha catchment in the sloping lands of South east Asia (Chaplot *et al*., 2005). Although these studies inform on the amount of catchment exports of sediments relative to the displaced soil material, our understanding of both the transport continuity of the eroded soil material from hillslope to catchment outlet and the several interactions between the different erosion mechanisms remain incomplete.

In an attempt to gain an improved understanding of soil erosion dynamics at the catchment level, workers have considered a series of embedded scales, while others benefitted from the use of tracers. Le Bissonnais *et al*. (1998), using a series of scales from the microplot to the catchment level (1, 10, 500 m^2 and 70 ha), pointed out that the continuity of sediment transport is largely dependent upon the soil surface characteristics of the considered area, crusted soils allowing sediment transport on longer distances. From the study of Puigdefabregas *et al*. (1999) in southeast Spain we learn that most detached sediments do not reach the lower parts of hillslopes or the catchment outlet because of the presence of few vegetated portions in hillslopes acting as runoff and sediment sinks. Mingguo *et al*. (2007) in the Loess Plateau in North China, similarly showed that vegetation is able to significantly reduce sediment losses at the hillslope level. In addition, these authors indicated a decreased impact of the vegetal cover at catchment level where gully erosion seemed dominant. Comparable studies by Chaplot *et al*. (2005) and Wang *et al*. (2010) inform on sediment and soil organic fluxes at different scales in an attempt to investigate the different erosion mechanisms interacting at catchment level. Vandaele and Poesen (1995) using catchment flux estimation together with linear erosion evaluation showed that between 37 and 63% of the total erosion measured at the outlets of two adjacent Belgium catchments can be attributed to ephemeral gully erosion, thus improving the understanding of sediment sources. These studies have improved our understanding of soil erosion processes and sediment source tracing. However, there are still large uncertainties regarding sediment sources and the continuity of sediment transport.

Environmental tracers such as ^{210}Pb and ^{137}Cs have been largely applied for sediment sourcing, as their use constitutes effective alternative techniques (Walling, 2005). Because ^{137}Cs fallouts accumulate in surface soil horizons (mainly to a depth of 0.2m under cropped fields), if little or none is detectable in sediments exiting a catchment, it can be deduced that these sediment have a subsoil origin. For instance, in New South Wales (Australia) Krause *et al*. (2003), using ^{137}Cs, ^{210}Pb Cu, Pb, Zn, Fe, Mn and K, identified riverbank sediments as the predominant catchment sediment source (98%). A similar result was found by Poulenard *et al*. (2009) in the French Alps by using infrared spectroscopy, a much cheaper technique. Li *et al*. (2003) in the Yangjuangou reservoir catchment of the Chinese Loess Plateau (northwest China) with different land use suggested that cultivated soils (both surface and sub-surface horizons) were the main contribution to the reservoir sedimentation, with an average ^{137}Cs concentration in sediments of 3.45 Bq kg^{-1} compared to 4.2 and 2.6 Bq kg^{-1} for the 0-5 cm and 0.5-0.20 cm soil layers, respectively. However, the existence of other potential sediment sources, such as surface and sub-surface forested or grassland soils with an average ^{137}Cs concentration of 8.24 Bq kg^{-1}, can be seen as a major limit for interpreting the results.

On the one hand, tracers allow sediment sources to be identified with relatively high accuracy but the techniques are expensive, difficult to implement for numerous sediment sources, and fail mostly in the identification of the erosion mechanisms, thus limiting the assessment of the areas of sediment generation, sedimentation and further remediation of erosion. Moreover, the contemporary use of tracers such as ^{137}Cs and ^{210}Pb emitted during the 1960s is being compromised by a half-life of less than 30 years, low concentrations or inhomogeneous spreading, especially in the southern hemisphere, and new deposition episodes associated with the Chernobyl and the more recent Fukushima disasters, thus putting an end point to the use of the technique in many areas. On the other hand, nested scales have been successful in evaluating the different erosion mechanisms interacting at catchment level but they show limitations in the quantification of sediment sources and in assessing the continuity of sediment transport. Because, for the most part, multi-scale studies and tracers have been used independently, a further understanding of soil erosion dynamics at catchment level would highly benefit from a more holistic approach involving both sediment flux estimation at embedded spatial scales and sediment sourcing methods that would be cost-effective and easy to implement.

In order to understand, erosion dynamics at the catchment level a holistic approach incorporating the assessment of soil erosion at embedded scales, as well as an investigation of the important sediment-producing areas within a 23 ha catchment will be made will be made. We hypothesise that knowledge of the factors governing soil erosion continuity at the catchment scale will aid in facilitating an improved understanding of soil erosion dynamics and finding ways in which soil erosion can be mitigated.

1.1 Research Objectives

The main objectives of this research are:

- to quantify runoff (R), sediment concentration and soil loss (SL) at nested scales, including plot scales of 1 and 10 m^2, and two catchment scales of 23 and 100 ha,
- to assess soil erosion dynamics from the plot to catchment level and identify controlling factors,
- to determine the locality of the significant sediment sources contributing to catchment soil loss within the 23 ha catchment.

1.2 Aims of the Overall Research Project

Globally, a substantial amount of research has focused on the impacts of commercial scale agriculture on nutrient fluxes and the effects of these on water quality. This project aims to focus on the effects of nutrient loss and sediment yield from rural smallholder agricultural areas which have received relatively little attention in South Africa. The research project objectives are:

- to define and quantify nutrient and organic carbon fluxes in a small-scale agricultural catchment,
- to scale up the water, nutrient and organic carbon fluxes from the 1 m^2 and 10 m^2 plots to the 1000 ha watershed through the catchments of 23 ha and 100 ha,
- to model nutrient fluxes within watersheds and to predict the impact of possible climate and land use changes.

1.3 Background of Project and Expected Research Benefits

This study forms part of a larger ongoing investigation (WRC K5/1904//1) monitoring nutrient and organic carbon fluxes from rural smallholder agriculture in the Potshini Catchment, KwaZulu-Natal, South Africa. The project is funded by the Water Research Commission (WRC). The WRC project is an expansion of an initial investigation which evaluated the spatial variation of interrill erosion within the hillslopes of the catchment. Additional information was required to understand soil erosion processes at the larger catchment scales. This is important for the Potshini community as the first investigation revealed that overgrazing exacerbates soil erosion and land degradation of the communal grazing lands. From a social perspective, this study will be beneficial for stakeholders of the Potshini community, as knowledge about soil erosion processes and mitigation strategies related to improved grazing management will be imparted to the community members.

1.4 Dissertation Structure

The first chapter of this dissertation contains the introduction, aims and objectives and project background which highlight the importance of the need to understand and mitigate soil erosion. The second chapter is a review of the relevant literature used during the work presented in this dissertation. Descriptions of the different forms of erosion, their controlling factors, their dynamics and methods of identifying important sediment-producing areas will be discussed. The third chapter will highlight the methodology which was followed during this investigation. The fourth chapter contains results and discussion sections about processes of soil erosion at the 1 and 10 m^2 plot scales considered during the 2009-2010 rainfall season. The fifth chapter presents results and discussion sections relating to the dynamics of soil erosion at the 1 and 10 m^2 plot levels and the 23 and 100 ha catchment scales processes and the identification of sediment sources within the 23 ha catchment. These were considered during the 2010-2011 rainfall season. The sixth chapter presents a conclusion where the main research findings are mentioned and recommendations based on these findings are proposed. This is followed by a consideration of future perspectives. The seventh chapter contains the list of references used as part of the foundation of the work presented in this dissertation. A section of appendices concludes this dissertation with research papers the author aspires to publish in relevant reputable scientific journals. The paper contained in Appendix One is in review with the journal of Earth Surface Processes and Landforms.

2. LITERATURE REVIEW

2.1 Introduction

Soil is a slowly renewed and invaluable resource which is vital for the survival for life on Earth. Soils make up the lithosphere of the Earth's surface and they are the product of physical, chemical and biological weathering of unconsolidated rock material (Paton *et al*., 1995). Soils have significant spatial variability. Their variability is governed by the deterministic soil forming factors of lithospheric material and topography and the initiative soil forming factors of climate (more specifically rainfall) and organism over the constant factor, time (Paton *et al*., 1995). The influence of the mentioned soil forming factors and processes such as rock weathering, podzol formation and organic matter accumulation are only significant at a temporal scale. The dynamic nature of soil leads on to the fact that soil material is constantly moving through the landscape from areas of high to low relief (Puigdefabregas *et al*., 1999).

The process of movement of soil through the landscape is termed erosion and the transport media of the erosion process are wind and water (Paton *et al*., 1995). Soil erosion by water during and subsequent to rainfall events will be discussed in this document. Erosion is a naturally occurring process which may be beneficial due to the redistribution of nutrients through the landscape (Puigdefabregas *et al*., 1999; Ritchie *et al*., 2006). An example of this may be floodplain soils adjacent to river banks or soils of low-lying fields in Asia which are highly efficient for agricultural use (Chaplot *et al*., 2009). Processes of soil erosion may also aid in the mitigation of emissions of atmospheric carbon by the burying of terrestrial carbon sources. However, soil erosion is a cause for concern, particularly in scenarios where the landscape is manipulated for anthropogenic use such as cultivated or livestock agriculture (Poesen *et al*., 2003; Valentin *et al*., 2005).

Soil erosion results in the loss of valuable top soil, soil organic carbon (SOC) and nutrients from the site of erosion. Erosion is also one of the major processes causing land degradation (Gregorich *et al*., 1998; Dawson and Smith, 2007). Cultivated land is vulnerable to erosion as a result of the removal of vegetation cover and the breakdown of soil structure from field preparation methods such as conventional tillage (Dlamini *et al*., 2010). Overgrazing by livestock, such as cattle may remove large amounts of grass cover and cause significant compaction which, in turn, results in accelerated soil erosion rates. Soils are essentially non-renewable within the time-span of human life and sites which have experienced particularly severe erosion are unable to support the growth of plants essential for organism survival. The offsite impacts associated with erosion are the degradation of stream channel water quality as the deposition of sediments may lead to turbidity of stream water sources. In addition, the introduction of increased amounts of nutrients or harmful substances may lead to eutrophication or the death of aquatic organisms (Le Bissonnais *et al*., 1998). The subsequent uplift and transport of sediments deposited in stream channels could lead to the sedimentation of reservoirs and lakes (Li *et al*., 2003; Devi *et al*., 2008). The consequence of this is a decrease in the capacity of these storage facilities and the risk of the degradation of water quality and eutrophication. The above-mentioned consequences incur significant expenses and hazards to human health and other organisms.

Soil erosion consists of three mechanisms, namely, detachment, transport and deposition (Kinnell, 2004). The process is initiated by the detachment and uplift of soil material, followed by transport of the sediment and the process is completed by deposition. These mechanisms are affected by various controlling factors such as rainfall, slope and soil characteristics, basal cover and land use practices (Poesen *et al*., 2003; Valentin *et al*., 2005). The dynamics of erosion vary both temporally and spatially through the landscape as a function of a variety of hydrological and geomorphological factors. The objective of this document is to make a review of; the mechanisms by which erosion occurs, the factors controlling the efficiency of the erosion mechanisms, the spatio-temporal variability of soil erosion, methods of determining the locality of sediment sources and the consequences of erosion.

2.2 Mechanisms and Controlling Factors of Erosion

In order to begin to understand the spatial and temporal variability of soil erosion it is necessary to understand the mechanisms by which the phenomenon occurs. Soil erosion consists of the mechanisms of detachment, transport and deposition. There are controlling factors which either exacerbate or mitigate the effectiveness of the process and ultimately the severity of erosion. There are different forms of erosion which occur, depending on the geomorphic characteristics of the location at which erosion is occurring.

2.2.1 Forms of erosion

Common forms of water erosion are splash, sheet, rill, gully, bank erosion, landslide, mass movement, glacial erosion (Kinnell, 2004). The forms of erosion which will be the focus of this document are splash, sheet, rill and gully erosion. In the context of a typical catchment, a distinction can be made between the forms of erosion occurring along a hillslope and in a stream channel. Splash, sheet, and rill erosion essentially occur at the hillslope level, with sheet erosion occurring on gentle slopes and rill erosion occuring on the steep slopes of a hillslope topo-sequence (Chaplot and Le Bissonnais, 2000; Descroix *et al*., 2008). Gully erosion occurs mainly in stream channels and in severe cases of soil erosion, rills may develop into gullies along a hillslope (Cammeraat, 2004). The fundamental forms of erosion which will be discussed in this chapter occur in both catchment locations. However, based on literature and field observations, there are certain erosion processes which are exclusive to gully erosion and they will be discussed separately.

2.2.2 Detachment of soil material and the factors of control

The requirement for the initiation of soil erosion is the detachment of soil material from the surface of the soil matrix (Kinnell, 2004). Constituents of the soil matrix include particles, particle aggregates of varying sizes and SOC. Detachment of the soil surface constituents occurs by raindrops, sheet flow and concentrated flow. In order for detachment to occur, threshold energies of detaching media need to be overcome (Kinnell, 2004). The effectiveness of detachment is controlled by rainfall, soil cover and soil characteristics.

At the onset of a rainfall event the initiation of soil erosion and the process of detachment occurs when raindrops impacting the soil surface cause the disaggregation of surface soil aggregates by slaking (rapid wetting), dispersion (slow wetting) and physical collision of drops with soil aggregates (mechanical breakdown) (Hillel, 2003; Chaplot *et al*., 2007). The breakup of soil aggregates into smaller constituent particles (clay and silt) and the dislodging of soil particles at the surface of the soil matrix provides loose material for transport by splash or flow. Furthermore, the breaking up of soil aggregates may expose enclosed SOC to mineralisation by microbes and the consequent release of CO_2 as a by-product into the atmosphere (Gregorich *et al*., 1998; Dawson and Smith, 2007). In addition, the breakup of soil aggregates provides smaller loose particles which may be moved into pore spaces at the soil surface by infiltrating rain water. The movement of the small particles into the surface pore spaces contributes to the reduction in permeability of the soil surface by the formation of a seal or crust (Le Bissonnais *et al*., 1998). Raindrops impacting the soil surface further facilitate a decrease in the degree of macro-porosity at the soil surface by compacting the soil surface soil particles. The processes of surface sealing, compaction crust formation by raindrops facilitates the generation of increased amounts of runoff as the duration of a storm proceeds (Al-Qinna and Abu-Awwad, 1998; Neave and Rayburg, 2007; Carmi and Berliner, 2008). Moreover, loss of SOC from the affected soil by exposure to mineralisation may result in the gradual decrease in the quality of the overall soil condition (Gregorich *et al*., 1998; Dawson and Smith, 2007; Ritchie *et al*., 2006).

In order for raindrop detachment to occur, threshold energies relating to inter-particulate bonding and friction of the surface of the soil matrix need to be overcome (Kinnell, 2004). Rainfall intensity is a measure of the amount of rain falling in a given time period. High intensity rainfall events are erosive due to the high energy of falling raindrops impacting the soil surface (Vandaele and Poesen, 1995, Cao *et al*., 2009). According to Bryan (2000), rainsplash kinetic energy (KE) (equation 2.1) is an important agent for splash erosion and the raindrop characteristics which affect KE are raindrop mass (m) and impact velocity (v) (Bryan, 2000).

$$KE = \frac{1}{2} mv^2 \qquad (2.1)$$

The requirement for maximum raindrop kinetic energy impact to occur is the unobstructed fall path of raindrops to the soil surface. An obstructed fall path could dissipate raindrop energy and reduce the total number of raindrops impacting the soil surface during a rainfall event (Bryan, 2000). Soil cover, such as mulch and vegetation, are effective for the mitigation of raindrop detachment (Molina *et al*., 2007). Chaplot and Le Bissonnais (2000) showed that sediment concentration in sheet runoff can be reduced to one third without raindrop impact for a runoff velocity of 15 cm s^{-1}. Raindrop detachment may be exacerbated by canopies located at a considerable distance above the ground. This may be due to an accumulation of raindrops at the canopy level resulting in an increase of the size of raindrops reaching the soil surface (Zhou *et al*., 2002).

Soil properties such as soil texture, soil clay type and soil organic matter (SOM) are factors affecting soil detachability. Soils which have a high silt and low SOM percentage are prone to crust formation reducing the infiltration rates of water into the soil profile, thus increasing the potential for rapid runoff generation (Shainberg and Shalhevet, 1984; Chaplot and Le Bissonnais, 2000; Li *et al*., 2009). Smectitic and other 2:1 expanding clays are prone to slaking and dispersion and are thus, easily detached by raindrops. These soils may also form crusts subsequent to slaking and dispersion causing a decrease in soil surface permeability (Shainberg and Shalhevet, 1984; Li *et al*., 2009). However, soil crusts formed by 2:1 expansive clays may form cracks. These cracks may serve as preferential infiltration pathways prior to the expansion of the clays on wetting. Research has shown that the formation of stable soil aggregates by the aid of SOM reduces soil erodibility and soil loss (Teixeira and Misra, 1997; Cerdà, 1998; Cerdà, 2000 Barthès and Roose, 2002). Teixeira and Misra (1997) conducted a study which compared soil losses from soils of low aggregate and high aggregate stability. They found that the soils with the greatest aggregate stability yielded the least amount of soil loss. This was due to the fact that large soil aggregates with diameters of approximately >2 mm were less easily entrained than smaller soil particles. Teixeira and Misra (1997) also reported that well-aggregated soils resistant to dispersion increase surface roughness and increase soil porosity thus reducing runoff flow velocity and increasing infiltration rates.

Sheet flow generally occurs on low gradient slopes (Cammeraat, 2004). If a rainfall event is of sufficient duration, depth and intensity, surface water will begin to accumulate and flow as Hortonian overland flow/surface runoff (van de Giesen *et al*., 2005). Surface runoff has the potential to detach soil particles, provided that it has adequate flow depth and flow velocity. At the early stage of runoff development, surface flow depth and flow speed is low due to the low intensity of the rainfall and/or insufficient time duration to allow for the development of erosive runoff. Surface runoff is therefore unable to detach soil particles. However, soil particle detachment may continue provided that rain continues to fall with adequate energy to penetrate surface flow depth (Bryan, 2000; Kinnell, 2004). As a rainfall event continues, flow depth may begin to increase as increased amounts of rain water are converted to surface runoff. As flow depth increases, the influence of raindrops on particle detachment decreases as raindrop energy is dissipated and little to no energy is expended on soil particle detachment (Bryan, 2000; Kinnell, 2004). Runoff erosivity is augmented as increased quantities of rainwater are converted to surface runoff corresponding to an increase in rainfall duration and intensity.

Factors affecting surface runoff depth and velocity affect the potential for soil particle detachment by sheet flow. Soil texture affects soil resistance to particle detachment. The detachment of large soil particles, such as sand or gravel, requires a large amount of flow energy because of their size, density and inter-particulate friction. Clay particles are equally difficult to detach from the soil matrix due to their cohesive nature and inter-particulate bonds (Hillel, 2003). Silt particles, due to their small size and lack of chemical reactivity giving rise to particle cohesiveness, are generally easily detached. A number of authors have documented the erodibility of silty soils (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000). However, the formation of soil aggregates by the intervention of SOM aids in increasing the affective particle size, particle cohesivity and it thus decreases the detachability of soil particles (Chaplot *et al*., 2009). An additional factor which may reduce particle detachment by surface flow is vegetation (Molina *et al*., 2007). The roots of vegetation cover may provide channels in the soil profile for downward water movement which may reduce the volume of surface water flow and detachment energy of surface flows. In addition, vegetation cover may also retard flow velocity and inhibit detachment (Dlamini *et al*., 2010). Factors which inhibit particle detachment by flow are only effective up to circumstantial thresholds. If these thresholds are overcome, particle detachment by raindrop impact and surface water flow will proceed.

Rainfall intensity has a significant effect on runoff erosivity as it partly governs the rate at which rainwater is converted to surface runoff (Parsons and Stone, 2006). The influences of the factors mitigating surface flow erosivity become negligible under high intensity rainfall. Slope gradient and length have a significant effect on the rate of energy acquisition of surface runoff (Agassi and Ben-Hur, 1991). Runoff is generally able to rapidly acquire high surface flow velocity on steep slopes which, in turn, increases runoff detachment capability (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000).

At the hillslope level, preferential runoff pathways may be present as a result of depressions in surface micro-topography or vegetation pattern and density (Cammeraat, 2004). Micro-depressions or bare patches between vegetation clumps serve as typical preferential runoff pathways. The flow of runoff traversing through these micro-scale regions concentrates. A consequence of this is the development of rills particularly on steep slopes where concentrated runoff flow is able to rapidly acquire velocity and erosive energy (Chaplot and Le Bissonnais, 2000; Cammeraat, 2004; Descroix *et al*., 2008). This results in the increased ability of concentrated runoff to incise and scour the soil over which it flows as shear stress thresholds of soil are overcome (Bryan, 2000). A result of the incision and scouring processes leads to the development of micro-channels, termed rills in their early stages of development. Rills are generally defined by a width which is greater than its depth when the depth is below approximately 25 cm. In severe cases of land degradation, rills may develop into gullies which generally have a depth considerably greater than their width. Concentrated flow is generally deeper and more erosive than sheet flow (Bryan, 2000).

Mass detachment processes occur during the processes of gully erosion and gully bank retreat. If subsurface soil horizons exposed to concentrated flow are continually incised by concentrated flow detachment, soil of the upper horizons becomes vulnerable to mass detachment processes (Chaplot, *et al*., 2010). Accumulation of water in gully walls increases the effective mass of the suspended horizon. This, coupled with expansion and contraction of the horizon soils, particularly in the presence of expansive clays, gradually weakens the bonds binding the soil matrix together (Chaplot, *et al*., 2010). Cracks may develop down the profile of the soil matrix, allowing for the rapid wetting of the gully soil horizon. The particle bonds binding the suspended soil to the soil matrix eventually fail resulting in large clumps of soil being deposited in the gully channel where they are vulnerable to being carried further downstream by flow transport processes (Chaplot, *et al*., 2010).

The previously discussed factors affecting sheet flow detachment also affect concentrated flow detachment in a very similar way. However, concentrated flow occurs within channels which have dimensions. If the cross-sectional area of the channel in which surface flow is moving increases, the velocity, and consequently the erosivity, of the surface flow will decrease (FAO, 2002).

2.2.3 Transport of soil material and the factors of control

The second stage of soil erosion is the transport of detached material from its source to a new location within the landscape. Soil material is transported by splash (Kinnell, 2004) which occurs subsequent to raindrop impact at the soil surface or by surface flow which occurs when an abundant supply of water is present at the soil surface as a result of, for example, rainfall intensity exceeding rates of soil infiltration by water (Stomph *et al*., 2002). Surface flow occurs as runoff at the soil surface or as concentrated flow in rills or gullies. A discussion about the different sediment transport mechanisms and the factors of control follows.

Soil material is made available for transport as a result of detachment by raindrop impact at the onset of a rainfall event or by flow during a rainfall event (Bryan, 2000). Transport of fine and light soil material such as fine silt, clay and SOC occurs by the splash action of raindrops at the soil surface subsequent to surface impact. Soil material is transported in a radial fashion surrounding the point of raindrop impact (Bryan, 2000; Kinnell, 2004). Splash erosion is an ineffective transport system because the net soil loss from the eroding area is negligible. The reason for this is that soil lost from a given point by splash transport is replaced by soil lost from a nearby site where splash erosion has occurred (Kinnell, 2004; Legout *et al*., 2005). The efficiency of splash transport increases with an increase in surface slope. An increase in slope gradient aids in increasing the efficiency of splash transport by promoting the net downward movement of splash droplets (Kinnell, 2004).

The effect of slope on splash transport has already been discussed in the previous section. Low-lying vegetation such as grass and shrubs may reduce the effectiveness of splash transport by reducing the fall velocity of raindrops and the quantity of sediment moved subsequent to raindrop detachment (Casermeiro *et al*., 2004). Low-lying vegetation may also reduce the effective size of impacting raindrops. However, tall vegetation canopies may improve the efficiency of splash transport by allowing for the re-aggregation of raindrops at the canopy surface (Zhou *et al*., 2002). Generally, high intensity rainfall events produce raindrops with high fall velocities. High velocity raindrops impacting the soil surface may result in large rain splash diameters allowing for greater sediment transport by splash erosion. However, soils which are cohesive and/or well-aggregated with low exchangeable sodium percentages (ESP), non-swelling clays and high organic carbon percentages are not easily dispersed (Shainberg and Shalhevet, 1984). These soils are consequently not easily transported by splash because clay particles are not easily detached from a clay-dominated soil matrix. Furthermore, soil aggregates, like large sand particles are not easily transported because of their large size (Barthès and Reese, 2002).

As a rainfall event proceeds, surface flows which are more efficient at moving soil material than rain splash become the dominant transport medium (Bryan, 2000; Kinnell, 2004). The change from splash to flow transport may be brought on by an increase in rainfall intensity exceeding soil infiltration by water or by a decrease in soil surface permeability or by saturation of the soil profile by water from recent rainfall events (Bryan, 2000). In some cases, for example, when surface flows occur initially, they are able to transport sediment, but as mentioned, they have insufficient energy to detach soil particles. The efficiency of surface flow as a transport medium is initially dependent on raindrop energy which lifts soil material into flow (Bryan, 2000). However, the transport ability of surface flow increases as the flow depth and velocity increase contributing rainfall. Eventually, transport of sediment by surface flows occurs with less aid from raindrop impact (Kinnell, 2004).

The manner in which soil particles are transported is dependent upon the size of the transported material. Soil material is transported by dragging (gravel), saltation (sand, silt and stable soil aggregates), suspension (clay) and in dissolved form (soil nutrients). Deposition also varies with the detachment-transport system in operation during an event. If splash transport is the dominant transport mechanism, sediment is deposited a short distance from the site of impact (Bryan, 2000). When flow transport occurs, sediment is lifted by means of raindrop impact and splash (Kinnell, 2004). The material lifted by the influence of a raindrop is moved a short distance by surface water flow and subsequently deposited. The cycle is repeated when the deposited material is lifted or rolled by another drop which again is quickly deposited due to inadequate flow energy and shallow flow depth and energy. This micro-cycle of detachment, upliftment, transport and deposition is illustrated in Figure 2.1. The diagram shows flow depth (h), particle uplift height (z), diameter of particle cloud (X_{cz}) and travel distance after uplift (X_{pz}). The rate at which deposition occurs reduces as flow energies increase (Kinnell, 2004).

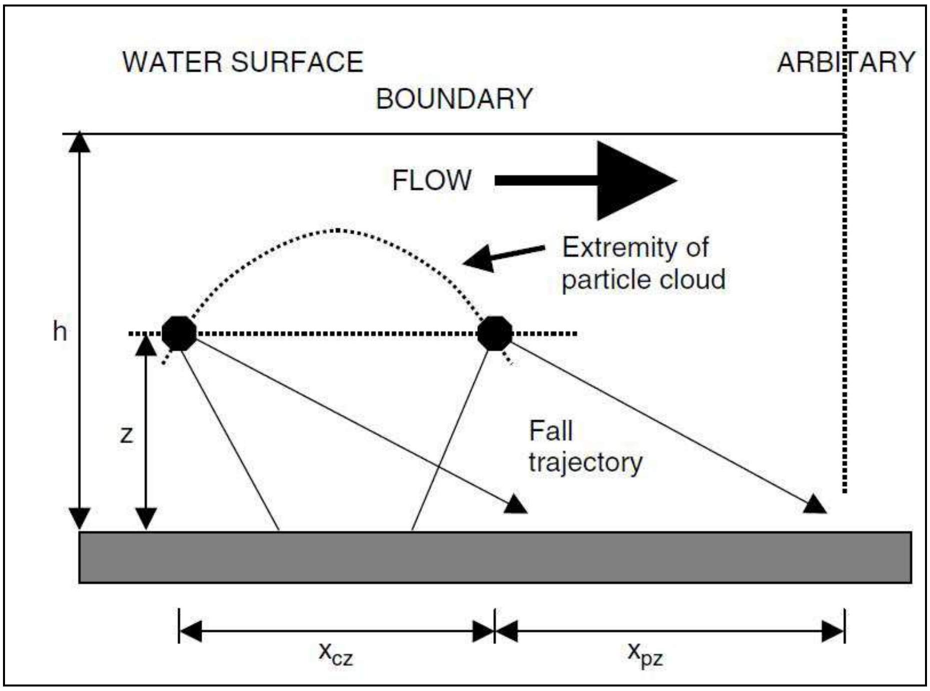

Figure 2.1 Cycles of particle uplift and deposition during sheet erosion (Kinnell, 2004)

The effectiveness of flow transport is a function of the depth and velocity of surface runoff (Kinnell, 2004). Vegetation has a significant effect on reducing the transport efficiency of surface runoff (Dlamini *et al*., 2010). Vegetation promotes SOM accumulation which improves soil structure and particle aggregation. This facilitates an increase in soil porosity and water infiltration into the soil profile (Puigdefabregas *et al*., 1999, Cammeraat, 2002). Soil particle aggregates, like large sand particles are also difficult to uplift into suspension and are thus less erodible than individual soil particles. Moreover, vegetation and plant residues promote soil surface roughness. This reduces surface flow erosivity by retarding runoff flow velocity as a result of surface obstructions. Runoff is significantly promoted by bare rock and soil surfaces as no significant obstructions to runoff flow are present. A study conducted by Mingguo *et al*. (2007) in the Loess Plateau in North China, located in the middle Yellow River basin showed that vegetation does reduce runoff volume;, however, the sediment reduction rate was higher than the runoff reduction rate at the plot scale.

2.2.4 Sediment deposition and the factors of control

Deposition in the context of soil erosion is the settling of the sediment as a result of insufficient transport energy or a decrease in quantity of the transport medium (Kinnell, 2004). Deposition is the final mechanism of the erosion cycle. It may occur several times during a rainfall event depending on the rainfall event and surface characteristics (Terrence, 2002). Flow velocity is a parameter that varies with flow discharge, surface roughness and slope gradient. During a rainfall event, reduction of flow velocity may occur as a result of a decrease in rainfall intensity toward the end or during a rainfall event. It may also be caused by depressions in microtopography or decrease in slope gradient at the hillslope level (Cammeraat, 2004). Soil material is preferentially sorted during the process of deposition. Generally, large dense particles such as sand are deposited soon after the loss in flow velocity, as more energy is required to keep them in motion, whereas smaller and/or less dense material such as fine silt, clay and particulate and dissolved SOC are deposited toward the end of the loss in flow velocity, as they are more easily kept in suspension (Gregorich *et al*., 1998; Ritchie *et al*., 2006).

2.3 Soil Erosion Dynamics

Soil erosion is a dynamic natural process with a spatial and temporal variability proportional to the area and timespan under consideration. The reasons for the increasing complexity of soil erosion as one considers larger areas of land over longer timespans is the increasing heterogeneity of the characteristics of the landscape (soils, slope, catchment size and shape) and the variability of the factors causing soil erosion (rainfall, slope, vegetation, land use and soil) (Puigdefabregas *et al*.,1999; Mingguo *et al*., 2007). The increasing complexity has a significant effect on the detachment, transport and deposition cycles occurring at different spatial and temporal scales. A number of authors have shown that there are different factors of erosion control which operate with varying degrees of significance at different scales (van de Giesen *et al*., 2005; Mingguo *et al*., 2007). It is important to understand spatial and temporal variations in soil erosion and the factors which govern its variability. The acquisition of this understanding will improve the quantification of soil erosion at the different spatial and temporal scales. The knowledge will also assist in the recognition of important contributing sources to soil loss at the catchment scale.

2.3.1 Spatial dynamics of soil erosion

Several authors have reported on the scale effect on erosion variability within a catchment and the variables governing aspects such as continuity and connectivity of soil erosion and the lack thereof (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000; Cerden *et al*., 2004; van de Giesen *et al*., 2005; Mingguo *et al*., 2007). The investigations of the scale effect revolve partly around the fact that measurements of soil loss at catchment outlets give little indication and often a significant underestimation of the erosion processes occurring within the catchment, particularly at the hillslope level (Stomph *et al*, 2002; Mingguo *et al*., 2007). Replication of sediment output measurements are also difficult to achieve at catchment outlets. Authors have also stated that measurements of soil loss at the plot scale, particularly the microplot scale do not account for soil variability at the catchment scale, however, replicated measurements which can better represent hillslope erosion dynamics are more practical at the microplot scale and plot scale (Le Bissonnais *et al*., 1998).

Le Bissonnais *et al*. (1998) conducted a study in the Blosseville catchment located in the northwest of the Paris basin (Pays de Caux). The aim of their investigation was to study the erosion parameters and mechanisms and to quantify runoff and sheet erosion at plot scales of $1m^2$, $20m^2$ and $500m^2$ and at a scale of 70 ha at the outlet of a small cultivated catchment. Measurements were taken during the winter and summer months. The soils on which the study was conducted had a low clay content (approximately 15%) and a low organic matter content (approximately 1.5%) and were therefore prone to crusting. The results for sediment concentrations of the 20 m^2, 500 m^2 plots and the 70 ha catchment outlet obtained by Le Bissonnais *et al*. (1998) show that values of sediment concentration were similar for the plots and significantly low in comparison to the catchment outlet. Bissonnais *et al*. (1998) attributed the difference in sediment concentrations between the plots and the outlet to catchment scale dynamics such as channel deposition and deposition on the lower concave section of the catena above the river. An additional reason for the decrease in sediment concentration with an increase in catchment area is the lack of runoff at the catchment outlet. During a rainfall event which generates runoff, detachment of soil material occurs by the combined processes of raindrop and flow detachment. Raindrop impact facilitates the detachment of soil material (Kinnell, 2004) and runoff frequently proceeds after the rainfall event has stopped. Therefore, less sediment is made available for transport by runoff and consequently a lower sediment concentration is measured at the catchment outlet.

A study conducted by Puigdefabregas *et al*. (1999) in Rambla Honda field site in southeast Spain observed the effect of vegetation on catchment heterogeneity with increasing spatial scale. Their investigation illustrated the dynamics of sediment deposition and mobilisation at vegetation clumps and bare soils, respectively. Puigdefabregas *et al*. (1999) also showed that during rainfall events, most water did not reach the lower hillslope of the catchment as a result of the vegetated portions of the hillslope acting as runoff and sediment sinks. Their study also revealed that runoff was rarely generated at the larger scale during rainfall events and that higher rainfall intensity thresholds were required for the generation of runoff at larger spatial scales. Their study supports the notion of an increase in the complexity of the dynamics of soil erosion with increasing spatial scale (Puigdefabregas *et al*., 1999).

Various geomorphological characteristics of a catchment affect the erosion processes occurring within and at the outlet of a catchment. In order to understand erosion dynamics at the catchment scale, knowledge should not be limited to information collected from runoff microplots as the measurements obtained may not be representative of the dynamics at larger scale (Cerdan *et al*., 2004). Chaplot and Le Bissonnais (2000) conducted an investigation in an experimental field located in the northwest part of the Paris basin (Pays de Caux). The soil of the area was prone to crusting on account of the low clay (120 ± 2 g kg^{-1}) and (14 ± 3 g kg^{-1}) (SOM) contents. The aim of the study was to observe the effect of slope (4 and 8%) on runoff coefficients (%), soil loss (g m^{-2} h^{-1}) and sediment concentration (g I^{-1}). Runoff plots with surface areas of 1 and 10 m^2 and 4 and 8% slopes were employed for the study. The results of their work indicate that there were higher runoff coefficients and soil loss rates for plots on steeper slopes (8%) (Table 2.1). However, sediment concentrations for the plots located on the 4 % slopes were significantly low, especially when compared to the 10 m^2 plot on the 8 % slope (Chaplot and Le Bissonnais, 2000). The attributed reason for this was because the 1 m^2 plots did not allow for the acquisition of flow velocity by runoff water which could have made it more erosive (Chaplot and Le Bissonnais, 2000). The results obtained by Chaplot and Le Bissonnais (2000) illustrate the dynamics of erosion and detachment, transport and deposition cycles occurring at different spatial scales under varying topographic conditions.

Table 2.1 Values of erosion parameters from plots and slopes of varying characteristics (Chaplot and Le Bissonnais, 2000)

Slope (%)	**Surface Area (m^2)**	**Runoff Coefficient (%)**	**Sediment Concentration (g I^{-1})**	**Soil Loss (g m^{-2} h^{-1})**
4	1	57	3.5	60
4	10	60	4.0	70
8	1	89	3.6	90
8	10	92	7.0	190

Cammeraat (2004) investigated the hydrological and erosion responses at different scales in a semi-arid catchment in southeast Spain. Cammeraat (2004) stated that three response areas, namely, the plot, hillslope and catchment scale, are found within a catchment. The delineation of the response areas is based on their spatio-temporal extent and the erosion processes and factors of control occurring at each scale. Cammeraat (2004) made mention of the importance of factors of erosion control such as vegetation cover, antecedent soil moisture content, soil surface roughness and rainfall characteristics and the significance of their roles differing across the spatio-temporal scales. Some factors such as soil surface roughness related to aggregate stability are important at the plot scale but are less significant at larger scales. At larger scales such as the hillslope level, rills are important as detention storage depressions for runoff water. The findings made by Chaplot and Le Bissonnais (2000) regarding importance of slope characteristics at larger scales and the lack of their importance at the plot scale compliment the findings made by Cammeraat (2004). Cammeraat (2004) also mentioned the increase in the threshold for runoff generation and soil loss with an increase in the size of the response area. For example, a low magnitude rainfall event would generate runoff and cause soil loss at the plot scale. However, a rainfall event with a considerably higher magnitude would be required for a runoff and soil loss response from the hillslope or catchment level. Figure 2.2 shows results obtained by Cammeraat (2004), illustrating an increase in threshold rainfall depth required for the generation of runoff. The graph illustrates that there is increased landscape heterogeneity with increasing spatial scale contributing to a delayed large scale hydrological response (Cammeraat, 2004). A possible reason for the decrease in hydrological response with increasing spatial scale could be attributed to the fact that that there is greater potential for the occurrence of infiltration and sedimentation at the sub-catchment or catchment scale (Cammeraat, 2004). The findings of this research support those made by Puigdefabregas *et al*. (1999).

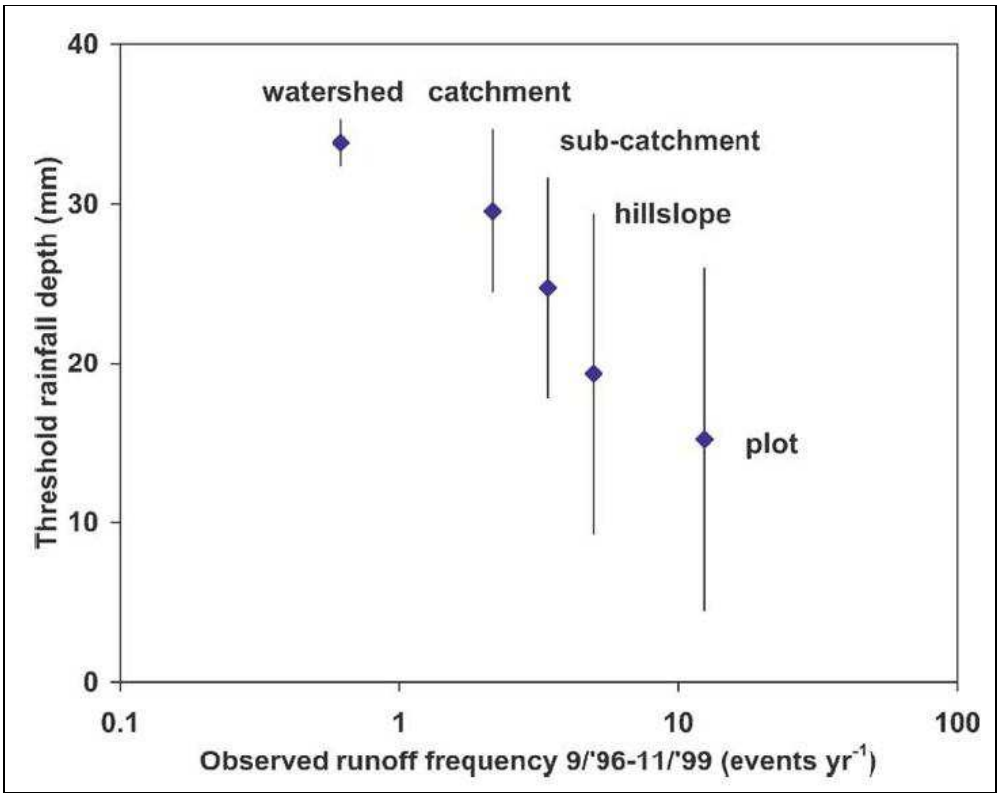

Figure 2.2 Threshold rainfall depth and runoff occurrence as a function of spatial area (Cammeraat, 2004)

2.3.2 Temporal dynamics of soil erosion

Soil erosion has temporal variability regarding the time at which various erosion mechanisms occur during a storm event. The effectiveness of each of the described mechanisms discussed in the previous chapter is dependent on raindrop energy (e) and/or flow energy (Ω). If either of the two types of energies does not exceed a respective critical energy value (e_c and Ω_c) required for the detachment of soil surface material, no soil erosion will occur (Kinnell, 2004). The dynamics of the mechanisms of detachment and transport and the associated energies required for their operation changing with the absence and presence of runoff water as a rainfall event proceeds are shown in Figure 2.3. At the onset of a rainfall event the critical energy (e_c) required for the detachment and transport of surface soil material by raindrop impact is low. As rainfall proceeds, e_c increases as a result of surface crusting imparting a resistance to soil particles against detachment and a reduction in soil infiltration by water (Kinnell, 2004). Kinnell (2004) described detachment-tranport systems similar to the mechanisms of erosion discussed in the previous chapter. RD-ST is the abbreviation for rainfall detachment-splash transport and it is the system which functions before the onset of runoff. On the commencement of runoff a thin film of moving water develops, detachment and transport occur by the combined action of raindrop detachment and splash and flow transport. This has been described by Kinnell (2004) as raindrop detachment-rainfall induced flow transport (RD-RIFT). A further change in mechanism operation develops as the depth of flow at the soil surface continues to increase. When this occurs, raindrops are still able to penetrate the film of water to detach soil surface material, however the influence of splash transport is negligible as flow is becomes the main transport mechanism (Kinnell, 2004). The system describing this stage of the erosion mechanism operation is rainfall detachment-flow transport (RD-FT). The change in mechanism operation is accompanied by an increase in e_c, caused by the presence of a film of runoff water which begins to dissipate raindrop energy (Kinnell, 2004). As a rainfall event continues to produce increased quantities of runoff at the soil surface, the value of e_c increases as the depth of surface flow increases and as a result, detachment and transport by overland flow become the dominant erosion mechanisms. This is otherwise described as flow detachment-flow transport (FD-FT) (Kinnell, 2004). As the depth of flowing water increases, surface flow acquires increased energy and is able to lift and transport loose soil surface particles provided that the energy of the flow is at least equal to

$\Omega_{c(loose)}$. If flow depth happens to increase further, particle detachment occurs by the flow of runoff water. It can be seen that at the onset of FD-FT the $\Omega_{c(bound)}$ required to detach particles is considerably high by comparison to the e_c value at the beginning of the rainfall event. The RD-ST, RD-RIFT and RD-FT systems described by Kinnell (2004) are characteristic systems describing sheet erosion and sheet flow at the low gradient positions of a hillslope where flow energies are generally low unless high intensity storm events rapidly supply rainwater for the supply of overland flow. FD-FT describes rill and gully erosion and concentrated flow conditions which are able to incised and incise and remove considerable amounts of erosion as a result of high velocity and significant flow depth (Poesen *et al*., 2003; Valentin *et al*., 2005).

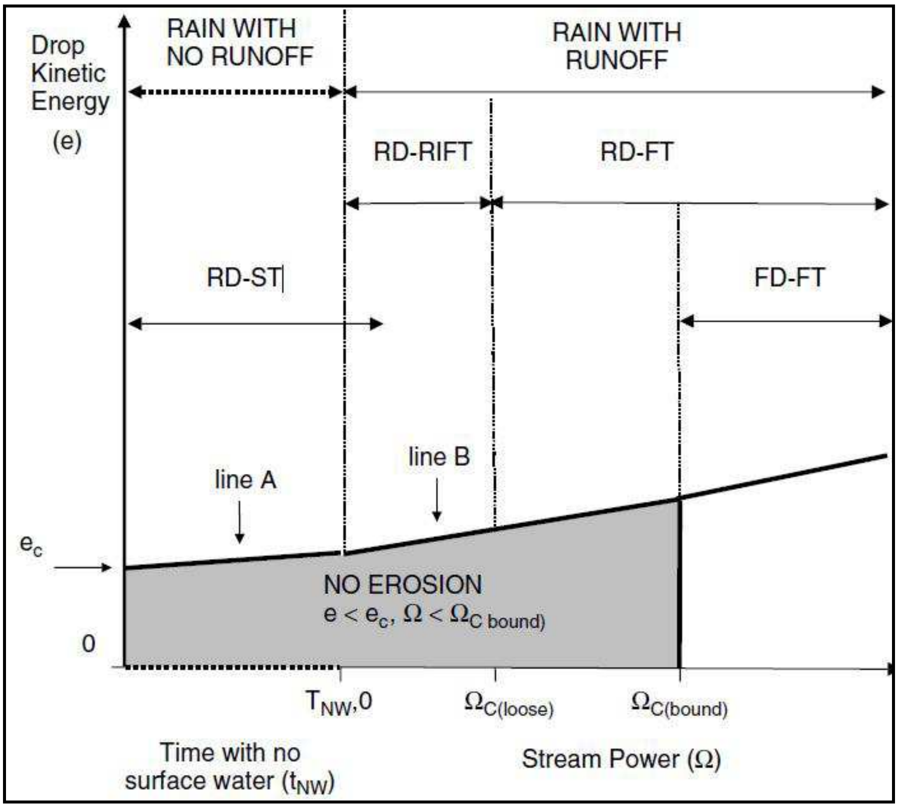

Figure 2.3 Representation of the detachment-transport systems and the associated energies required for detachment and transport (Kinnell, 2004)

The effect of the temporal dynamics of soil erosion during a rainfall event can be illustrated using a typical hydrograph showing the variability of rainfall intensity as a function of time. Figure 2.4 illustrates the concept of the effect of rainfall intensity on the erosion mechanisms occurring during a storm event. At the onset of rainfall, the mechanisms of raindrop detachment, splash transport and deposition are in operation. The erosion mechanisms change when a critical flow producing intensity (I_c) exceeds the infiltration rates of water into a soil profile. At this stage, overland flow develops and the systems described by Kinnell (2004), which include overland flow, begin to play a significant role in soil erosion. Mass deposition occurs when rainfall intensity subsides resulting in a decrease in the amount of water available for surface flow.

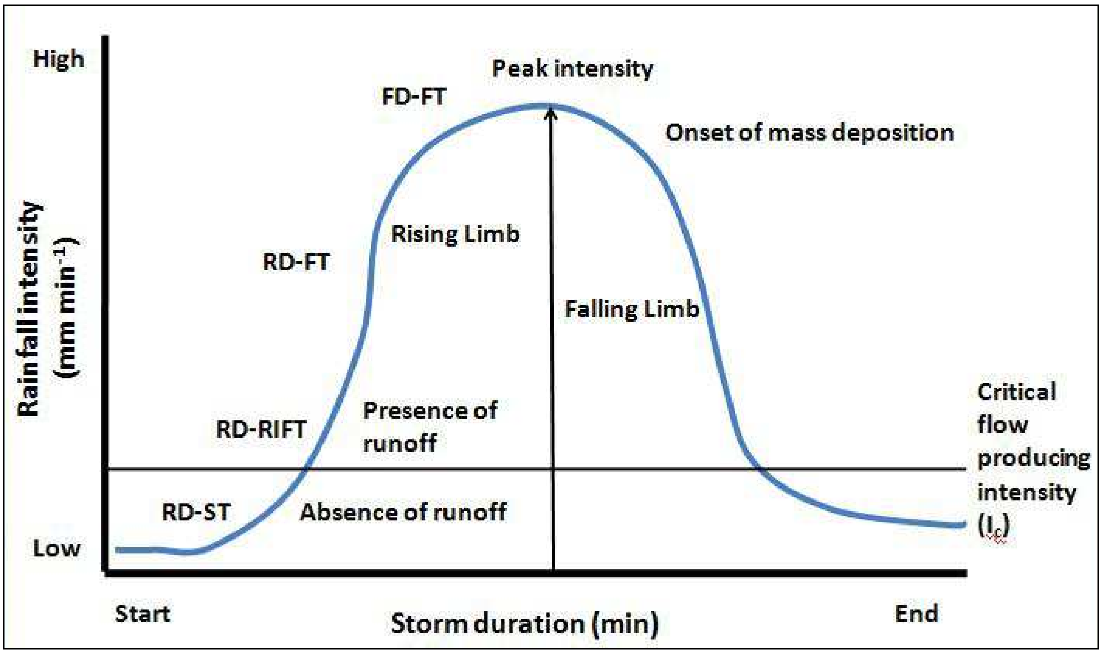

Figure 2.4 Typical variability of rainfall intensity during a rainfall (after Stomph *et al*., 2002; Kinnell, 2004)

2.3.3 Spatio-temporal variations in runoff and erosion

Stomph *et al*. (2002) describes the beginning of the generation of runoff as the point in time when rainfall intensity exceeds infiltration capacity. The hydrograph corresponding to the evolution of runoff can be divided into a rainfall excess phase and a recession-infiltration phase. The rainfall excess phase can be further divided into a build up phase and an equilibrium phase (Figure 2.5) (Stomph *et al*., 2002). The start and end of the build up phase is marked by the initiation of runoff and the contribution of the most distant region of the catchment to streamflow at the catchment outlet, respectively. The equilibrium phase occurs when water flowing at the catchment surface continues to reach the catchment outlet regardless of the magnitude of the travel distance (Stomph *et al*., 2002). The recession-infiltration phase occurs when rainfall intensity begins to subside. During this phase runoff continues to occur however the upslope regions of the catchment become progressively drier as runoff water moves to the low elevation regions of the catchment (Stomph *et al*., 2002).

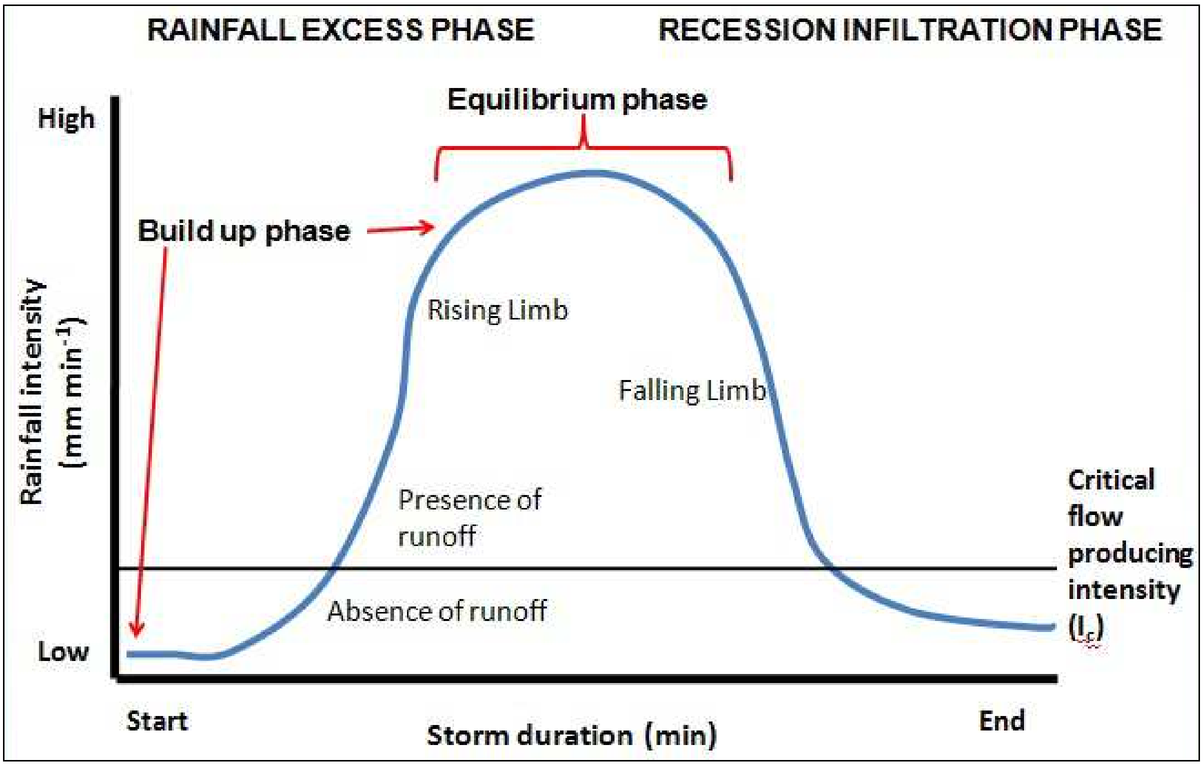

Figure 2.5 Spatio-temporal dynamics erosion (after Stomph *et al*., 2002)

Stomph *et al*. (2002) conducted a laboratory investigation to determine the effect of slope length on runoff response. Laboratory experiments were conducted in the Department of Plant Sciences at Wageningen University on experimental slopes of 1.5, 3.0 and 6.0 m with uniform gradient. Simulated rainfall events of uniform intensity were applied to slopes for durations of 1, 1.5, 2.5 and 3.75 min. A graphical representation of the obtained results can be seen in Figure 2.6. The results show the response of the different slope lengths to rainfall of varying durations. In Figure 2.6 (a) it can be seen that the 1.5 m slope had the greatest discharge (± 1.5 I min^{-1} m^{-1}) and the 6 m slope had the lowest discharge (± 0.3 I min^{-1} m^{-1}). All three slopes did not go beyond the build up phase. The discharge measured from each of the slopes increased when the duration of the applied rainfall was 1.5 min as shown Figure 2.6b. The 1.5 m slope reached equilibrium, however the 3.0 and 6.0 m slopes still had not advanced passed the build up phase. When the duration of the applied rainfall increased to 2.5 min (Figure 2.6c), all three slopes had significantly high discharges of ± 2.8 I min^{-1} $m^{-1}$and a complete cycle from rainfall excess phase to recession infiltration phase was achieved. The same scenario occurred for Figure 2.6d (Stomph *et al*., 2002). The slope lengths are analogous to catchments of varying sizes. According to Cammeraat (2004) and Mingguo *et al*. (2007), small catchments have a higher hydrological response than large catchments. A further result obtained by Stomph *et al*., 2002 relates to the discharge amount from a long duration event of high intensity event. Figure 2.7 shows the discharge response of the three slopes used by Stomph *et al*. (2002). It can be seen that the 6 m slopes had the highest discharge (± 18 I min^{-1}). The reason for this was because a larger area contributed to the total discharge measured at the end of the 6 m slope. The duration and intensity of the rainfall event were also sufficient enough to allow for continuous flow of runoff from the most distant point of the slope. This scenario is analogous to catchments of varying sizes. Significant discharges at the outlet of a large catchment will only be observed under high intensity events of long duration (Stomph *et al*., 2002; Cammeraat, 2004; and Mingguo *et al*., 2007).

The severity of erosion systems vary within rainfall seasons and within rainfall events. A study conducted by Vandaele and Poesen (1995) assessed the spatial and temporal variability of erosion forms in two cultivated zero order sub-catchments between Brussels and Leuven in Central Belgium. During their research 60 to 70% of the total erosion measured at the outlets of two adjacent catchments (400 and 600 m^3) took place during high intensity, low frequency rainfall events which occurred during late spring and early summer. The loss of soil was caused by rill and ephemeral gully erosion. Vandaele and Poesen (1995) also noted that the contribution of ephemeral gully erosion to soil loss had significant seasonal variability. Ephemeral gully erosion contributed between 37 to as much as 63% to total soil loss depending on the occurrence of high intensity, low frequency rainfall events.

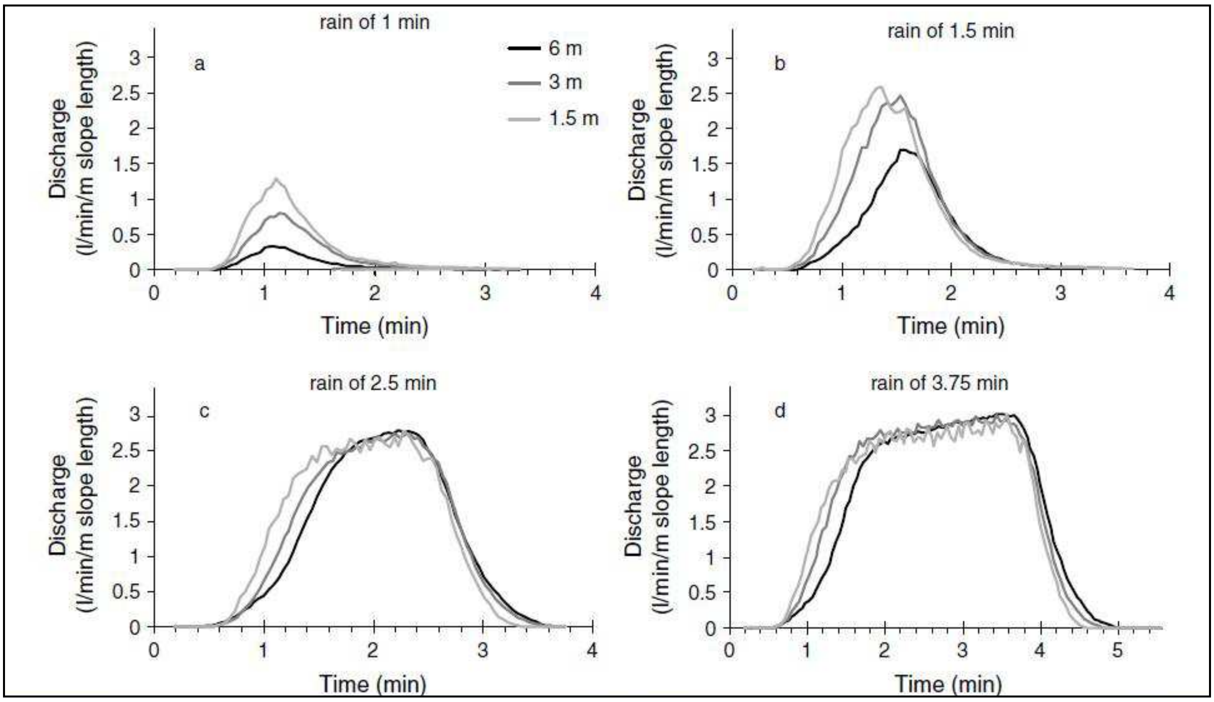

Figure 2.6 Runoff response as a function of rainfall duration and slope length with (a), (b), (c) and (d) depicting discharge responses to rainfall 1, 1.5, 2.5 and 3.75 min respectively (Stomph *et al*., 2002)

2.4 The Contribution of Different Sediment Sources to Catchment Soil Loss

The determination of the most significant contributor to catchment soil loss is difficult because of the heterogeneities and multiple processes occurring at the catchment scale (Krause *et al*., 2003; Descroix *et al*., 2008). In this chapter the techniques and sediment characteristics that have been used to trace sediment origins will be reviewed. Details on sediment source tracing aids in determining the contribution of the different erosion forms to catchment soil loss will also be reviewed.

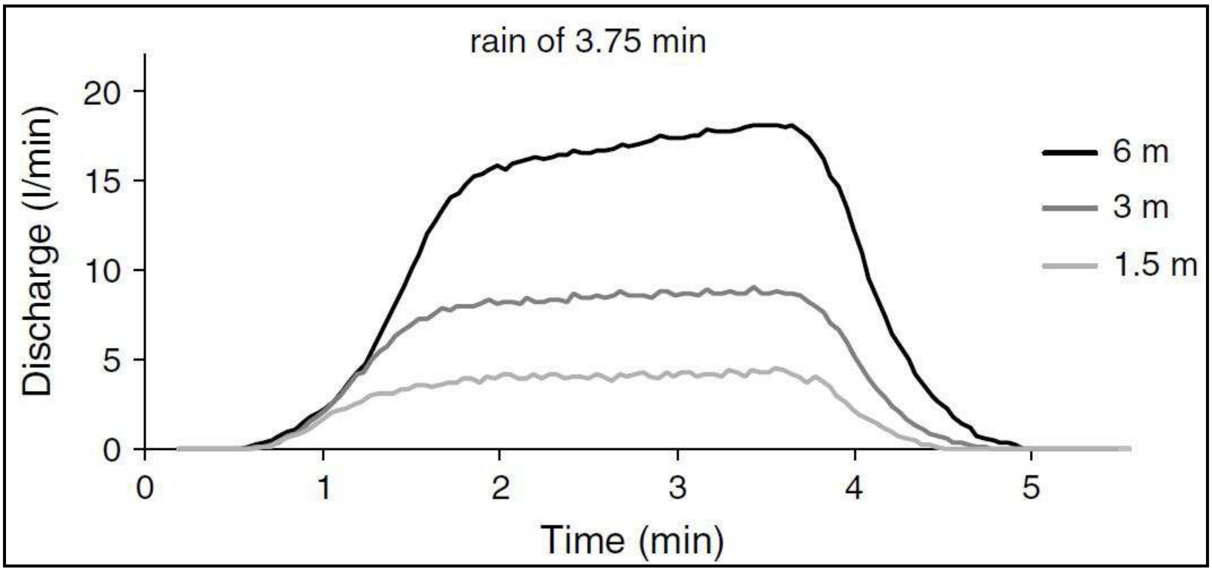

Figure 2.7 Discharge from slopes of varying lengths during long duration rainfall (Stomph *et al*., 2002)

2.4.1 Catchment sediment outputs and sediment source tracing

The soil exiting a catchment outlet may have hillslope (Descroix *et al*., 2008), gully or stream channel origins (Collins *et al*., 2001; Krause *et al*., 2003; Wu *et al*., 2008), or in some instances, all three. In addition, sediment at the confluence of two rivers may have origins of the same spectrum from two different catchments (Chappell *et al*., 2006). In order to understand which sources contribute to catchment soil losses, it is necessary to examine the qualitative properties of the sediment lost and soil at potential sediment sources. Similarities in sediment sources may give a trustworthy indication as to which areas of a catchment, and to a greater extent, which catchment is contributing to soil loss and what measures of erosion mitigation need to be undertaken. Soil texture, clay type, nutrients, colour and elemental constituents are qualitative properties of soil used to “fingerprint” or trace sediment sources (Krause *et al*., 2003; Li *et al*., 2003; Valentin *et al*., 2005; Chappell *et al*., 2006). The following section will discuss ways in which a few of these parameters have been used to trace sediment sources.

Chappell *et al*. (2006) carried out an investigation in the Yangtse River system in China with the aim of determining sources of sediments upstream of the trunk of the river system.

Twenty three sand samples were collected from the major tributaries in the western Yangtse River catchment and the eastern catchment. The concentrations of Mg, Ca, Sr, Ti, Mn and Fe and cosmogenic ^{10}Be in quartz sand grains of the collected sand samples were analysed. The attributed reason for the use of ^{10}Be was that ^{10}Be is unaffected by changes in altitude and erosion rate and it was believed that it would provide a good indication of the location of sediment sources within the Yangtse River catchment. The results of the analysis of the chemical variables of the sand samples revealed that the dominant source of sand in the river system was the western Yangtse River catchment (Chappell *et al*., 2006).

Reservoir sedimentation is a global cause for concern, since it reduces reservoir storage capacity. This creates significant setbacks for those affected as less water is available for domestic use, industry and agriculture. An additional consequence is the introduction of harmful chemicals such as trace heavy metals which are harmful to humans and aquatic organisms or the introduction of nutrients which could lead to reservoir eutrophication. Li *et al*. (2003) conducted an investigation in the Chinese Loess Plateau in northwest China to assess the sediment production and sediment sources at the hillslope and catchment scales in the Yangjuangou reservoir catchment. The fallout ^{137}Cs technique was employed to determine the distribution of sediment sources on hills and gullies. Soil loss data were obtained from the reservoir at the catchment outlet. The determination of sediment sources and dominant erosion forms contributing to reservoir sedimentation was done by comparing the activities of ^{137}Cs and the ^{210}Pb/^{137}Cs ratios in surface and subsurface soils with those of sediment deposited at the catchment outlet above the reservoir (Li *et al*., 2003). The results of the study indicated that, the cultivated hillslopes were significant contributors to reservoir sedimentation. However, gully erosion was the main erosion form contributing to reservoir sedimentation (Li *et al*., 2003). The following section will highlight case studies which have determined the relative contribution of erosion forms to catchment soil loss by using sediment source tracing methods.

2.4.2 Catchment sediment outputs and the different erosion forms

A number of authors have recognized the impact of land use practices on soil erosion and catchment soil loss (Li, *et al*., 2003; Descroix *et al*,. 2008). When evaluating the contribution of erosion forms to catchment soil loss, it is imperative that knowledge of catchment land use is acquired. Descroix *et al*. (2008) conducted an investigation in Western Sierra Madre to determine the respective contribution of gully and sheet erosion to catchment soil loss. Field observations and field measurements of runoff and soil loss were made using runoff plots as well as catchment scale observations. They noted that measured soil losses in the study area were high and that gullies were few. Overgrazing and deforestation were the attributed reasons for the high runoff and soil loss rates (Descroix *et al*., 2008). In addition, the compaction of the grazing land by cattle contributed to a reduction in water infiltrability into the soil and consequent rapid runoff generation and soil loss. The results of their study indicated that sheet erosion caused the most significant catchment soil losses within the study area. According to Descroix *et al*. (2008), soil losses as a result of sheet erosion were two orders of magnitude greater than those of gully erosion.

In a different scenario in New South Wales, Australia, Krause *et al*. (2003) conducted a study to determine the dominant source contributing to soil loss from a 1.2 km^2 gullied catchment. Krause *et al*. (2003) used several soil parameters (fallout radionuclide, ^{137}Cs, the heavy metals; copper (Cu), lead (Pb), and zinc (Zn), the trace metals; iron (Fe) and manganese (Mn) and the base cation, potassium (K)) to determine the locality of the sediment sources and the erosion forms contributing to catchment soil loss. The significance of a wide spectrum of soil parameters was to increase the confidence level in the obtained results. The results of the study indicated that of the two potential sediment sources (gully wall and grazed pasture), gully walls were the main sediment source. Gully walls contributed as much as 98% to soil loss from the study catchment.

The study by Vandaele and Poesen (1995) documented the significant contribution of gully erosion to gross catchment soil loss (37 to 63%). Wu *et al*. (2008) investigated the contribution of gully erosion to total soil loss in the black soil region of north-eastern China. The study involved the monitoring of gully erosion processes and gully development during 2002 to 2005 using real-time kinematic GPS. The results of their research revealed that gully heads retreated at an average rate of 8.4 m yr^{-1}. Their results also showed that gully erosion processes contributed to an average sediment production rate of 1145 t yr^{-1} which was 1.5 times higher than the sediment produced by surface erosion processes (Wu *et al*., 2008).

A number of authors have documented the fact that sediments eroded from a hillslope do not necessarily reach the catchment outlet and, in some instances, may not move further than a few meters from the site of initial detachment depending on the factors of erosion control (Vandaele and Poesen, 1995; Chaplot and Le Bissonnais, 2000). Several authors have also documented the severe effect of gully erosion on land degradation and the importance of gullies as sediment sources (Vandaele and Poesen, 1995; Krause *et al*., 2003; Li *et al*., 2003; Poesen *et al*., 2003; Valentin *et al*., 2005; Wu *et al*., 2008). The main reason is that concentrated flow in gully systems has higher energy and is far less inhibited than sheet flow at the hillslope level. Furthermore, gully bank collapse also supplies significant amounts of soil for transport in gully systems (Chaplot *et al*., 2010). However, contrary evidence of the role of sheet erosion has been obtained. According to other observations, the contribution of gully erosion to total catchment soil loss can be of negligible importance, when compared to sheet erosion (Descroix *et al*., 2008). Apparent contradictory results may be explained by the fact that the contribution of the different erosion forms to sediment outputs from a catchment are a function of the intensity and duration of a storm event (Stomph *et al*., 2002). For instance, it is likely that the sediment output from a catchment during and subsequent to a low intensity, short duration rainfall event may originate from areas close to the catchment outlet within the catchment. Conversely, sediment outputs from a high intensity event of long duration are likely to originate from erosion occurring at the hillslope level and within gully and stream channels. In addition, one can expect that if there are few gullies in a catchment their contribution to total catchment soil loss may be minimal depending on gully, rainfall and soil characteristics (Descroix *et al*., 2008). Catchment characteristics such as gradient, basal cover and sediment properties may also increase sheet erosion rates by increasing its efficiency (Descroix *et al*., 2008). For example, poor sediment aggregation provides material which is easy to transport due to low mass, thus, low entrainment energy of the transport medium. Steep gradients allow for the rapid acceleration of overland flow and a lack of basal cover reduces soil surface roughness which provides an unobstructed flow path for overland flow.

2.5 Discussion and Conclusion

The objective of this literature review was to consider the mechanisms by which soil erosion occurs, the factors controlling the efficiency of the erosion mechanisms, the spatio-temporal variability of soil erosion, methods of determining the locality of sediment sources and the consequences of soil erosion. It can be seen that the process is a phenomenon with significant negative effects particularly under circumstances giving rise to accelerated soil erosion rates. Excessive soil erosion causes land and environmental degradation (Chappell *et al*., 2006), economic expense and social poverty (Descroix *et al*., 2008). Soil erosion degrades the affected site by removal of valuable fertile top soil thus reducing the opportunity for the establishment of agricultural systems or the continuation of agriculture. Soil erosion incurs financial expenses for farmers as large amounts of fertiliser, which are applied to bare soils during field preparation of crop growth, are potentially lost. This coupled with loss of a nutrient rich topsoil can severely diminish expected crop yields and may even cause bankruptcy. Subsistence farmers who make a direct living off the crops grown on what little land they have are at risk of being of experiencing greater degrees of poverty as a consequence of soil erosion. In addition, cattle owned by subsistence farmers may also be at risk of undernourishment as little grass grows on degraded land. In severe instances of gully erosion, land is disfigured and the construction of infrastructure and roads becomes impractical in some instances on account of financial constraints. Figure 2.8 shows a scenario near Mount Frere in the province of the Eastern Cape, South Africa where gully erosion, caused, in part, by overgrazing, has rendered the land useless for most productive anthropogenic activities. Eutrophication of terrestrial water bodies, reservoir sedimentation, destruction of aquatic ecosystems, and the introduction of harmful substances into terrestrial water bodies are forms of environmental degradation as a consequence of soil erosion (Sharma, 1995). Large sums of money are expended in remediation and restoration efforts which could otherwise have been avoided through the establishment of correct and effective mitigation measures. Generally, populations located downstream from the site of the occurrence of soil erosion experience the negative offsite impacts of soil erosion (Valentin *et al*., 2005). Despite the numerous negative impacts of soil erosion, it is a beneficial process, especially when rates of soil erosion are not increased by factors such as anthropogenic activity. Soil erosion redistributes soil material through the landscape (Puigdefabregas *et al*., 1999) and facilitates the concentration of fertile soil material in low relief areas which is beneficial for agriculture. Soil erosion serves as a carbon sink mechanism by sequestering carbon in soil profiles. This may reduce atmospheric carbon emissions and mitigate climate change (Chaplot *et al*., 2009).

Figure 2.8 Gully erosion and consequent land degradation in a rural settlement approximately 30 km from Mount Frere in the Eastern Cape, South Africa

Gully erosion is generally considered to be the most severe case of soil erosion and land degradation. The formation of gullies occurs in severe cases of soil erosion and is the cause of severe land degradation and significant catchment soil loss (Figure 5.1). Soil erosion is a dynamic process which has significant variability, both temporally and spatially. In order to mitigate and avoid severe erosion caused by natural and anthropogenic activities it is imperative that an understanding of the catchment scale erosion dynamics is acquired. Knowledge based on micro-scale investigations is useful, however it only forms the foundation for the acquisition of essential knowledge about the hydrological and geomorphological functioning and responsiveness of the landscape.

3. METHODOLOGY

3.1 Study Site Description

The study area is situated in Potshini, an agricultural area situated approximately 10 km from Bergville in KwaZulu-Natal, South Africa (S: 29.36°; E: 28.82°). Potshini is localised in the north-sloping lands of the upper Thukela Basin (30 000 km^2) (Figure 3.1).

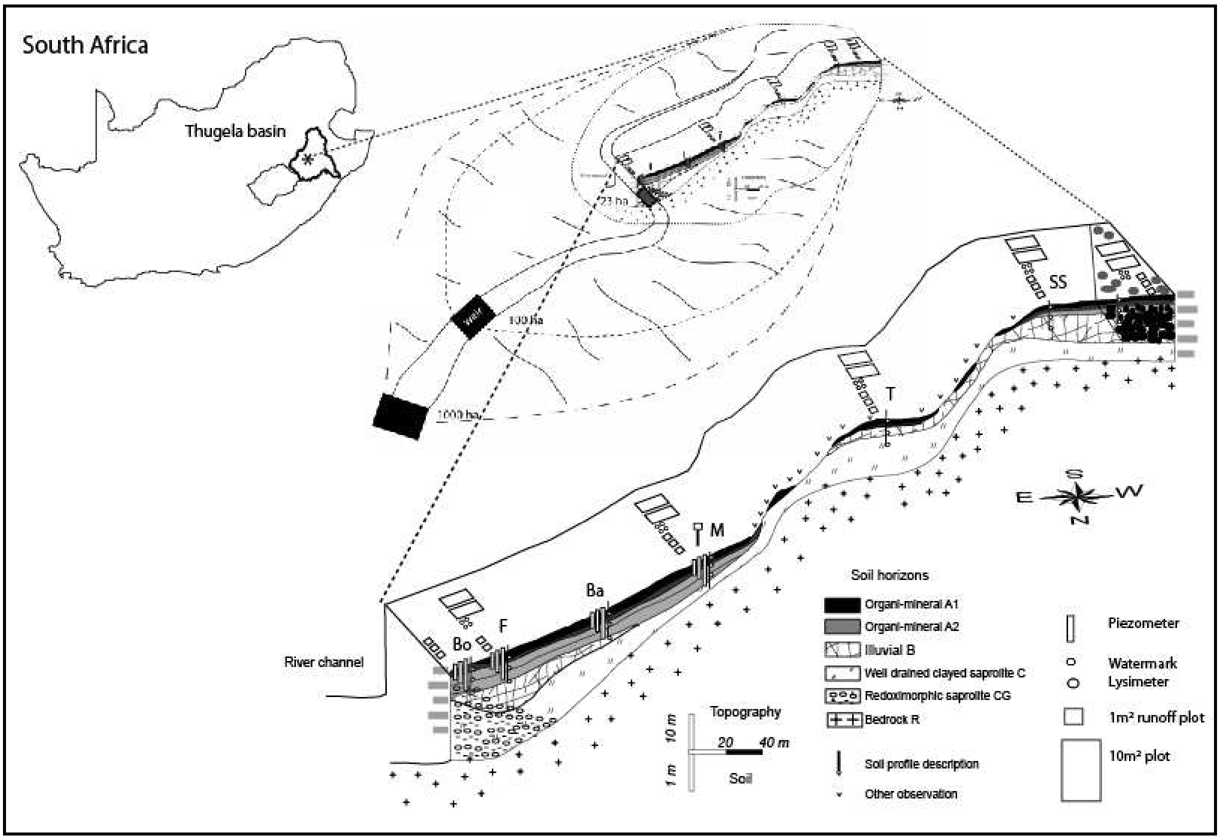

Figure 3.1 Location of the study area and experimental design (Chaplot, 2011)

The climate is humid, sub-tropical with a summer rainfall pattern (October-March) (Schulze, 1997). According to a 30-year rainfall record, the mean annual precipitation of Bergville is 684 mm per annum with a potential evaporation of 1600 mm per annum and a mean annual temperature of 13 °C (Schulze, 1997). The study area consists of a 1000 ha catchment with 2 embedded catchments of 23, 100 ha corresponding to three different land uses, namely; unmodified grazing land (23 ha) homesteads and subsistence (100 ha) and commercial scale agriculture (1000 ha). The steep slopes of the Potshini Catchment are concentrated within the 23 ha head water catchment were the mean slope is 15.3% while the mean slope gradient is about 9% for the 100ha level. The stream network which flows through the 1000 ha catchment begins in the 23 ha headwater catchment where a large gully is gradually widening and retreating as a result of fluvial processes. The stream channel feeds into a dam located on a commercial farm in the 1000 ha catchment. The dam is vulnerable to sedimentation as a result of soil erosion occurring upstream. The stream water is used by the community members for household purposes. Additional sources of water for domestic use are located at two borehole pumps within the 100 and 1000 ha catchments

3.2 Experimental Design

An assessment of soil water erosion rates at different spatial scales was made with the core hypothesis that variations in these would be in response to dominant processes taking place within the landscape. Observations have shown that soil erosion processes vary considerably spatially and temporally, there is however a general consensus that the main detachment and transport process at the cm^2 scale is splash erosion and that a circumstantial threshold surface area is required for the dominant operation of overland flow detachment (herein termed runoff detachment) (lateral erosion) or stream channel erosion (linear erosion).

In this soil water erosion study, local erosion processes consisting mainly of splash and slight rain-impacted flow (Kinnell, 2004) were evaluated using conventional 1 m^2 (1×1m) erosion plots. The evaluation of sheet erosion herein referred to as rain-impacted flow tranport (RIF) erosion (Kinnell, 2004) was done using 10 m^2 (2×5m^2) erosion plots. The reason for the use of 5 m long plots was that field observations have shown that eroded soil aggregates deposited in local depressions whose distance was between 3 and 5 m. This plot length also aided in minimising detachment transport and deposition cycles, which facilitated the avoidance of the underestimation of RIF erosion processes. Wischmeier and Smith (1978) would have been inappropriate for this study as their use may have facilitated the development of rills while the purpose of the plots was to evaluate lateral erosion processes. Although erosion plots are commonly used in soil erosion studies, there are limitations particularly when using smaller plots such as the 1 m^2 plots. The reason for this is due to the potential for sediment being splashed out of the plot during rainfall events. The 1 m^2 and 10

m^2 plots were installed at five topographic positions (from the footslope to the shoulder) of a typical hillslope showing the presence of deep Acrisols at footslopes and hillslope plateau and shallow Acrisols middle-slope. The mean slope gradient at the shoulder dolerite (SDOL) and sandstone (SST), terrace (T), middle slope (M) and foot slope (F) were 18, 22, 29, 24 degrees respectively. Three 1 m^2 plot and two 10 m^2 plot replicates were installed at each slope position. The 0.1 and 0.3 m high metal borders surrounding the 1 m^2 and 10 m^2 plots respectively were inserted in the soil to a depth of 0.1 m. It was assumed that the 1 m^2 and 10 m^2 plots described the diversity of the entire hillslope because they were installed on hillslope positions exhibiting different soil types, basal covers and slope gradients. Erosion processes operating at the 23 and 100 ha catchment scales were evaluated using delivery observations for water and sediment.

3.3 Quantification Methods

3.3.1 Soil sampling strategy

Field measurements of water erosion were carried out from 15th December 2009 to 30th April 2010 and 18th October 2010 to 15th May 2011. It was assumed that measurements were made under steady-state soil loss conditions because no significant soil cracking or features of rill erosion were observed within the 1 m^2 and 10 m^2 plots. On 1 m^2 and 10 m^2 plots runoff (R) depths in the reservoirs were measured after each rainfall event using a measuring tape. A volumetric determination of R was made using the calibrated equations:

Aliquot samples of 500 ml were taken after the determination of R depth. The samples were oven-dried at 50 ^oC and weighed to determine average sediment concentration (SC). This method, although efficient, has its limitations for the reason that the aliquot may not be representative of the sediment which was eroded during preceding rainfall event. Soil loss (SL) was determined by the product of R and SC. During this study, a total of 900 samples were collected from 34 erosive rainfall events. Rainfall event characteristics such as rainfall amount, maximum and average rainfall intensity were estimated using an automatic rain gauge with a 6-min step counter located at the study site. Conventional H flumes coupled to

ISCO 6712 and 3700 series automatic samplers were situated at the outlets of the 23 and 100 ha catchment respectively. The automatic water samplers were used to quantify catchment runoff and soil losses during base flow periods and on the rising and falling limb of a hydrograph during rainstorm events.

Soil samples from the different 1 m^2 and 10 m^2 plots and the stream network were collected in the field. They consisted of a 1 kg bulk sample. Surface 0-0.005m and subsurface 0.5-0.9m horizons were considered in this study. At the microcatchment and catchment levels sediment samples were collected using automatic samplers during rainfall events and manual sampling in between events. Due to the quantity of soil material required for particle size analysis for the pipette method (20 g) and analysis of total soil fertility (±350 g), sediment samples were collected from the erosion 1 m^2 and 10 m^2 plots after eight consecutive rainfall events at a time. A total of 52 sediment samples were collected.

3.3.2 Analysis of selected soil and sediment chemical properties

The soils and sediments for carbon and nitrogen analysis were air-dried. The fraction of soil material < 2 mm was obtained by sieving through a nylon mesh. The soil material underwent analysis for total carbon (C) and nitrogen (N) by complete combustion using a Leco TruSpec Carbon Nitrogen analyser. After analysis of the nutrient content of the fertility it was decided that C and N were appropriate indicators of soil nutrients as C content is an indication of soil organic matter content and soils with high soil organic matter are generally fertile.

3.3.3 Analysis of selected soil and sediment physical properties

An adaptation of the pipette method (Gee and Bauder, 1986) was used to determine the particle size distribution of the soils and sediments. Air dried soil material with a mass of 20 g was sieved (< 2 mm fraction) and dispersed by the addition of 10 ml of Calgon (sodium hexametaphosphate and sodium chloride) and 15 ml of distilled water. Samples were subsequently treated ultrasonically for 3 minutes. The dispersed sample was carefully passed through a 0.053 mm sieve into a 1 litre sedimentation cylinder, distilled water was added to increase the volume to 1000 ml. The sand fraction (> 0.053 mm) was oven dried at the 105 ^{o}C for 24 hours. The sand fraction was then subdivided by means of a sieve stack into very fine (< 0.106 mm), fine (0.106 – 0.250 mm), medium (0.250 – 0.500 mm) and course sand (> 0.500 mm). The < 0.053 mm fraction in the sedimentation cylinders was then brought into suspension by agitation using a handheld a plunger. The quantities of coarse silt (0.02 - 0.053 mm) fine silt (0.002 - 0.02 mm) and clay (< 0.002 mm) were determined according to Stoke's law by sedimentation and pipette sampling, after appropriate settling times for each size fraction. The fine silt and clay were also dried at 105 ^{o}C. The average percentages of soil and sediment sand, silt and clay at the different scales were fitted to a texture triangle after the texture triangle compiled by the USDA in an attempt to assess the trends and selectivity of soil erosion mechanisms at the different scales.

Air dry sediment colour was determined using a Munsell colour chart. The hue component of the colour description for soils was transformed to a numerical value called the colour development equivalent. The CDE combines the redness of hue with its purity (chroma). This combined aspect of soil color appears to be closely related to color development, which, in turn, may be related to soil development. Using this method of numerical transformation, a hue of 10YR was assigned a numerical notation of 1.0, 7.5YR a notation of 2.0, 5YR a notation of 3.0, and 2.5YR a notation of 4.0, thus indicating an increasing level of redness.

It was expected that sediments eroded from the 1 m^2 plots would be enriched in clay in comparison to the *in-situ* soil due to predominant low energy transported limited erosion mechanisms. Erosion mechanisms at the 10 m^2 and catchment scales were presumed to get progressively less selective with an increase in particle transport efficiency. Because clay particles are the most chemically reactive fraction of a soil and soil organic matter is light in comparison to the particle fraction of the soil it was assumed that sediments eroded at the 1 m^2 and 10 m^2 plot level would be enriched in nutrients in comparison to the *in-situ* soil. Sediments eroded at the 23 and 100 ha scales were presumed to similar in content to the *in-situ* soil due to the predominant subsoil origin of the eroded sediments. Sediments deposited at the 1000 ha scale were assumed to be enriched in sediments in comparison to the 23 and 100 ha scales due to preferential deposition of clays and nutrients in the dam.

Runoff (R) was expressed in litre of water per m^2, sediment concentration (SC) in gram per litre and soil losses (SL, the product of SC by R) in gram per square metre. In addition we estimated SLw, the soil losses flux, expressed in gram per metre width of plot.

3.3.4 Statistical analysis

Multivariate analysis was applied to the data. A first Principal Component Analysis (PCA) generated using soil erosion variables at the different scales as dependent variable versus environmental characteristics as supplementary variables was generated. A second PCA was applied to the data to find relationships between redness (hue), value, chroma, clay, fine silt course silt, very fine sand, fine sand, medium sand, course sand, C and N. A PCA was used as it has been previously shown to be well-adapted to large sets of variables and to identify the structure or dependence in data sets (Webster, 2001). The ADE4 software (Chessel *et al.*, 2004) was used for this study.

4. PLOT SCALE EROSION DYNAMICS

4.1 Results

4.1.1 Assessment of the surface characteristics of the plot locations

Table 4.1 shows that the average vegetation coverage (cov %) at the plot positions was 78% and varied between 64% at M and 93% at F. The soil clay content (clay %) was 36% with a variation between 28% at the F and 54% at SDOL. The average slope gradient (slope %) of the plots was 22% and varied between 18% at SDOL and SST and 29% at M. Of the plot soils derived from dolerite (F, M, T and SD) the surface at M was the most degraded. The soil derived from sandstone material (SST) was comparable to SDOL in terms of vegetation cover and slope gradient. However, the sandstone material gave rise to a considerably lower clay content at SST (31 %) compared to the SDOL (54 %).

Table 4.1 Characteristics of the study hillslope positions F (footslope), M (midslope), T (terrace), SDOL (shoulder dolerite) and SST (shoulder sandstone): Crust: percentage of soil surface with crusts; Cov: percentage of soil surface coverage by vegetation; Clay: soil clay content; ρ_b: soil bulk density; S: mean slope gradient; ρ_b: bulk density (Dlamini *et al*., 2010)

Plot	**Crust (%)**	**Cov (%)**	**Clay (%)**	**S (%)**	**ρ_b (g cm^{-3})**
F	7	93	28	25	1.23
M	36	64	27	29	1.19
T	19	81	40	22	0.96
SDOL	22	78	54	18	0.96
SST	25	75	31	18	1.15
Average	*22*	*78*	*36*	*22*	*1.10*

4.1.2 Evaluation of the 2009 -2010 rainfall characteristics

The characteristics of the measured rainfall events are summarised in Table 4.2. The total rainfall at Potshini for the 2009-2010 rainy season, 675 mm which is slightly below the 30 year average (684 mm). The minimum and maximum rainfall amount (RA) antecedent rainfall from onset of rainy season to end of erosion event (AR), rainfall intensity (I) and maximum half hour intensity (I_{30}) values indicate that rainfall characteristics were highly variable during the rainfall season. A further indication of this is given by the variance of antecedent rainfall (AR) which had a value of 20468.7. The highest I_{30} value was 64.8 mm h^{-1} which is greater than the 2-year return period 90% occurrence value of 61 mm h^{-1}. The lowest I_{30} value was 0.4 mm h^{-1}. The average I30 value (2.7mm h^{-1}) was well below the 2 year return period value (49 mm hr^{-1}). The mode, median, first and third quartile RA and I_{30} values indicate that the majority of the rainfall events which occurred during the rainfall season were of low amounts and low intensities.

4.1.3 Evaluation of occurrence and severity of soil erosion

The series of measured soil erosion events are summarised in Table 4.3. The maximum values of SC and SL (40.6 g L^{-1} and 149.5 g m^{-2} respectively) were higher for the 10 m^2 plots than the 1 m^2 plots (27.4 g L^{-1} and 30.9 g m^{-2} respectively). A similar trend was followed for the averages of R, SC and SL at the two spatial scales. The median values of R indicate that the 1 m^2 plots were generally more responsive to rainfall than the 10 m^2 plots. The mode, first and third quartile values for R, SC and SL indicate that there were few erosive rainfall events, which is concordant with the rainfall characteristics (Table 4.2).

The mean and maximum values of R, SC and SL at F, M, T, SDOL and SST are given in Table 4.3. The average R at each of the plot locations was similar, although the maximum R values varied considerably. Average and maximum sediment concentration and soil loss values were the highest at the M and SST positions which may be explained by the steep slope and low vegetation coverage at M and the sandstone derived soil material at SST which is prone to crusting (Table 4.1). SC and SL at F, T and SDOL were notably lower in comparison.

Table 4.2 General statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for selected rainfall characteristics of the 17 rainfall events of the 2009-2010 rainy season. (I: average rainfall event intensity; Imax: maximum rainfall event intensity; I_{30}: average thirty minute rainfall event intensity; I_{30}max: maximum thirty minute rainfall event intensity; RA: rainfall amount; RDur: rainfall hours; ARD: cumulative antecedent rain days; AR: antecedent rainfall from onset of rainy season to end of erosion event; AR_3: three day antecedent rainfall; AR_{10}: ten day antecedent rainfall)

	I	**Imax**	**I_{30}**	**I_{30}max**	**RA**	**RDur**	**ARD**	**AR**	**AR_3**	**AR_{10}**
Mean	3.1	23.3	2.7	18.0	25.6	2.1	62.0	201.1	16.9	38.3
SD	1.7	18.2	1.6	16.1	19.8	1.6	39.7	138.8	14.2	18.7
SE	0.4	4.4	0.4	3.9	4.8	0.4	9.6	33.7	3.8	4.3
CV	54.7	78.0	59.0	89.2	77.3	75.1	64.0	69.0	84.2	49.0
Variance	3.1	350.6	2.7	274.7	417.4	2.7	1671.1	20468.7	215.2	373.0
Min	0.8	0.8	0.4	0.4	0.2	0.3	6.0	21.0	0.6	13.4
Max	6.6	69.6	6.1	64.8	64.8	6.4	142.0	435.6	54.6	68.8
Mode	0.8	0.8	0.4	10	n/a	1	n/a	n/a	10.8	25.4
Quartile 1	2.2	9.6	1.7	7.2	8.2	1.0	36.0	101.4	5.6	20.6
Median	2.6	20.8	2.3	17.2	21.0	1.8	49.0	181.4	14.4	35.8
Quartile 3	3.8	28.8	3.8	21.6	42.8	3.3	100.0	328.6	20.6	59.2
Skewness	0.6	1.1	0.4	1.5	0.6	1.2	0.5	0.4	1.4	0.2
Kurtosis	-0.3	1.2	-0.4	2.8	-0.7	1.3	-0.9	-1.3	1.9	-1.7

Table 4.3 General statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for runoff (R), sediment concentration (SC), soil loss (SL) and soil loss by unit width (SLw) at the 1 m^2 (n = 255) and 10 m^2 (n=170) plot scales

	R		**SC**		**SL**		**SLw**	
	L m^{-2}		**g L^{-1}**		**g m^{-2}**		**g m^{-1}**	
	1m^2	**10m^2**	**1m^2**	**10m^2**	**1m^2**	**10m^2**	**1m^2**	**10m^2**
Mean	4.9	5.4	1.5	2.2	3.2	9.8	3.2	4.9
StDev	5.6	7.2	3.7	4.8	5.0	23.4	5.0	11.7
SE	0.4	0.6	0.2	0.4	0.3	1.8	0.3	0.6
CV	114.1	133.4	250.9	220.7	152.7	240.0	152.7	120
Variance	31.8	52.5	13.6	23.1	24.9	554.6	24.9	277.3
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	33.0	38.1	27.4	40.6	30.9	149.5	30.9	74.75
Mode	3.5	1.7	0.2	n/a	n/a	0.8	n/a	0.4
Quartile 1	1.0	1.1	0.2	0.3	0.3	0.6	0.3	0.3
Median	2.8	2.6	0.5	0.8	1.3	1.9	1.3	0.95
Quartile 3	8.0	8.0	0.9	2.5	3.9	5.7	3.9	2.85
Skewness	2.4	2.5	5.3	6.5	3.2	4.1	3.2	2.05
Kurtosis	8.0	6.7	31.9	49.9	12.6	18.3	12.6	9.15

4.1.4 Evolution of runoff, sediment concentration and soil loss

Figure 4.1a indicates that the R values (L m^{-2}) at both plot scales were approximately equal for the majority of the rainfall season. However, slightly more runoff was generated from the 10 m^2 plots (91.6 L m^{-2}), compared to the 1 m^2 plots (83.5 L m^{-2}). Cumulative SL values indicate that soil losses increased steadily and approximately equally at the two plot scales until the 10th event (Figure 4.1b). Subsequently, soil losses from the 10 m^2 plots increased more rapidly than those from the 1 m^2 plots in response to an increase in the number of rain days, cumulative rainfall amount and an increase in frequency of intense rainfall events. Total cumulative SL values were 55.2 g m^{-2} and 165.8 g m^{-2} at the 1 and 10 m^2 plots respectively.

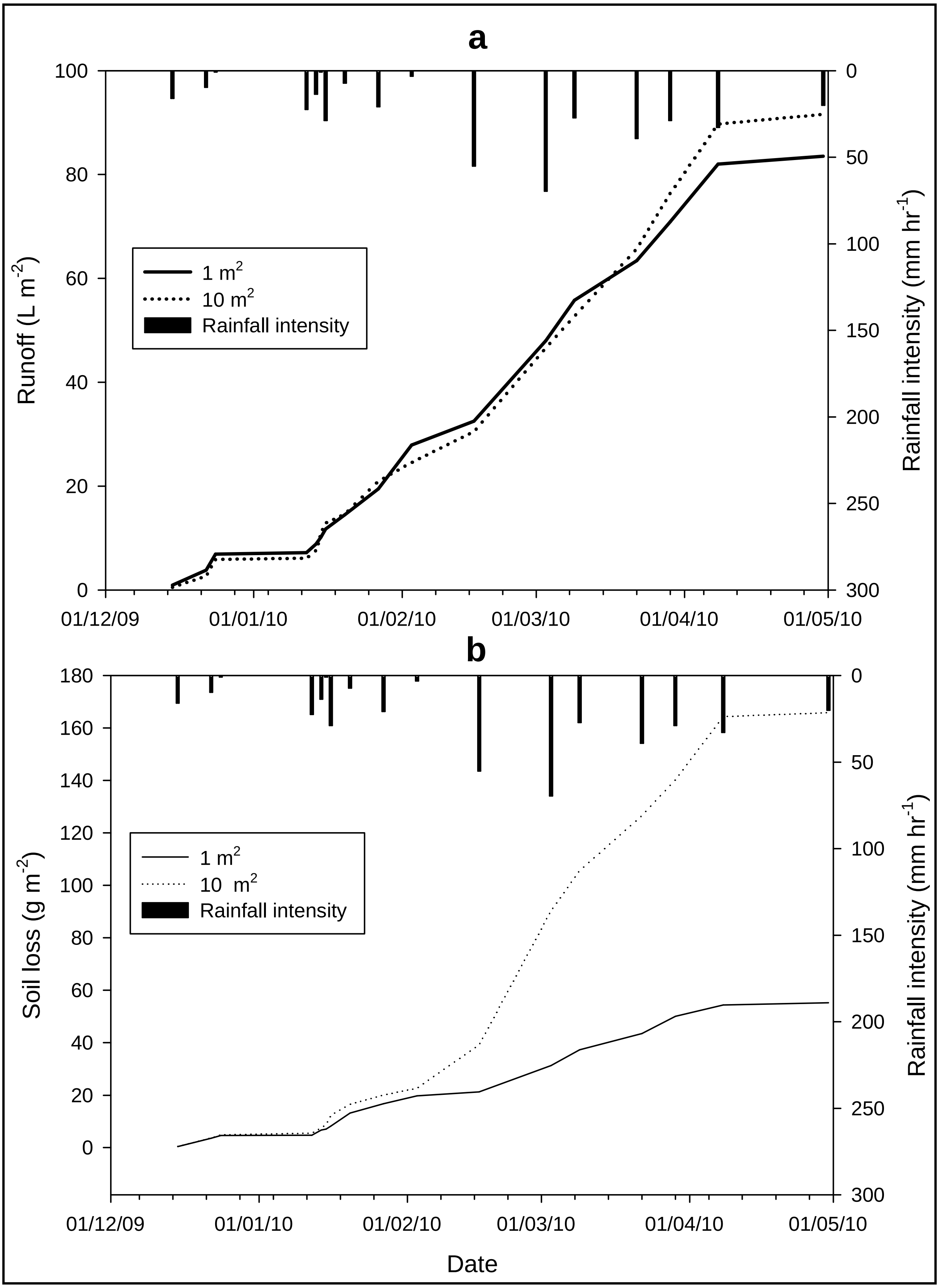

Figure 4.1 Average cumulative runoff (a) and cumulative soil loss (b) at the 1 m^2 and 10 m^2 plot scales

4.1.5 Total soil loss variations across the hillslope

The ratio of the soil loss at the 1 m^2 and 10 m^2 plot scales (1:10) is a measure of the relative contribution of splash and RIF erosion to soil loss at the various hillslope positions. A ratio value less than 1 indicated that RIF erosion was the larger contributor of the two erosion types. A measure of the cumulative ratio of the soil loss rates from the 17 events is shown in Figure 4.2. A lower total cumulative soil loss value is indicative of the fact that RIF erosion is more operative at a given location in comparison to the other hillslope positions. It can be seen that M had the lowest cumulative soil loss ratio, followed by the F and SST positions.

4.1.6 The impact of selected environmental factors on the soil loss ratios

An evaluation of the impact of the selected rainfall characteristics and soil factors listed in Table 4.4 on the 1:10 m^2 soil loss ratios for each of the 17 erosive rainfall events was performed using an ANOVA analysis. ARD, AR, clay and ρ_b were the only significant variables ($p<0.05$). The first two principal components (PC) generated from all environmental factors accounted for 60% of the data variability (Figure 4.3). The first PC explained 32% of the total data variance and was negatively correlated to all rainfall characteristics. The second PC which accounted for 28% of data variance correlated with *in-situ* soil variables i.e. positively with clay percentage and high vegetation coverage and negatively to crusting, bulk density and slope steepness. Runoff and soil losses correlated to both PCs, although there was a tendency for R to be most strongly correlated with PC1. The 1:10m^2 scale ratio for SL had a correlation coefficient of 0.05 with PC1 and 0.32 with PC2 which implies that soil factors had a greater impact on the relative contribution of individual sheet erosion mechanisms (splash and RIF) to soil loss than rainfall characteristics.

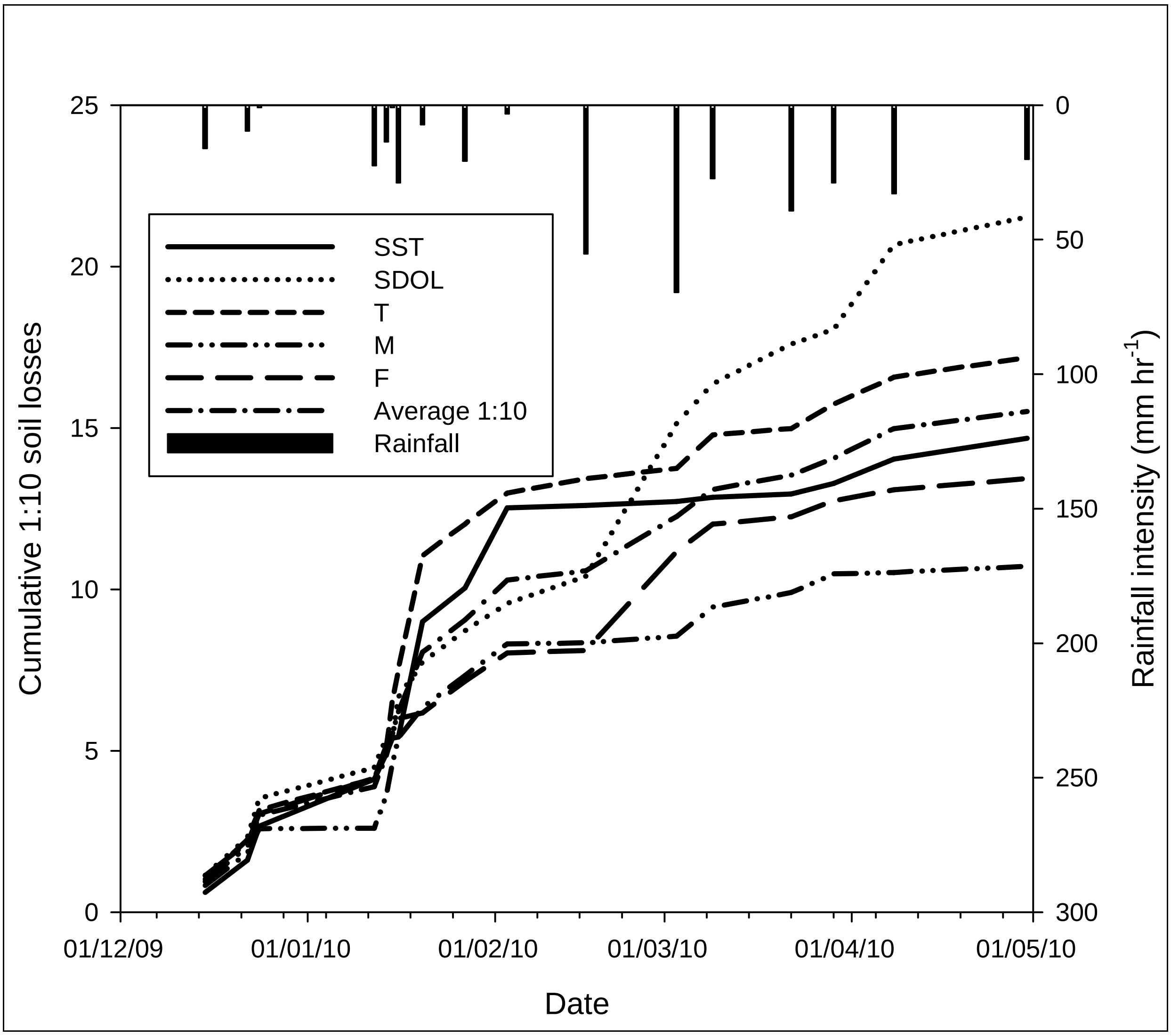

Figure 4.2 Cumulative 1:10 soil loss ratios at each hillslope position computed from the 17 erosive rainfall events for the 2009-2010 rainfall season and the maximum rainfall intensity of the events

Table 4.4 ANOVA between the 1:10m^2 soil loss ratio and some selected environmental factors: (I: average rainfall intensity; Imax: maximum rainfall intensity; I_{30}: average thirty minute rainfall intensity; I_{30}max: maximum thirty minute rainfall intensity; RA: event rainfall amount; RDur: rainfall event duration; ARD: cumulative antecedent rain days; AR: antecedent rainfall since onset of rainy season; AR_3: antecedent three day rainfall; AR_{10}: antecedent ten day rainfall; Crust: percentage of soil surface with crusts; Cov: percentage of soil surface coverage by vegetation; Clay: soil clay content; ρ_b: soil bulk density; S: mean slope gradient.

Variable	r	Degree freedom	F	p
I	-0.44	4	3.11	0.1
Imax	-0.12	4	4.11	0.06
I_{30}	-0.40	4	3.18	0.09
I_{30}max	0.03	4	3.68	0.07
RA	0.13	4	0.98	0.34
RDur	0.25	4	0.17	0.67
ARD	-0.31	4	5.46	0.03*
AR	-0.29	4	5.45	0.03*
AR_3	0.10	4	0.9	0.34
AR_{10}	0.13	4	1.4	0.23
Crust	-0.07	4	0.4	0.52
Cov	0.07	4	0.4	0.52
Clay	0.26	4	6.14	0.01*
ρ_b	0.22	4	4.6	0.03*
S	-0.2	4	3.38	0.07

*significant at p<0.05 level

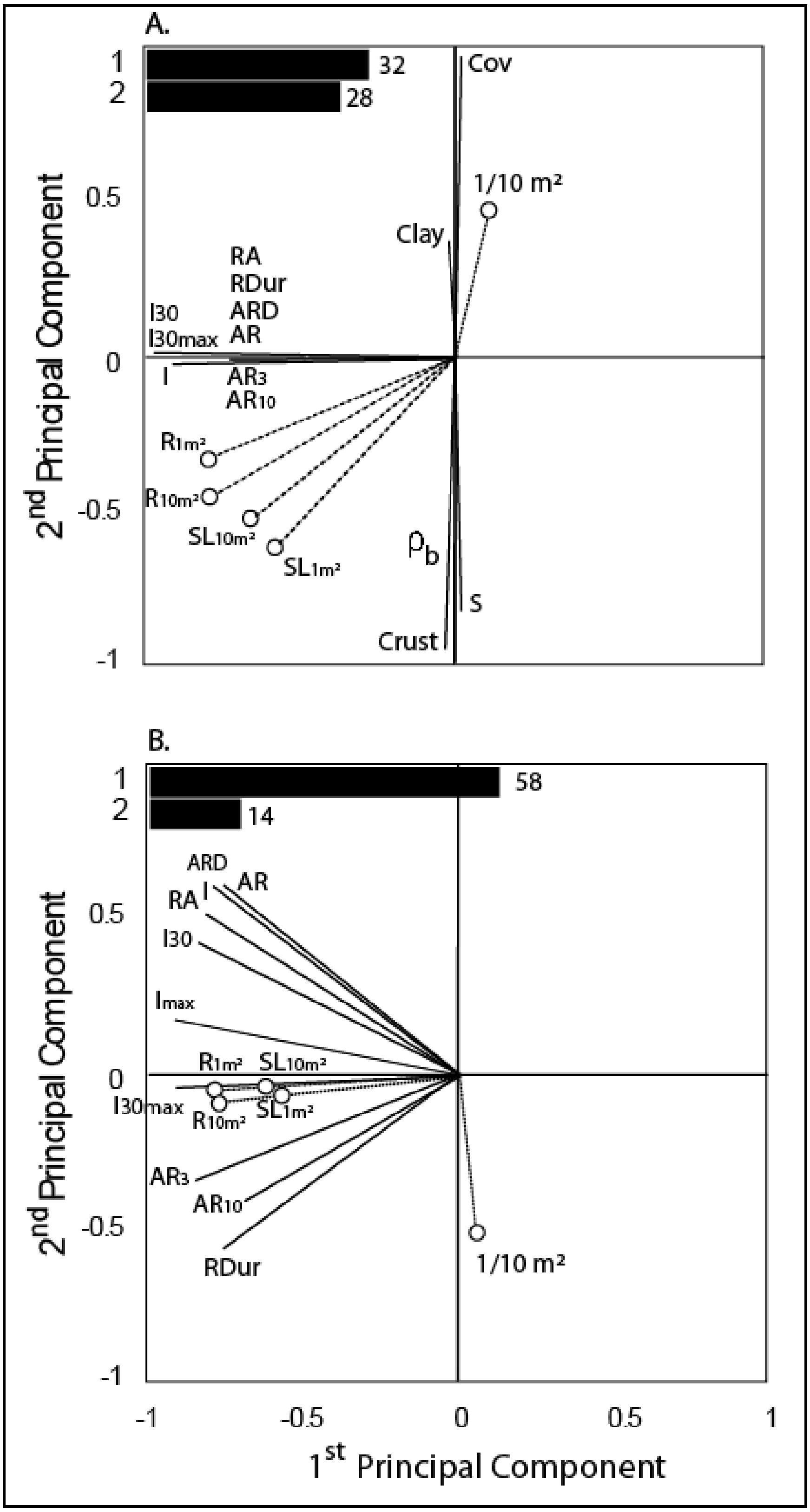

Figure 4.3 Principal components analysis (PCA) of 'factor scores' for (A) soil and rainfall factors; and (B) rainfall factors only. Position of the centroids for runoff (R) and soil losses (SL) at the two plot scales, and of 1:10 m^2 scale ratio for soil loss

4.2 Discussion

4.2.1 Dominant erosion at the 1 and 10 m^2 plot scales

The cumulative soil losses over the study period were about three fold greater from the 10 m^2 plots than from the 1 m^2 plots. This indicates that splash erosion at the site is considerably less erosive than RIF erosion as the former is a very localized process of erosion compared to the latter (Kinnell, 2004). Greater runoff erosivity on longer plots is likely due to an increase in flow velocity enabling RIF erosion to become operative and/or dominant (Stomph *et al.*, 2002; Chaplot and Le Bissonnais, 2003). Although the results indicate that splash erosion was considerably less erosive than RIF erosion, soil loss values may have been underestimated due sediment being splashed out of the plots during rainfall events.

4.2.2 Factors controlling contribution of splash and RIF erosion

The contribution of RIF to overall sheet erosion increased with increasing rainfall intensity (Bryan ,2000; Kinnell, 2004; Parsons and Stone, 2006) as greater rainfall intensity resulted in faster generation of overland flow. These results, however, differ from these of Chaplot and Le Bissonnais (2003), who obtained small differences between 1 and 5 m long plots with high rainfall intensity on a gentle slope with loamy soil. This was explained by greater ponded runoff absorbing the raindrop kinetic energy and lowering detachment and transport processes. Several other environmental factors controlled the scale ratio of sheet erosion. Irrespective of the characteristics of the rainfall events, greater RIF contribution to sheet erosion occurred on steep slopes and on crusted and compacted soils. Crusted or compacted soils are expected to generate greater amounts of overland flow while steep slopes allow greater flow velocity (Agassi and Ben-Hur, 1991; Torri and Poesen, 1992; Fox and Bryan, 1999). Conversely, RIF erosion was shown to be more efficient under high grass coverage. This is probably due to faster soil infiltration reducing the amount of overland flow (Puigdefabregas *et al.*, 1999; Cammeraat, 2002; Dlamini *et al.*, 2010) and to the physical barrier that grass tufts offer to overland flow acceleration (Molina *et al.*, 2007). Vegetation also provides a barrier to raindrops, thus reducing splash erosion (Chaplot *et al.*, 2003).

Of the selected soil characteristics, clay content was statistically significant ($P<0.05$) in having an impact on the 1:10 m^2 soil loss ratio. Soils with high clay contents have high surface area and soil organic carbon contents and are thus generally strongly aggregated (Bhattacharyya *et al*., 2009). A positive relationship between soil clay content and low erosion differences between the long and short plots might be due to the relatively high infiltration rates of aggregated clay soils (Teixeira and Misra, 1997), limited overland flow connectivity and increasing soil roughness (Darboux *et al*., 2005) which in turn decrease the flow velocity and RIF efficiency.

Interestingly, irrespective of rainfall event characteristics or soil surface conditions, RIF contribution to sheet erosion sharply increased in the second half of the rainy season, i.e., after what appears to be a threshold for cumulative rainfall. The sharp increase in soil losses from longer plots relative to the shorter ones occurred from the 10th rainfall event which corresponded to a cumulative antecedent rainfall of 190 mm if rain out of the annual amount of 675 mm. This result might be explained by the establishment of a shallow water table causing saturation of the soil surface. Once the water table reaches the soil surface, infiltration decreases to zero, initialising overland flow and thus RIF erosion. Overall, the scale issue for sheet erosion appears to be controlled by soil surface conditions (in relation to Hortonian flow) in the first half of the rainfall season, while in the second half, RIF seems to predominate because of the contribution of soil saturation causing infiltration excess and overland flow. Finally, rainfall intensity surprisingly had no significant impact on sheet erosion efficiency.

5. CATCHMENT SCALE EROSION DYNAMICS

5.1 Results

5.1.1 Evaluation of rainfall characteristics

The 2010-2011 rainfall season was a considerably wet season. The total rainfall of 1055.4 mm at Potshini, was considerably higher than the 2009-2010 amount of 675mm and the MAP of 684 mm. The characteristics of the considered rainfall events which occurred during the 2010-2011 rainfall season are summarised in Table 5.1. General statistics of the rainfall characteristics such as mean and maximum rainfall amount (RA) and rainfall intensity (I) and maximum half hour intensity (I_{30}) values indicate that rainfall characteristics were highly variable and of a high magnitude during the rainfall season. The highest and most erosive event had an I_{30} of 52.8 mm h^{-1} with a standard error of 4.2 mm h^{-1}. This is less that the 2 year return period 90% occurrence value of 61 mm h^{-1} and surprisingly less than the 2009-2010 maximum of 64.8±3.9 mm h^{-1}. The mean and maximum rainfall event duration changed from 2.1±0.4 and 6.4±0.4 hours to 1.0±1.3 and 16.8±1.3 hours for the 2009-2010 and 2010-2011 rainy seasons respectively. The median, first and third quartile RA and I_{30} values indicate that the majority of the rainfall events which occurred during the rainfall season relatively high depths and intensities.

5.1.2 Evaluation of soil erosion at the different spatial scales

The general statistics of series of soil erosion event characteristics occurring between 18th October 2010 and 15th March 2011 are summarised in Table 5.2. Maximum R decreased from the 1 m^2 and 10 m^2 plots, and 23 ha catchment (89.0±5.3, 49.5±4.1 and 31.4±2.9 L m^{-2}) and increased sharply at the 100 ha catchment (169.3±6.6 L m^{-2}). The maximum SL values at all scales were considerably high, apart from those observed at the 100 ha scale. As expected, SL was highest at the 10 m^2 plot scale (558.5±12.9 g m^{-2}). Maximum SL decreased at the 1 m^2

plot level (127.8±6.0 g m^{-2}) and increased slightly at the 23 ha level (234.1±9.0 g m^{-2}). The 100 ha catchment yielded a maximum SL of 8.9±1.6 g m^{-2}. Maximum values of SC at the 23 and 100 ha catchment scales were also comparatively low. The median values of R indicate that the 1 m^2 and 10 m^2 plots experienced similar overland flow behaviour, however the 100 ha catchment yielded the largest runoff amount.

Table 5.1 General statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for selected rainfall characteristics of the 17 rainfall events of the 2010-2011 rainy season. (I: average rainfall event intensity; Imax: maximum rainfall event intensity; I_{30}: average thirty minute rainfall event intensity; I_{30}max: maximum thirty minute rainfall event intensity; RA: rainfall amount; RDur: rainfall hours; ARD: cumulative antecedent rain days; AR: antecedent rainfall from onset of rainy season to end of erosion event; AR_3: three day antecedent rainfall; AR_{10}: ten day antecedent rainfall)

	I	**Imax**	**I_{30}**	**I_{30}max**	**RA**	**Rdur**	**ARD**	**AR**	**AR_3**	**AR_{10}**
Mean	4.1	28.1	4.1	22.3	55.4	1.0	107.0	685.8	29.4	89.0
SD	2.6	21.0	2.3	17.3	52.2	1.6	51.8	353.4	28.2	97.6
SE	1.6	4.6	1.5	4.2	7.2	1.3	7.2	18.8	5.3	9.9
CV	63.3	74.5	56.2	77.7	94.2	161.6	48.4	51.5	96.1	109.6
Variance	6.8	439.1	5.4	300.0	2723.4	2.6	2678.7	124912.0	797.1	9521.7
Min	1.3	4.0	1.0	3.6	0.2	0.3	10.0	31.4	0.2	6.8
Max	12.8	64.0	10.6	52.8	177.6	16.8	187.0	1055.4	103.4	436.8
Mode	n/a	11.2	n/a	10.8	n/a	0.3	n/a	n/a	n/a	n/a
Quartile 1	2.7	11.6	2.6	10.0	25.0	0.3	76.0	425.3	9.7	34.0
Median	3.4	16.8	3.5	12.8	31.6	0.3	120.0	859.0	23.0	53.0
Quartile 3	4.6	53.2	5.0	42.0	75.4	1.0	145.0	954.7	42.7	109.5
Skewness	2.2	0.7	1.3	0.8	1.1	4.7	-0.5	-0.9	1.4	2.8
Kurtosis	6.5	-1.4	1.7	-1.2	0.3	32.6	-0.6	-0.8	1.5	9.2

Table 5.2 General statistics of the soil erosion characteristics (R: runoff; SC: sediment concentration; SL: soil losses; SLw: soil flux per meter width) as function of plot scale for the 2010-2011 rainfall season

	R				SC				SL				SLw	
	L m^{-2}				**g L^{-1}**				**g m^{-2}**				**g m^{-1}**	
	1m^2	**10m^2**	**23ha**	**100ha**	**1m^2**	**10m^2**	**23ha**	**100ha**	**1m^2**	**10m^2**	**23ha**	**100ha**	**1m^2**	**10m^2**
Mean	15.5	23.4	5.1	31.2	1.3	2.9	7.7	2.0	23.9	82.3	47.5	2.0	23.9	41.2
SD	17.0	28.2	8.4	43.2	1.0	3.4	9.0	2.7	35.7	167.6	80.4	2.7	35.7	83.8
SE	4.1	5.3	2.9	6.6	1.0	1.8	3.0	1.6	6.0	12.9	9.0	1.6	6.0	6.5
CV	109.4	120.9	165.7	138.7	78.3	117.2	117.0	133.3	149.4	203.5	169.4	133.3	149.4	101.8
Variance	289.5	798.0	70.6	1869.6	1.0	11.4	80.6	7.1	1275.1	28083.3	6467.9	7.1	1275.1	14041.7
Min	0.8	0.7	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0
Max	49.5	89.0	31.4	169.3	4.0	10.6	27.4	8.9	127.8	558.5	234.1	8.9	127.8	279.3
Mode	n/a	n/a	n/a	0.0	n/a	n/a	n/a	0.0	n/a	n/a	n/a	0.0	n/a	n/a
Quartile 1	3.3	3.2	0.5	1.5	0.6	0.8	1.7	0.5	2.4	4.6	0.3	0.5	2.4	2.3
Median	7.9	7.4	1.0	20.4	0.9	1.0	3.3	1.2	5.3	7.6	4.8	1.2	5.3	3.8
Quartile 3	28.5	44.2	8.4	43.2	1.8	4.0	11.1	2.6	35.7	82.3	80.4	2.6	35.7	41.2
Skewness	1.0	1.3	2.4	2.3	1.2	1.4	1.3	2.1	2.0	2.5	1.6	2.1	2.0	1.2
Kurtosis	-0.4	0.5	5.8	6.2	1.4	0.8	0.7	3.7	3.6	5.1	1.1	3.7	3.6	2.5

An assessment of the temporal evolution of the cumulative R at the different spatial scales indicates that the 1 m^2 and 10 m^2 plots experienced similar overland flow responses during the series of rainfall events (Figure 5.1). R values indicate that the 1 m^2 and10 m^2 plots were considerably responsive due to the timely generation of runoff upon the occurrence of rainfall events. The cumulative R values at the 1 m^2 and 10 m^2 plot scales were 234.3 L m^{-2} and 270.2 L m^{-2} respectively. The 100 ha catchment became responsive as the rainfall season proceeded. Interestingly, the greatest response occurred in February 2011 after several large rainfall events. The 100 ha yielded a cumulative R of 530.2 L m^{-2}. The 23 ha catchment was comparatively not as responsive as the other scales and yielded a cumulative R of 86.2 L m^{-2}.

A further evaluation of the temporal evolution of SL at the mentioned scales shows that soil losses were greatest at the 10 m^2 plot scale by comparison (Figure 5.1). The cumulative soil loss value at the 10 m^2 plot scale was approximately 1399.8 g m^{-2} in comparison to 406.2 g m^{-2} at the 1 m^2 plot scale. Despite having a considerably low cumulative R by comparison the 23 ha catchment yielded a SL considerably higher (807.1 g m^{-2}) than the 1 m^2 plot and 100 ha scales (406.3and 33.9 g m^{-2} respectively). Results show that cumulative soil losses decreased by approximately 4129 % between the 10 m^2 plots and the 100 ha catchment. Although this result may illustrate increasing complexity of erosion processes within increasing scale it may be an under estimation due to the limitations of the measurements of soil losses at the plot scales.

A measure of the SC trends at the spatial scales with temporal evolution is shown in Figure 5.2. The SC results indicate that sediment concentrations at the three smaller scales (1 m^2, 10 m^2 and 23 ha) corresponded to changes in rainfall characteristics during the rainy season. Sediment concentrations at 1 m^2 and 10 m^2 plot scales were relatively high at the onset of the rainfall season and gradually decreased in January 2011. Interestingly at approximately the same time SC values at the 23 ha level increased rapidly in response to rainfall events of high intensity and particularly high depths (i.e. 26.6 g L^{-1} in response to 139.8 mm of rainfall with a maximum intensity of 64 mm h^{-1}). The 1 m^2 and 10 m^2 plots and 100 ha catchments yielded SC values 1.92, 14.3 and 0.1 g L^{-1} for the same event.

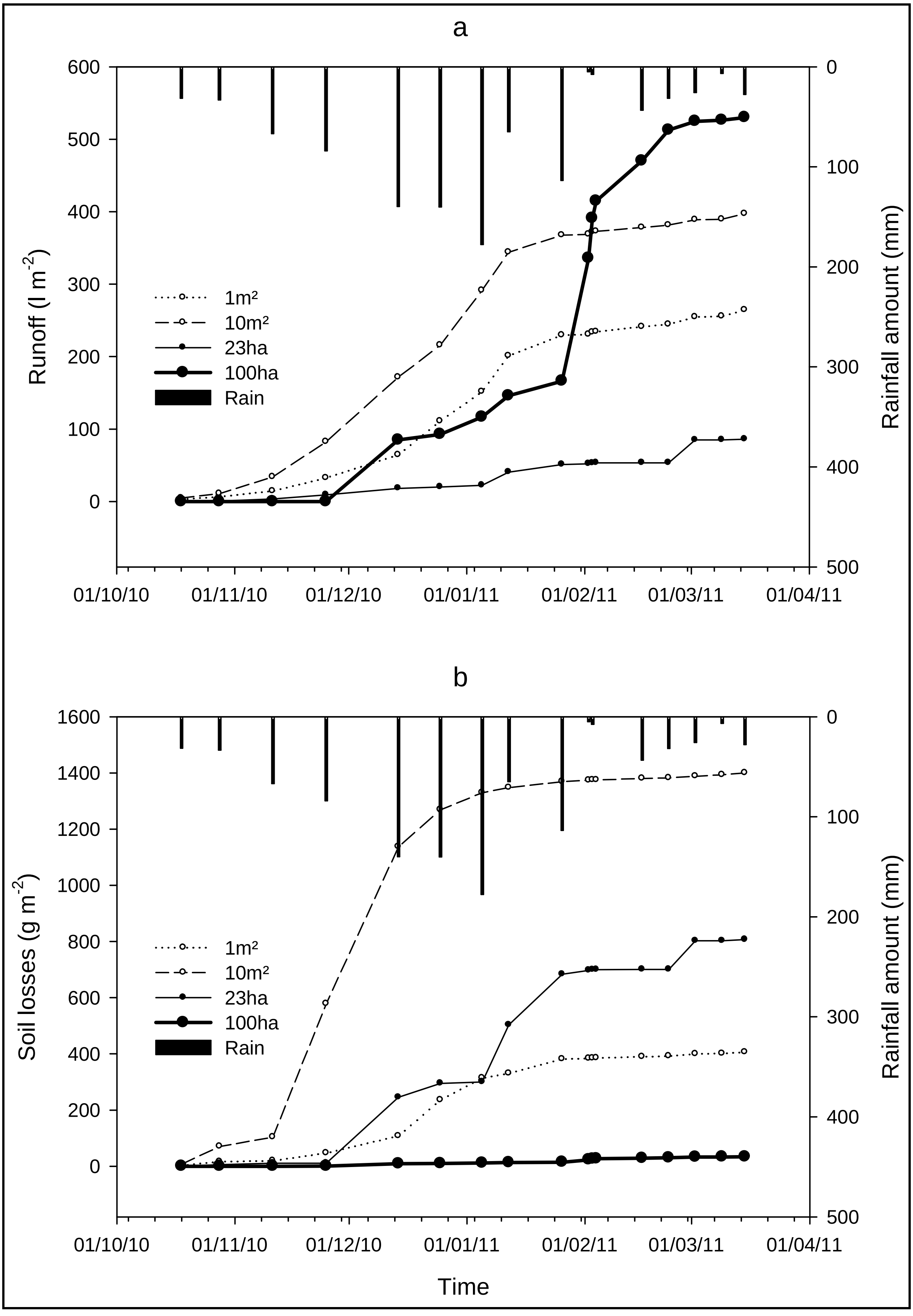

Figure 5.1 Cumulative runoff and soil losses over time and at the different scales

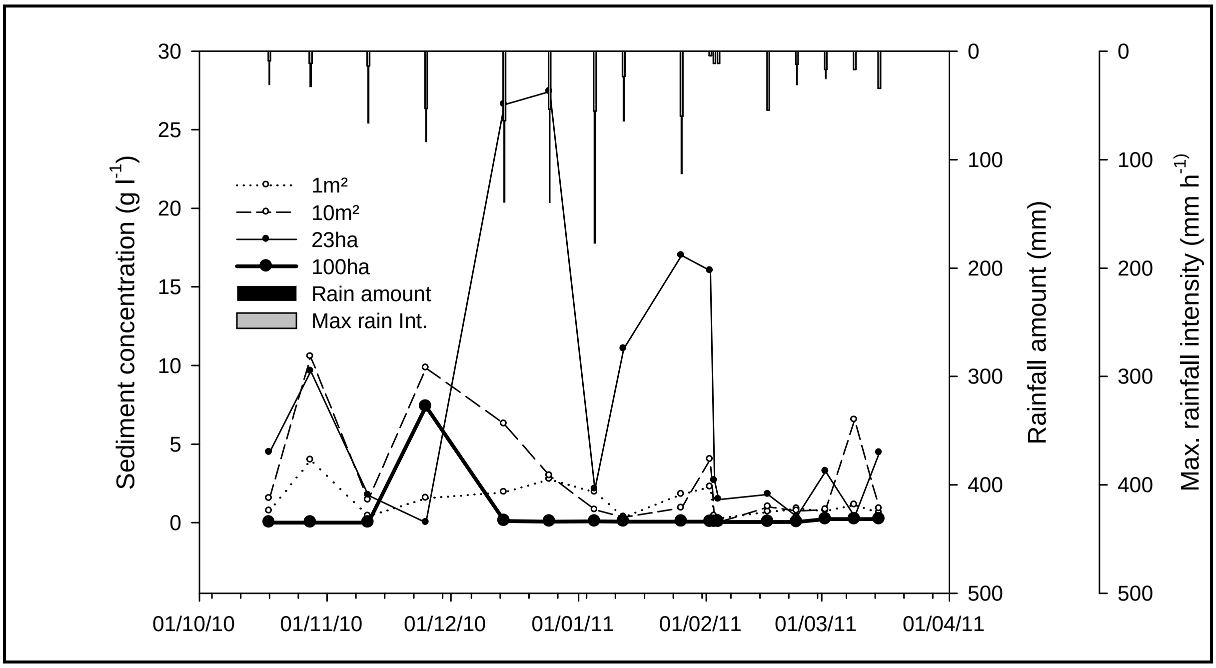

Figure 5.2 Sediment concentration and its variations over time and at the different scales

5.1.3 Factors controlling erosion fluxes

An evaluation of the correlation of selected environmental factors and the soil erosion variable to assess their impact on soil erosion processes and soil losses at the different scales (Table 5.3). Of the selected environmental factors rainfall amount (RA), maximum rainfall event intensity (Imax), maximum half hour rainfall event intensity (I_{30}max), rainfall event duration (RDur), antecedent rainfall three and ten days prior to sample collection (AR_3 and AR_{10}) had the most significant impact on soil erosion variables particularly at the 1 m^2 and 10 m^2 plot scales. The correlation and therefore the influence of the factors tended to decrease with increasing spatial scale at the 23 and 100 ha catchments. Increasing landscape heterogeneity may have caused selected environmental factors to become less significant.

The principal component analysis (PCA) accounting for 53 % of the data variability and which compared soil erosion (dependent) variables at the different spatial scales against selected environmental (supplementary) variables (Figure 5.3) showed that R and SL at the 1 m^2 and 10 m^2 plot scales were significantly correlated to the antecedent rainfall conditions as an indication of antecedent moisture content (AMC) and strongly correlated to rainfall event characteristics such as amount and intensity. Figure 5.3 also indicates that fewer environmental characteristics were significantly correlated to the soil erosion variables at the 23 ha level. Correlation values and proximity of variables on the PCA show that rainfall amount and duration and significant effects on sediment concentrations while AR_{10} had significant effects on soil losses. At the 100 ha level poor correlations existed between all the selected environmental variables as indicated by the length and direction of the lines representing R,SC and SL in relation to the positions of the environmental variables (Figure 5.3). Minor, yet noteworthy, correlations existed between the antecedent rainfall amount three and ten days and maximum I_{30}. Correlations were stronger between these variables were stronger at the 100 ha level compared to the 23 ha level.

Table 5.3 Correlation matrix between soil erosion variables and environmental factors (RA: event rainfall amount; I: average rainfall intensity; Imax: maximum rainfall intensity; I_{30}: average thirty minute rainfall intensity; I_{30}max: maximum thirty minute rainfall intensity; RDur: rainfall event duration; ARD: cumulative antecedent rain days; AR: antecedent rainfall since onset of rainy season 3 or 10 days prior to the event)

	RA	I	Imax	I_{30}	I_{30}max	RDur	AR	ARD	AR_3	AR_{10}
R_1m^2	**0.83***	-0.16	**0.65***	-0.17	**0.68***	**0.81***	-0.1	-0.14	**0.54***	**0.61***
SC_1m^2	0.38	-0.20	0.25	-0.27	0.28	0.24	-0.39	-0.41	0.11	0.22
SL_1m^2	**0.87***	-0.09	**0.71***	-0.10	**0.74***	**0.80***	-0.19	-0.19	**0.51***	**0.50***
R_10m^2	**0.88***	-0.12	**0.70***	-0.13	**0.73***	**0.62***	-0.32	-0.31	**0.67***	0.42
SC_10m^2	0.06	0.10	0.11	0.00	0.17	0.01	**-0.52***	-0.46	-0.12	-0.17
SL_10m^2	**0.51***	-0.09	**0.58***	-0.01	**0.60***	0.38	-0.45	-0.37	0.32	0.09
R_23ha	0.11	-0.16	0.08	-0.17	0.09	0.11	0.17	0.16	0.04	0.28
SC_23ha	**0.50***	-0.35	0.42	-0.37	0.35	**0.58***	-0.17	-0.19	0.12	0.47
SL_23ha	0.43	-0.22	0.42	-0.24	0.33	0.36	0.03	0.00	0.28	**0.62***
R_100ha	-0.11	0.03	0.28	0.01	0.42	0.19	-0.29	-0.22	0.13	-0.03
SC_100ha	0.12	0.03	0.28	0.01	0.42	0.19	-0.29	-0.22	0.13	-0.03
SL_100ha	0.09	-0.2	0.12	-0.18	0.05	-0.12	0.17	0.16	0.02	0.10

* Bold correlations are significant at p<0.05

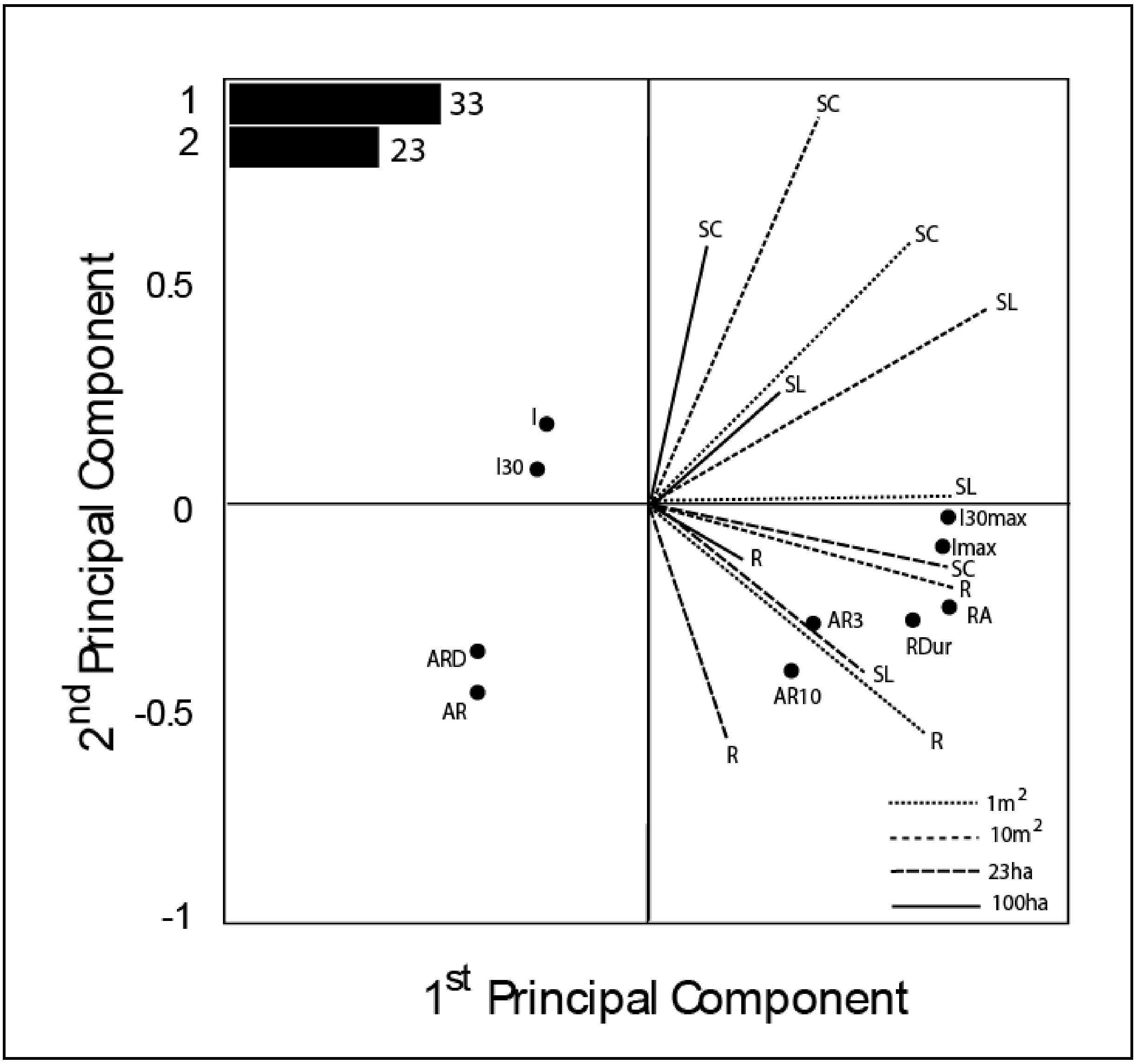

Figure 5.3 Principal Component Analysis generated using soil erosion variables at the different scales as dependent variables versus environmental characteristics as supplementary variables

5.1.4 Quality of sediments at the different scales

Selected sediment and soil physical characteristics were analysed as a preliminary exercise to understand soil erosion dynamics at the given scales (Table 5.4). Additional sources to the mentioned scales are introduced and are listed in Table 5.4. The considered surface soil horizons were located on the hillslope where the 1 m^2 and 10 m^2 plots were located and thus was a source of material for hillslope eroded sediment. It was assumed that 23 ha riverbed sediments and 23 ha sediments would have a mixture of origins from surface and deep soil horizons. Sediments showed an initial enrichment of fine soil particles (clay and fine silt) at the 10 m^2 plot scale. A decrease in the percentage of fine particles in correspondence to an increase of sand percentage was observed with increasing spatial scale. A similar trend was followed when comparing the average *in-situ* soil particle size distribution to that of the eroded sediments at the different spatial scales.

Table 5.4 Characteristics (Clay: clay content ; FiSi: fine silt content; CoSi: coarse silt content; CoSa: coarse sand content; MeSa: medium sand content; FiSa: fine sand content; VFiSa: very fine sand content; Redness: Munsell redness; Value: Munsell value; Chroma: Munsell chroma; C: total carbon content; N: total nitrogen content) of sediments and soils collected within the study area

	Clay	**FiSi**	**CoSi**	**CoSa**	**MeSa**	**FiSa**	**VFiSa**	**Redness**	**Value**	**Chroma**	**C**	**N**
1m^2	40.3	15.8	8.6	6.2	15.7	7.6	5.9	3.2	4	4.4	5.8	0.6
10m^2	36.1	14.8	5.5	11.7	19.5	9.7	2.6	3.2	4	4.4	3.9	0.4
23 ha riverbed	31.8	11.4	5.7	1.8	6	35.5	7.9	3	4.4	6	1.9	0.2
23ha	29.7	16.7	8.1	3.2	10.1	25.7	6.4	3	4	6	4.3	0.2
100ha	28	10	6.8	0.5	22.9	29.7	2.4	2	6	6	0.1	0.1
1000 ha	49.3	27.3	4.4	1.2	3.7	7.5	6.8	2	4.5	2.8	1.2	0.2
Average	***32.8***	***15.0***	***5.5***	***4.1***	***17.2***	***20.1***	***5.3***	***2.7***	***4.5***	***4.9***	***3.2***	***0.3***
Surf soil hor.	35.9	17.6	6.2	0.5	4.2	25.3	10.3	3.8	3.2	3.4	2.2	0.2
Deep soil hor.	39.7	15.5	9.1	0.8	4.2	21.5	9.2	3.4	4.3	4.6	0.6	0
Average	***37.4***	***16.5***	***7.65***	***0.65***	***4.2***	***23.4***	***9.75***	***3.6***	***3.75***	***4***	***1.4***	***0.1***

Regarding the Munsell colour characteristics, a slight decrease in redness of soil material was observed from the 1 m^2 and 10 m^2 plot scales to the catchment scales. Subtle to no differences were observed between the value of the first three considered scales (4 for the 1 m^2 and 10 m^2 plot scales and 23ha to 4.4 for the 23ha catchment riverbed), however, Value of the 100 ha sediments increased to 6, followed by a decrease decrease in value to 4.5 at the 1000 ha dam. A distinct difference was observed between the Chroma at the 1 m^2 and 10 m^2 plot scales (4.4) compared to the 23 ha riverbed, 23 ha catchment and 100 ha catchment (6). Soil material chroma decreased to 2.8 at the 1000 ha scale.

Eroded sediments at the 1 m^2 and 10 m^2 plot and 23 ha scales were generally enriched in total carbon % (C) and total nitrogen % (N) compared to the *in-situ* surface soil material. Riverbed sediment was, however, depleted in C and N, compared to the sediments at the other scales and enriched compared to the deep soil horizons. At the 100 ha catchment, sediments were depleted in C and N, while the 1000 ha dam sediments were more enriched.

5.1.5 Physical and chemical characteristics of eroded sediments

Results of soil particle distribution of soil and sediments were superimposed onto a United States Department of Agriculture (USDA) texture triangle (Figure 5.4A). Sediments eroded at the 1 m^2 were enriched in clay in comparison to the surface soil material (0-0.05 m) while 10m^2 sediments were slightly depleted in clay. Sediments located at the 23 ha catchment riverbed and the 23 and 100 ha catchment outlets were also depleted in clays compared to deep soil horizons (0.4-0.5m). Sediments located at the 1000 ha level were enriched in clay compared to the other scales. According to the USDA texture classification, sediments eroded at the 1 m^2 level were classified as clay/clay loam; sediments eroded at the 10 m^2 and 23 ha levels were classified as clay loam however their high sand and contents placed them close to sandy loam textured sediments; sediments eroded at the 100 ha level were classified as sandy clay loam and 1000 ha sediments were classified as clay textured.

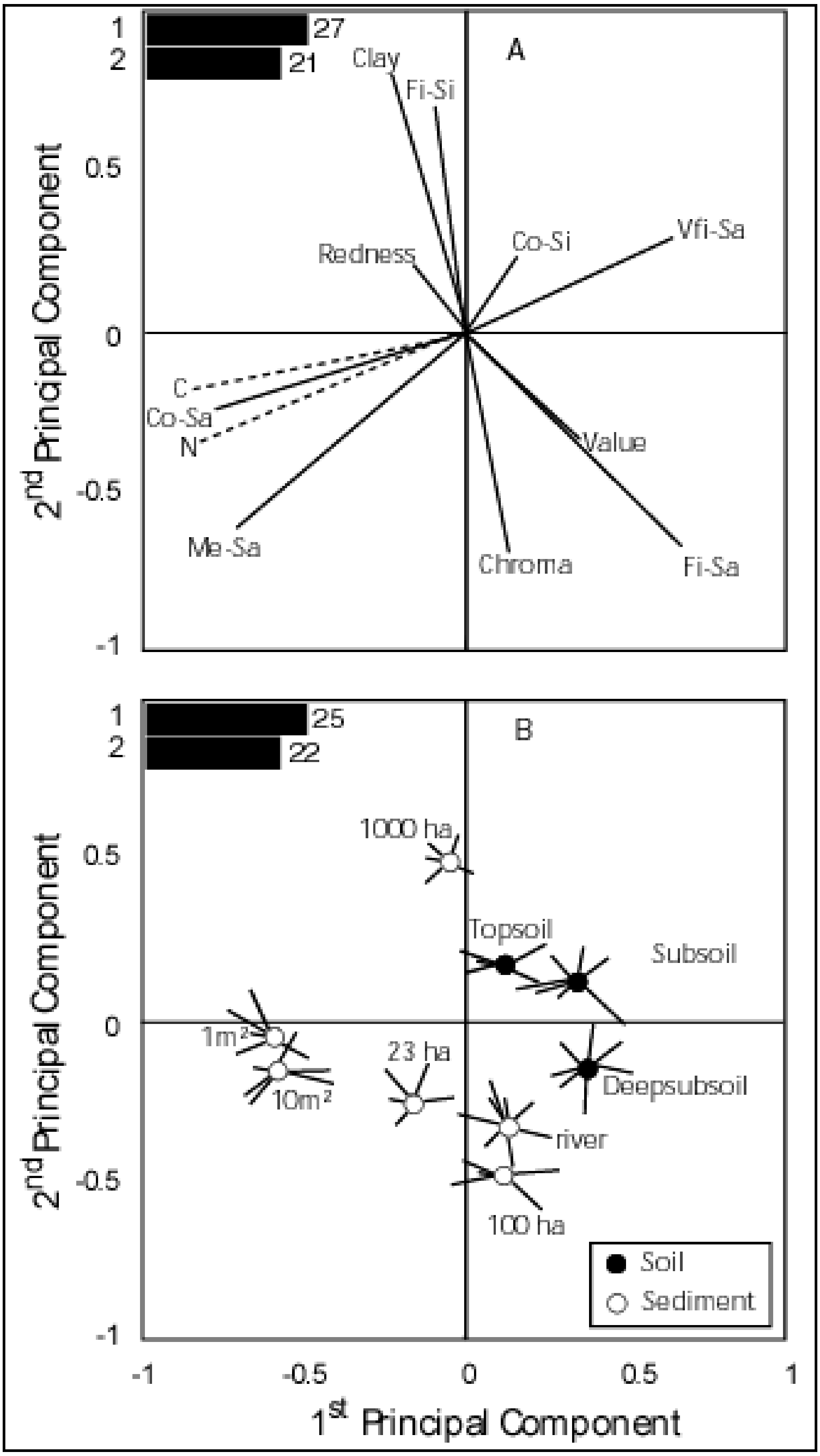

Figure 5.4 Average particle size distribution for soils and sediments (A) and for 1 and 10 m^2 plot sediments versus surface soil horizons at three landscape positions (F: footslope; T: terrace; SST: shoulder sandstone) (B)

Two PCs were generated (Figure 5.5A and B), the first was to compare physical and chemical properties of sediments and soils from the different locations within the 23 ha research catchment while the second compared the grouped properties of the soils and sediments. The correlation between the soil physical and chemical properties indicated that strong correlations existed between clay and fine silt (Fi-Si); total carbon (C) and total nitrogen (N), course sand (Co-Sa) and medium sand (Me-Sa); chroma, value and fine sand (Fi-Sa) (Figure 5.5A). Figure 5.5B shows that the 1 and 10 m^2 plot sediments had similar properties and were therefore located within close proximity to each other. Erosion processes created dissimilarities between *in-situ* surface soil and *ex-situ* 1 and 10 m^2 plot sediments in response to selectivity of erosion processes. Stronger similarities were found between river sediments and deep soil horizons as a result of the low selectivity of erosion processes yielding comparable textural properties, increased yellowness and lightness and low total C and N percentages in soils and sediments. A measure of the Euclidean distance of the 23 ha sediment to the river and 1 and 10 m^2 plot sediments reveals that lateral erosion processes at the hillslope level contributed to 37% of the total catchment soil loss whereas a 63% contribution was made by linear erosion processes within the stream network.

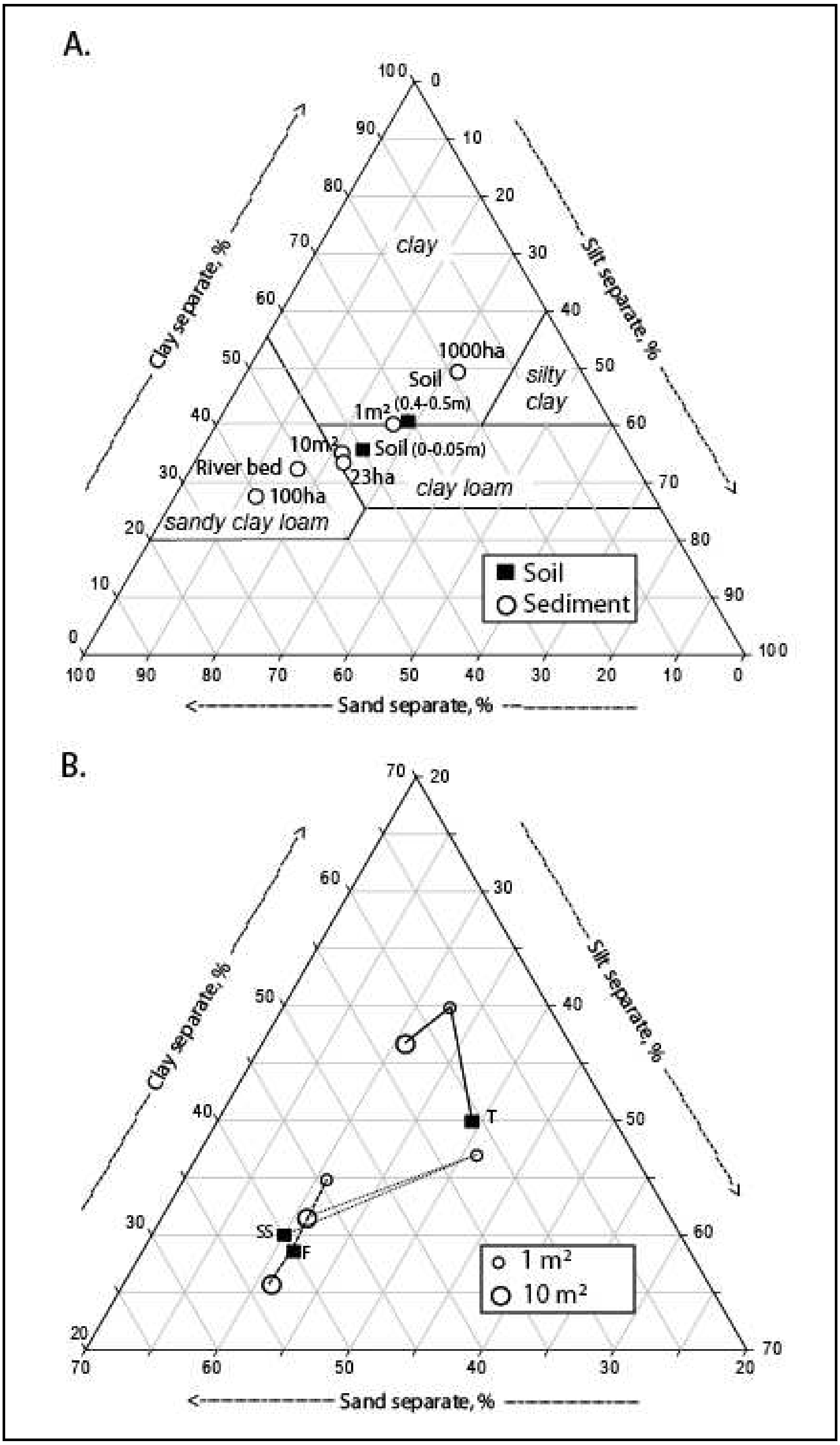

Figure 5.5 Principal Component Analysis generated using environmental characteristics as dependent variables and position of soils and sediments with average value and replicate as supplementary variables

5.2 Discussion

5.2.1 Evaluation of soil erosion fluxes at the different spatial scales

Soil loss results at the different scales indicate that soil erosion processes vary considerably within the landscape. The differences in soil losses at the 1 m^2 and 10 m^2 plot levels are explained by the predominant scale-dependent erosion mechanisms in operation. Previous studies have indicated that soil erosion processes are dependent upon spatial scale and that soil erosion is transport limited at short slope lengths (> 1 m). At local scales the basic erosion mechanisms of splash erosion are dominant as surface runoff which is essential for sheet erosion has little opportunity to gain gravitational acceleration to entrain and transport soil material a considerable distance (Le Bissonnais *et al*., 1998; Bryan 2000; Chaplot and Le Bissonnais, 2000; Kinnell, 2004; Ghahramani *et al*., 2011; Mayor *et al*., 2011). Sheet erosion was more operative at the 10 m^2 plot level. On account of greater slope lengths facilitating the acquisition of greater runoff velocity allowing for the transport of more sediment per m^2 at the 10 m^2 level than at the 1 m^2 level (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000; Ghahramani *et al*., 2011).

The significant decrease in soil losses between the 10 m^2 plot and 23 ha catchment level is due to numerous detachment, transport and deposition cycles causing erosion discontinuity from the hillslope to the catchment outlet. Investigations have shown that the opportunity for runoff infiltration increases with increasing spatial scale thus aiding sedimentation and that catchment scale soil loss measurements are often an underestimation of the total soil erosion processes occurring in a given catchment (Cammeraat, 2004; Mingguo *et al*., 2007; Mayor *et al*., 2011). Further decreases in soil losses at the 100 ha catchment outlet are attributed to greater increases in landscape heterogeneity, threshold requirements related to rainfall characteristics and catchment morphology such as greater catchment length and reduced slope gradient and (Cammeraat, 2004). Cumulative runoff increased sharply in late January 2011 to values well above the other considered scales. This increase was attributed to groundwater exfiltration supplementing 100 ha stream flows as well as an increase in catchment wetness resulting in greater runoff continuity during rainfall events. The increase in runoff at the 100 ha level was not accompanied by an increase in soil losses possibly due to the presence of sedimentation areas within the 100 ha catchment. The consistent decrease in soil losses with increasing spatial scale is supported by the notion of increased landscape heterogeneity and complexity of erosion processes both contributing to more sediment retention with increased spatial scale (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000; Cammeraat, 2004; Ghahramani *et al*., 2011; Mayor *et al*., 2011).

Sediment concentration patterns at the different scales indicate that more sediment per unit runoff was eroded in the first half of the rainy season. The accumulation of loose material at the 1 m^2 and 10 m^2 plot levels by factors such as biological activity may explain the initial high sediment concentrations in 2010 in comparison to 2011. The sharp increase in sediment concentration during December 2010 may be explained by large amount of runoff in the stream channel entraining and transporting sediment deposited close to the 23 ha outlet. In addition the deposition of soil material into the fluvial system from the scouring of stream banks also provided loose soil material for runoff transport.

5.2.2 Factors controlling soil erosion fluxes

The correlation matrix and PCA indicate that antecedent rainfall conditions as an indication of increasing antecedent soil moisture (AR_3 and AR_{10}) and rainfall depth (RA), duration (RDur) and intensity (Imax, and I_{30}max) had significant positive correlations ($P<0.05$) with runoff rates and soil losses. The positive correlations at the 1 m^2 and 10 m^2 plots are explained as follows: Increased AMC (AR_3 and AR_{10}) reduces soil sorptivity and soil hydraulic conductivity of the soil profile allowing for increased potential for R generation during rainfall events (Bryan, 2000; Cammeraat, 2004), Imax and I_{30}max supply raindrops with high kinetic energy, which are able to detach soil material providing loose material for transport by adequate amounts of R with sufficient surface flow velocity (Vandaele and Poesen, 1995; Bryan, 2000; Cao *et al*., 2009). Moreover, the rapid supply of rainwater for overland flow ensures rapid R generation and connectivity with high erosive energy (Parsons and Stone, 2006); RDur and RA further facilitated the occurrence of R connectivity which provided the opportunity for greater sediment transport distances during rainfall events thus increasing SL from larger spatial areas (Stomph *et al*., 2002). Surprisingly Imax and I30max were marginally correlated with sediment concentrations at the 1 and 10 m^2 levels. This may have been a result of general moderate to high basal cover at the 1 m^2 and 10 m^2 plot locations (Mayor *et al*., 2011).

Correlations between the environmental and soil erosion variables decreased with increasing spatial scale (23 ha and 100 ha). The possible reason for this is a shift in scale dependency of erosion inducing factors (Cammeraat, 2004; Mingguo *et al*., 2007). Positive correlations between SC and RA and RDur are explained by high magnitude long duration rainfall events increasing runoff transport efficiency of sediment. No significant correlations were found between the environmental and soil erosion variables at the 100 ha level. Previous studies indicate that the likely cause is related to increased landscape heterogeneity contributing to an increased mosaic of factors governing soil erosion trends and decreased connectivity and continuity of erosion processes (Cammeraat, 2002; Cammeraat, 2004; Mingguo *et al*., 2007).

5.2.3 Sediment characteristics as an indication of soil erosion dynamics

Particle size distribution trends of the eroded sediments at the different indicate is explained particle selectivity of erosion mechanisms decreasing with increasing erosion efficiency. The selectivity of erosion processes between the 1 m^2 and 10 m^2 plot levels is illustrated further in Figure 5.4B where selected individual hillslope positions are shown. Erosion was predominantly transport limited at the 1 m^2 level due to the prevention of the adequate generation of erosive runoff flow velocities (Kinnell, 2004). Predominant splash erosion processes at the 1 m^2 scale were only able to erode fine material during rainfall events resulting in sediments being enriched in clay in comparison to the surface soil horizon (Wang *et al*., 2010). The decreased clay percentage of the 10 m^2 sediments is indicative of reduced selectivity of erosion processes due to increased contribution of rain-impacted flow erosion at the 10 m^2 level (Teixeira and Misra, 1997, Kinnell, 2004). Differences in the particle size distribution between the 10 m^2 level and the surface soil horizon were negligible due to the less selective erosion mechanisms. Mechanisms of lateral and linear erosion (streambank erosion) contribute to catchment soil loss at the 23 and 100 ha levels which explain the continued enrichment of coarser soil material at these scales. Sediments at the outlet of the 1000 ha catchment were enriched in clay in comparison to the other scales due to the deposition of the suspended load.

Nutrient (C and N) enrichment of sediments at the 1 and 10 m^2 levels compared to surface soil horizons is a result of the preferential removal of light organic soil material during erosion events (Table 4) (Lal, 2005; Rumpel *et al.,* 2009; Wang *et al*., 2010). Within the 23 ha river network bed load sediments were depleted in C and N compared to deep soil horizons. This is possibly due to the preferential erosion of exposed subsurface horizons by river bank and gully erosion processes followed by the favoured removal and transport of fine and light soil material by fluvial processes (Lal, 2005; Rumpel *et al.,* 2009; Wang *et al*., 2010). The C and N enrichment of sediments at the 23 ha level compared to surface and deep soil horizons and the 10 m^2 sediments is most likely a result of the deposition of fine material and nutrients transported from the upper areas of the 23 ha river network and the hillslope (Wang *et al*., 2010). Field observations show that the flume where deposition occurs is adjacent to an area of significant deposition of soil material which has resulted in the proliferation of a grassed section of the fluvial system.

5.2.4 Sediment characteristics as sediment source tracers

Previous studies have indicated that the use of particle size distribution alone may have limitations unless the potential sources had distinctly different particle size distributions (Kurashige and Fusejima, 1997). In this study, sediments eroded at the 10m^2 and 23 ha outlet had similar particle size distributions which may be a function of erosion efficiency. The identification of sources within the 23 ha catchment was thus supplemented using colour and total C and N of the 23 ha soils and sediments as additional parameters. Sediments lost from the 23 ha were slightly enriched in total C and N and similar in redness value and chroma to the sediments of the stream channel. Thus, a greater contribution to catchment soil loss was made by processes of linear erosion within the 23 ha stream channel.. This notion was supported by erosion discontinuity from the hillslope to the 23 ha catchment outlet indicated by the total soil loss results at the considered scales (Le Bissonnais *et al*., 1998). Krause *et al*. (2003) who adopted a multi-parameter approach to sediment fingerprinting made similar findings in a 1.2 km^2 catchment in New South Wales where gully erosion had a greater contribution to catchment soil loss than erosion occurring on grazed pastures. Li *et al*. (2003) reported that gully erosion was the main contributor to reservoir sedimentation in the Yangjuangou reservoir catchment in China. Collins *et al*. (2001) found that in cultivated catchments soil losses from gullies and channel banks can be substantially lower than those measured from cultivated fields. With regard to this study, vegetated areas of the hillslope retained a large amount of sediment eroded by sheet erosion processes. Descroix *et al*. (2008) also obtained a greater sheet erosion contribution to catchment soil loss compared to gully erosion in the Western Sierra Madre. It was noted, however, that few gullies were present in their research catchment.

The 37 % contribution of lateral erosion processes to total catchment soil loss from the 23 ha catchment was also facilitated by the small size of the considered catchment. Literature has shown that hillslopes may contribute to significant soil loss from small catchments due to their low thresholds for runoff generation and enhanced potential for runoff continuity (Cammeraat, 2004). Furthermore, the close proximity of the potential sources increased the likelihood of the contribution of more potential sources to total catchment soil loss.

6. GENERAL CONCLUSIONS

In this study conducted in the Potshini area in the Drakensberg region of South Africa the main objectives were to quantify R, SC and SL at nested scales which included 1 and 10 m^2 plots and 23 and 100 ha catchments; assess soil erosion dynamics from the plot to catchment level and identify controlling factors and to determine the locality of the significant sediment sources contributing to catchment soil loss within the 23 ha catchment in an attempt gain an improved understanding of soil erosion dynamics at the landscape level. Two main conclusions can be drawn from this study.

Different processes of soil erosion exist and these are highly dependent on spatial and temporal scales. It was found that the local processes of splash erosion are dominant at the 1 m^2 level due to comparatively low soil losses resulting from erosion processes being transport limited at this scale. Furthermore, erosion processes occurring at the 1 m^2 level are selective for the reason that clay particles and organic matter are preferentially removed. With an increase in spatial scale to the 10 m^2 level soil losses increase in correspondence to the operation of more erosive forms of lateral erosion such as rain-impacted flow. At the 10 m^2 scale, runoff is able to accumulate and accelerate, obtaining more energy for entraining and transporting soil particles over a greater distance from their initial location. Erosion processes are less selective at the 10 m^2 level due to the transport of a greater percentage of coarser silt and sand particles. Efficiency of erosion at the plot scales varied within the rainfall season. We observed similar soil loss trends in the first few weeks of each of the rainfall seasons occurring during the study period (2009-2011). Thereafter, soil losses increased at both plot scales in response to increases in rainfall intensity, duration, frequency and increased antecedent soil moisture content. Total seasonal soil losses decreased at the 23 ha level despite the operation of more erosion mechanisms such as sheet erosion at the hillslope level and gully and stream bank erosion within the stream network. This is due to an increase in heterogeneity and variability of landscape characteristics such as slope and basal cover and complexity of erosion processes such as increased detachment, transport and deposition cycles. The results obtained in this study indicate that sedimentation seems to become dominant at this scale particularly at the hillslope level. The same trend was observed at the

100 ha level where the lowest soil losses were observed despite the operation of lateral and linear erosion processes.

Properties of eroded sediments such as particle size distribution, colour and total C and N content give an indication of soil erosion processes at the different scales. Our results indicate that light and fine soil material (clays and particulate organic matter) were preferentially eroded at the 1 m^2 level, and sediments eroded at this scale were enriched in clays and total C and N in comparison to the surface soil horizon. Selectivity of erosion processes decreased at the 10 m^2, 23 ha and 100 ha levels in response to increased efficiency of erosion processes such as rain-impacted flow, streambank and gully erosion.

Properties of eroded sediments also give an indication of the dominant forms of erosion and the locality of important sediment-producing areas. The results indicate that the dominant form of erosion contributing to catchment soil loss were the processes of stream bank and gully erosion. Approximately 63% of the sediments at the 23 ha level were delivered by gully erosion during erosive rainfall events. This is detrimental for the quality of the 23 ha catchment for the reason that gully widening is rather than upward retreat occurring. The research presented in this dissertation also indicates that common properties of eroded sediments such as particle size distribution, colour and total C and N may be useful substitutes for elements commonly used in sediment fingerprinting research such as fallout radionuclides (i.e. ^{137}Cs)

6.1 Recommendations

In order to mitigate sheet erosion efficiency at the hillslope level, it is important to ensure the integrity of *in-situ* soil surface factors controlling sheet erosion processes by avoiding the occurrence of activities such as overgrazing. Overgrazing leads to soil surface compaction which creates unfavourable conditions for the growth of vegetation and it also results in excessive removal of basal cover. This exposes the soil surface to raindrop kinetic energy facilitating increased particle detachment from the soil matrix. Furthermore, reduced basal cover reduces soil surface roughness allowing for increased runoff flow velocity and increased sediment transport. Adequate vegetation cover can reduce the operative area for soil erosion processes such as RIF, thus, decreasing erosion efficiency (Bredero *et al.*, 1988;

Dlamini *et al*., 2010). An additional measure in reducing sheet erosion efficiency would be to reduce effective slope length by creating contour embankments or by planting resilient vegetation such as vetiver grass (Beckedahl, 2008). Reducing the likelihood of soil saturation is may reduce soil erosion efficiency as sheet erosion rates tend to increase spatially under the occurrence of runoff connectivity at the soil surface which is most commonly induced under conditions of reduced rain water infiltration. Soil saturation may be reduced by the planting of trees which due to increased rates of transpiration would aid in reducing the rise in the level of the water table.

Securing gully banks by stone packs or mass gravity structures such as gabions may aid in reducing rates of gully widening in the lowlands of the 23 and 100 ha catchments (Beckedahl, 2008). Trees are also able to increase the stability of the soil matrix increasing resilience to gully wall collapse (Chaplot, 2011). An additional intervention strategy may be to reduce the slope angle of the gully and stream banks of affected areas in the stream network (Chaplot, 2011).

6.2 Future perspectives

The present study integrated observations of soil erosion occurring at the plot and catchment scales. Controlling factors of soil erosion processes were identified and recommendations s.based on these were suggested. Additionally, this study quantified the contribution of lateral and linear erosion to catchment soil loss in the 23 ha sub-catchment. The results obtained in this study suggest techniques which could potentially aid in mitigating soil erosion and improving the quality of the soil resource in the Potshini Catchment. However, there is a need to extrapolate the obtained results to larger catchment scales. The aim as part of the future perspectives is to validate selected erosion models, such as the LISEM model using the data collected during this study and from previous years of observations in the Potshini Catchment. Moreover, there is a need to investigate the efficiency of selected remediation techniques for gully erosion under soils of different extents of degradation. The aspiration of this research project is to undertake the above-mentioned objectives in the framework of a PhD.

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8. APPENDICES

8.1 Appendix One

Hill slope soil erosion dynamics and environmental factors of control in the Drakensberg, South Africa

Hill slope soil erosion dynamics and environmental factors of control

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Abstract
Soils are dynamic and constantly moving from high to low relief areas of the landscape by processes of soil erosion. Although the impact of sheet erosion on soil redistribution across landscapes is undisputed, the relative contribution of the causative processes, mainly splash and rain impacted flow and their determining factors are less studied. To investigate these as parts fifteen 1 m^2 (1×1m) and ten 10 m^2 (2×5m) plots were installed on a hillslope in the foothills of the Drakensberg, South Africa. Data of runoff (R), sediment concentration (SC), and soil loss (SL) obtained during the 2009-2010 rainy season at the two spatial scales and from different soils, geology, vegetation cover and topographic conditions were used to identify the main determining factors of sheet erosion. The average runoff from 17 erosive events ranged between 4.9±0.4 L m^{-2} on the 1 m^2 plots and 5.4±0.6 L m^2 on the 10 m^2 plots, although these differences were not significant (>0.05). Sediment losses were significantly higher on the 10 m^2 plots compared to the 1 m^2 plots (2.2±0.4 vs 1.5±0.2 g L^{-1} for SC; 9.8±1.8 vs 3.2±0.3 g m^{-2} for SL) which illustrated a greater efficiency of sheet erosion processes on longer slopes. The average 1:10 m^2 ratio for SL of 0.33 decreased considerably as soil clay content (r=0.26) and soil bulk density (r=0.22) decreased and as antecedent rainfall increased (r=-0.31). Results from a principal component analysis (PCA) where PCA1 and PCA2 explained 60% of the variability suggested a tendency for the ratio to decrease (i.e., sheet erosion efficiency increased) with increasing soil crusting and slope gradient (r=0.32 with PCA2). The relative contribution of the different sheet erosion mechanisms and/or the overall efficiency of sheet erosion were determined by both *in-situ* (slope gradient, soil clay content and soil crusts) and *ex-situ* (antecedent rainfall).
Key words: erosion plot, runoff, sediment concentration, soil loss.

Introduction

It has been recognised that water movements within landscapes are one of the main mechanisms of soil evolution (Paton *et al*., 1995). The acceleration of soil erosion by water in all climates in response to anthropogenic modification of landscapes is a serious threat to natural ecosystem functionalities (Chaplot and Le Bissonnais, 2003; Podwojewski *et al*., 2008) because of the loss of soil and its constituent nutrients. This results in a net decline in land productivity and per capita food production (Gregorich *et al*., 1998; Dawson and Smith, 2007).

Soil erosion consists of the mechanisms of detachment, transport and sedimentation (Kinnell, 2004). Sheet erosion describes water erosion which does not occur in concentrated channels within the landscape. In this diffuse form soil particle detachment occurs mainly by raindrop impact and by overland flow under intense rainfall (Kinnell, 2004; Ghahramani *et al*., 2011). Soil particle transport occurs by rainsplash (a subsequent process to raindrop impact) and by overland flow, while sedimentation takes place when moving water loses energy to below a critical value based on the nature of the material being transported (Kinnell, 2004). Raindrop detachment and splash translocation are collectively known as splash erosion, whereas detachment and transport by overland flow are collectively referred to as overland flow erosion. Splash erosion is localised and does not transport soil material far from its source. Overland flow erosion is a more effective form of sheet erosion that develops from splash erosion during a rainfall event of sufficient duration and intensity (Kinnell, 2004). These two forms of erosion rarely occur independently of each other at the hillslope scale, however, their degrees of operation do vary spatially and temporally (Chaplot and Le Bissonnais, 2000; Stomph *et al*., 2002; Cammeraat, 2004; Kinnell, 2004; van de Giesen *et al*., 2005). Moreover, the relative contribution of splash and overland erosion is also expected to depend on the geomorphic characteristics of the landscape and the controlling factors to which the soil is exposed (Puigdefabregas *et al*., 1999; van de Giesen *et al*., 2005; Mingguo *et al*., 2007). For this reason the combined processes of soil particle detachment by raindrops and overland flow transport will be referred to as rain-impacted flow (RIF) erosion in this paper.

Knowledge of the relative contribution of each erosion type constitutes a key step in the implementation of erosion remediation techniques. Few papers have investigated the relative contribution of different forms of sheet erosion to soil loss and the controlling factors at the hillslope level. South Africa in common with many countries that experience periodic rainfall events of high intensity is greatly affected by soil erosion. The aim of this study was to quantify splash and RIF erosion on a natural pasture using plots of two different sizes. Due to the fact that splash erosion is a point form of erosion and RIF erosion requires a considerable diatance to be significantly operative (Kinnell, 2004) it was expected that splash erosion would be dominant on the 1 m^2 plots and RIF erosion on the 10 m^2 plots.

Methods and materials

Description of experimental site.

The experiment was conducted within a 23 ha catchment in the communal settlement of Potshini (longitude: 29.36°; latitude: 28.82°) situated in the Thukela River basin (30,000km²) of the KwaZulu-Natal Province, South Africa (Figure 1). Potshini has a tropical, sub-humid climate characterised by spring to summer (October-March) rainfall (Schulze, 1997). At Bergville, situated approximately 10 km east of the study site, the mean annual precipitation (MAP) is 684 mm. The potential evaporation is 1600 mm annum^{-1}, the mean annual temperature (MAT) is 13°C and frost is common in winter (Schulze, 1997). According to a 30 year data series obtained from the meteorological national database a rainfall event with a maximum half hour intensity of 49 mm h^{-1} (I_{30}) has a 2 year return period with a 90% occurrence between 37 and 61 mm h^{-1}. The return period for a rainfall event with a maximum half hour intensity of 76 mm h^{-1} is 10 years and for 115 mm h^{-1} the return period is 100 years. Altitude ranges from between 1381 and 1492 m above sea level in and the topography is fairly gentle with a mean slope gradient of ±15.3^{o} within the 23 ha catchment. However, the hillslope on which the study was conducted has steep slopes with gradient values as high as 29. The geology shows a horizontal irregular succession of fine-grained sandstone, shale, siltstone and mudstone (King, 2002) intruded by Karoo dolerite sills. The catchment is used by the local community as unimproved pasture for cattle. Rills and gullies have developed as a consequence of poor grazing management.

Evaluation of *in-situ* splash and RIF erosion

Experimental erosion plots of 1 m^2 (1×1m) and 10 m^2 (2×5) were installed at preselected landscape positions, namely, footslope (F), midslope (M), terrace (T), shoulder sandstone (SS) and shoulder dolerite (SD) of the study hillslope (Figure 1). The soil type at each of the hillslope positions were deep Acrisol at F; shallow Acrisol at the M and T; deep yellowish Acrisol at SST and deep reddish Acrisol at SDOL. Surface characteristics of the hillslope positions are summarised in Table 1. Three 1 m^2 and two 10 m^2 erosion plots were installed at each of the five hillslope positions. The plots were orient parallel to the length of the hillslope. Steel sheets inserted to a depth of 0.1 m into the soil were used for the plot boundaries. The basal cover for all the plots at each slope position per m^2 were equal.

Sediment was collected at the downslope end of each plot via a gutter connected to a reservoir by a length of PVC pipe. Field measurements were carried out from the 15th December 2009 to the 30th April 2010 which was the last rainfall event of the season. It was assumed that measurements were made under steady-state soil loss conditions since no significant soil cracks or features of rill erosion were observed within any of the plots. Runoff depths in the reservoirs were measured after each rainfall event using a measuring tape. A volumetric determination of R was made using a calibrated equation. Aliquot samples of 500 ml, taken after the determination of R, were oven dried at 50 ^{o}C and weighed to determine average sediment concentration (SC). Soil loss (SL) was determined by the product of R and SC. During the study, a total of 450 samples were collected from 17 erosive rainfall events. Rainfall event characteristics such as rainfall amount, maximum and average rainfall intensity were estimated using an automatic rain gauge with a 6-min step counter located at the study site. An evaluation of the contribution of splash and RIF erosion to soil losses at the two scales was done using 1:10 m^2 ratios of R, SC and SL for all the events. A ratio less than 1 indicated that RIF was the more dominant form of erosion causing soil loss.

Statistical analysis

To compare the mean of the 1 and 10m² plot data for R, SC and SL, a paired *t-test* of the null hypothesis that the means of the two populations are equal, was used. P values of 0.05 were used to reject the null hypothesis. Variance analysis was performed under the null hypothesis that there are no differences in means between groups in the population. The variance estimated from the within-group variability should be approximately the same as the variance estimated between-groups. An ANOVA with the 1:10 m² ratio of soil loss as the dependent variable and the soil and rainfall characteristics as independent variables was performed. Statistical significances of results were evaluated at $p = 0.05$. This was complemented by a principal component analysis (PCA) using ADE4 software (Chessel et al., 2004). Two PCAs were carried out, one which included all the environmental variables and one which considered only the rainfall characteristics.

Results

Assessment of the surface characteristics of the plot locations

Table 1 shows that the average vegetation coverage (cov %) at the plot positions was 78% and varied between 64% at M and 93% at F. The soil clay content (clay %) was 36% with a variation between 28% at the F and 54% at SDOL. The average slope gradient (slope %) of the plots was 22% and varied between 18% at SDOL and SST and 29% at M. Of the plot soils derived from dolerite (F, M, T and SD) the surface at M was the most degraded. The soil derived from sandstone material (SST) was comparable to SDOL in terms of vegetation cover and slope gradient. However, the sandstone material gave rise to a considerably lower clay content at SST (31 %) compared to the SDOL (54 %).

Evaluation of the 2009 -2010 rainfall characteristics

The characteristics of the measured rainfall events are summarised in Table 2. The total rainfall at Potshini for the 2009-2010 rainy season, 675 mm which is slightly below the 30 year average (684 mm). The minimum and maximum rainfall amount (RA) and rainfall intensity (I) and maximum half hour intensity (I_{30}) values indicate that rainfall characteristics were highly variable during the rainfall season. The highest I_{30} value was 64.8 mm h^{-1} which is greater than the 2 year return period 90% occurrence value of 61 mm h^{-1}. The lowest I_{30} value was 0.4 mm h^{-1}. The average I30 value (2.7mm h^{-1}) was well below the 2 year return period value (49 mm hr^{-1}). The mode, median, first and third quartile RA and I_{30} values indicate that the majority of the rainfall events which occurred during the rainfall season were of low amounts and low intensities.

Evaluation of occurrence and severity of soil erosion

The series of measured soil erosion events are summarised in Table 3. The maximum values of SC and SL (40.6 g L^{-1} and 149.5 g m^{-2} respectively) were higher for the 10 m^2 plots than the 1 m^2 plots (27.4 g L^{-1} and 30.9 g m^{-2} respectively). A similar trend was followed for the averages of R, SC and SL at the two spatial scales. The median values of R indicate that the 1 m^2 plots were generally more responsive to rainfall than the 10 m^2 plots. The mode, first and third quartile values for R, SC and SL indicate that there were few erosive rainfall events, which is concordant with the rainfall characteristics (Table 2).
The mean and maximum values of R, SC and SL at F, M, T, SDOL and SST are given in Table 4. The average R at each of the plot locations was similar, although the maximum R values varied considerably. Average and maximum sediment concentration and soil loss values were the highest at the M and SST positions which may be explained by the steep slope and low vegetation coverage at M and the sandstone derived soil material at SST which is prone to crusting (Table 1). SC and SL at F, T and SDOL were notably lower in comparison.

Evolution of runoff, sediment concentration and soil loss with rainfall intensity

Figure 2a indicates that the R values (L m^{-2}) at both plot scales were approximately equal for the majority of the rainfall season. However, slightly more runoff was generated from the 10 m^2 plots (91.6 L m^{-2}) compared to the 1 m^2 plots (83.5 L m^{-2}).

Cumulative SL values indicate that soil losses increased steadily and approximately equally at the two plot scales until the 10th event (Figure 2b). Subsequently, soil losses from the 10 m^2 plots increased more rapidly than those from the 1 m^2 plots in response to an increase in the number of raindays, cumulative rainfall amount and an increase in frequency of intense rainfall events. Total cumulative SL values were 55.2 g m^{-2} and 165.8 g m^{-2} at the 1 and 10 m^2 plots respectively.

Total soil loss variations across the hillslope

The ratio of the soil loss at the 1 m^2 and 10 m^2 plot scales (1:10) is a measure of the relative contribution of splash and RIF erosion to soil loss at the various hillslope positions. A ratio value less than 1 indicated that RIFE was the larger contributor of the two erosion types. A measure of the cumulative ratio of the soil loss rates from the 17 events is shown in Figure 3. A lower total cumulative soil loss value is indicative of the fact that RIFE is more operative at a given location in comparison to the other hillslope positions. It can be seen that M had the lowest cumulative soil loss ratio followed by the F and SST positions.

Correlation between 1:10 m^2 ratios for soil loss and selected environmental factors

An evaluation of the impact of the selected rainfall characteristics and soil factors listed in Table 5 on the 1:10 m^2 soil loss ratios for each of the 17 erosive rainfall events was performed using an ANOVA analysis (Table 5). ARD, AR, clay and ρ_b were the only significant variables (p<0.05).

The first two principal components (PC) generated from all environmental factors accounted for 60% of the data variability (Figure 4). The first PC explained 32% of the total data variance and was negatively correlated to all rainfall characteristics. The second PC which accounted for 28% of data variance correlated with *in-situ* soil variables i.e. positively with clay percentage and high vegetation coverage and negatively to crusting, bulk density and slope steepness. Runoff and soil losses correlated to both PCs, although there was a tendency for R to be most strongly correlated with PC1. The 1:10m^2 scale ratio for SL had a correlation coefficient of 0.05 with PC1 and 0.32 with PC2 which implies that soil factors had a greater impact on the relative contribution of individual sheet erosion mechanisms (splash and RIF) to soil loss than rainfall characteristics.

Discussion

Dominant erosion at the 1 and 10 m^2 plot scales

The cumulative soil losses over the study period were about 3 fold greater from the 10 m^2 plots than from the 1 m^2 plots. This indicates that splash erosion at the site is considerably less erosive than RIF erosion as the former is a very localized process of erosion compared to the latter (Kinnell, 2004). Greater runoff erosivity on longer plots is likely due to an increase in flow velocity enabling RIF erosion to become operative and/or dominant (e.g. Stomph *et al*., 2002; Chaplot and Le Bissonnais, 2003).

Factors controlling contribution of splash and RIF erosion

The contribution of RIF to overall sheet erosion increased with increasing rainfall intensity (Bryan ,2000; Kinnell, 2004; Parsons and Stone, 2006) as greater rainfall intensity resulted in faster generation of overland flow. These results, however, differ from these of Chaplot and Le Bissonnais (2003) who obtained, on a gentle slope with loamy soil, only small differences between 1 and 5 m long plots with high rainfall intensity. This was explained by greater ponded runoff absorbing the raindrop kinetic energy and lowering detachment and transport processes. Several other environmental factors controlled the scale ratio of sheet erosion. Irrespective of the characteristics of the rainfall events, greater RIF contribution to sheet erosion occurred on steep slopes and on crusted and compacted soils. Crusted or compacted soils are expected to generate greater amounts of overland flow while steep slopes allow greater flow velocity (e.g. Agassi and Ben-Hur, 1991; Torri and Poesen, 1992; Fox and Bryan, 1999). Conversely, RIF erosion was shown to be more efficient under high grass coverage. This is probably due to faster soil infiltration reducing the amount of overland flow (Puigdefabregas *et al*., 1999; Cammeraat, 2002; Dlamini *et al*., 2010) and to the physical barrier grass tufts offer to overland flow acceleration (e.g. Molina *et al*., 2007). Vegetation also provides a barrier to raindrops, thus reducing splash erosion (Chaplot *et al*., 2003).

Of the selected soil characteristics, clay content was statistically significant (P<0.05) in having an impact on the 1:10 m^2 soil loss ratio. Soils with high clay contents have high surface area and soil organic carbon contents and are thus generally strongly aggregated (Bhattacharyya *et al*., 2009). A positive relationship between soil clay content and low erosion differences between the long and short plots might be due to the relatively high infiltration rates of aggregated clay soils (Teixeira and Misra, 1997), limited overland flow connectivity and increasing soil roughness (Darboux et al., 2005) which in turn decrease the flow velocity and RIF efficiency.

Interestingly, irrespective of rainfall event characteristics or soil surface conditions, RIF contribution to sheet erosion sharply increased in the second half of the rainy season, i.e., after what appears to be a threshold for cumulative rainfall. The sharp increase in soil losses from longer plots relative to the shorter ones occurred from the 10th rainfall event which corresponded to a cumulative antecedent rainfall of 190 mm if rain out of the yearly amount of 675 mm. This result might be explained by the establishment of a shallow water table causing saturation of the soil surface. Once the water table reaches the soil surface, infiltration decreases to zero, initialising overland flow and thus RIF erosion. Overall, the scale issue for sheet erosion appears to be controlled by soil surface conditions (in relation to Hortonian flow) in the first half of the rainfall season, while in the second half, RIF seems to predominate because of the contribution of soil saturation causing infiltration excess and overland flow. Finally, rainfall intensity surprisingly had no significant impact on sheet erosion efficiency.

Conclusion

In this study on a sloping land area of South Africa affected by sheet erosion, our main objective was to determine the relative contribution of the main sheet erosion processes and their controlling factors in an attempt to define suitable measures for soil erosion mitigation. Results from plots of different surface areas and with different slope lengths, soils, geology, vegetation and topographic conditions were as follows:

- Sheet erosion and its efficiency to detach and transport soil material was highly spatially and temporally variable confirming previous investigations;
- The efficiency of sheet erosion and/or the contribution of rain impacted flow (RIF) compared to splash erosion was controlled by slope gradient, soil clay content, soil crusting and antecedent rainfall, with the *ex-situ* factor having the greatest influence;
- Antecedent rainfall seems to play the most significant role in the occurrence of sheet erosion processes compared to other climatic variables, with runoff connectivity as cumulative rainfall associated soil water content increase.

In order to mitigate sheet erosion efficiency at the landscape level it is important to ensure that overgrazing and soil saturation does not occur. Communal or commercial cattle grazing needs to be managed to ensure land degradation by the removal of basal cover does not occur. Moreover results on the relative contribution of soil properties, water table establishment and rainfall characteristics on sheet erosion would allow improvement of existing models such as the (USLE) (Wischmeier and Smith, 1978), SWAT (Arnold *et al*., 1998) or other rainfall-runoff-soil models (Nearing, 2000) for improved spatial and temporal prediction of overland flow and soil erosion.

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Table 1. Characteristics of the study hillslope positions F (footslope), M (midslope), T (terrace), SDOL (shoulder dolerite) and SST (shoulder sandstone): Crust: percentage of soil surface with crusts; Cov: percentage of soil surface coverage by vegetation; Clay: soil clay content; ρ_b: soil bulk density; S: mean slope gradient; ρ_b: bulk density

Plot	Crust (%)	Cov (%)	Clay (%)	S (%)	ρ_b (g cm^{-3})
F	7	93	28	25	1.23
M	36	64	27	29	1.19
T	19	81	40	22	0.96
SDOL	22	78	54	18	0.96
SST	25	75	31	18	1.15
Average	*22*	*78*	*36*	*22*	*1.10*

Table 2. General statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for selected rainfall characteristics of the 17 rainfall events of the 2009-2010 rainy season. (I: average rainfall event intensity; Imax: maximum rainfall event intensity; I_{30}: average thirty minute rainfall event intensity; I_{30}max: maximum thirty minute rainfall event intensity; RA: rainfall amount; RDur: rainfall hours; ARD: cumulative antecedent rain days; AR: antecedent rainfall from onset of rainy season to end of erosion event; AR_3: three day antecedent rainfall; AR_{10}: ten day antecedent rainfall).

	I	Imax	I_{30}	I_{30}max	RA	RDur	ARD	AR	AR_3	AR_{10}
Mean	3.1	23.3	2.7	18.0	25.6	2.1	62.0	201.1	16.9	38.3
SD	1.7	18.2	1.6	16.1	19.8	1.6	39.7	138.8	14.2	18.7
SE	0.4	4.4	0.4	3.9	4.8	0.4	9.6	33.7	3.8	4.3
CV	54.7	78.0	59.0	89.2	77.3	75.1	64.0	69.0	84.2	49.0
Variance	3.1	350.6	2.7	274.7	417.4	2.7	1671.1	20468.7	215.2	373.0
Min	0.8	0.8	0.4	0.4	0.2	0.3	6.0	21.0	0.6	13.4
Max	6.6	69.6	6.1	64.8	64.8	6.4	142.0	435.6	54.6	68.8
Mode	0.8	0.8	0.4	10	n/a	1	n/a	n/a	10.8	25.4
Quartile 1	2.2	9.6	1.7	7.2	8.2	1.0	36.0	101.4	5.6	20.6
Median	2.6	20.8	2.3	17.2	21.0	1.8	49.0	181.4	14.4	35.8
Quartile 3	3.8	28.8	3.8	21.6	42.8	3.3	100.0	328.6	20.6	59.2
Skewness	0.6	1.1	0.4	1.5	0.6	1.2	0.5	0.4	1.4	0.2
Kurtosis	-0.3	1.2	-0.4	2.8	-0.7	1.3	-0.9	-1.3	1.9	-1.7

Table 3. General statistics (SD: standard deviation; SE: standard error; CV: coefficient of variance) for runoff (R), sediment concentration (SC), soil loss (SL) and soil loss by unit width (SLw) at the 1 m^2 (n = 255) and 10 m^2 (n=170) plot scales.

	R L m^{-2}		SC g L^{-1}		SL g m^{-2}		SLw g m^{-1}	
	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2	1m^2	10m^2
Mean	4.9	5.4	1.5	2.2	3.2	9.8	3.2	4.9
StDev	5.6	7.2	3.7	4.8	5.0	23.4	5.0	11.7
SE	0.4	0.6	0.2	0.4	0.3	1.8	0.3	0.6
CV	114.1	133.4	250.9	220.7	152.7	240.0	152.7	120
Variance	31.8	52.5	13.6	23.1	24.9	554.6	24.9	277.3
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	33.0	38.1	27.4	40.6	30.9	149.5	30.9	74.75
Mode	3.5	1.7	0.2	n/a	n/a	0.8	n/a	0.4
Quartile 1	1.0	1.1	0.2	0.3	0.3	0.6	0.3	0.3
Median	2.8	2.6	0.5	0.8	1.3	1.9	1.3	0.95
Quartile 3	8.0	8.0	0.9	2.5	3.9	5.7	3.9	2.85
Skewness	2.4	2.5	5.3	6.5	3.2	4.1	3.2	2.05
Kurtosis	8.0	6.7	31.9	49.9	12.6	18.3	12.6	9.15

Table 4. Mean and maximum runoff (R), sediment concentration (SC) and soil loss (SL) from the 1 m^2 (n = 255) and 10 m^2 (n = 170) plot scales for the five hillslope positions; footslope (F), midslope (M), terrace (T), SDOL (shoulder dolerite) and SST (should sandstone).

	R $L\ m^{-2}$				SC $g\ l^{-1}$				SL $g\ m^{-2}$			
	Mean		Max		Mean		Max		Mean		Max	
Plot	$1m^2$	$10m^2$	$1m^2$	$10m^2$	$1m^2$	$10m^2$	$1m^2$	$10m^2$	$1m^2$	$10m^2$	$1m^2$	$10m^2$
F	2.5	2.7	9.3	5.9	1.4	1.7	16.0	15	0.9	1.9	3.9	8.1
M	7.6	10.2	33	38.1	1.1	5.4	3.7	52.6	7.7	26.2	30.9	149.5
T	3.7	4.3	10.5	30.5	3.4	3.8	27.4	4.6	2.7	3.7	13.4	12.9
SDOL	3.9	3.3	11.8	11.1	1.9	0.9	8.0	3.4	1.8	1.7	5.4	3.9
SST	7.0	7.0	25.7	23.7	0.5	2.6	2.5	20.1	3.1	15.2	10.6	92.2

Table 5. ANOVA between the 1:10m^2 soil loss ratio and some selected environmental factors: (I: average rainfall intensity; Imax: maximum rainfall intensity; I_{30}: average thirty minute rainfall intensity; $I_{30}max$: maximum thirty minute rainfall intensity; RA: event rainfall amount; RDur: rainfall event duration; ARD: cumulative antecedent rain days; AR: antecedent rainfall since onset of rainy season; AR_3: antecedent three day rainfall; AR_{10}: antecedent ten day rainfall; Crust: percentage of soil surface with crusts; Cov: percentage of soil surface coverage by vegetation; Clay: soil clay content; ρ_b: soil bulk density; S: mean slope gradient.

Variable	r	Degree freedom	F	p
I	-0.44	4	3.11	0.1
Imax	-0.12	4	4.11	0.06
I_{30}	-0.40	4	3.18	0.09
$I_{30}max$	0.03	4	3.68	0.07
RA	0.13	4	0.98	0.34
RDur	0.25	4	0.17	0.67
ARD	-0.31	4	5.46	0.03*
AR	-0.29	4	5.45	0.03*
AR_3	0.10	4	0.9	0.34
AR_{10}	0.13	4	1.4	0.23
Crust	-0.07	4	0.4	0.52
Cov	0.07	4	0.4	0.52
Clay	0.26	4	6.14	0.01*
ρ_b	0.22	4	4.6	0.03*
S	-0.2	4	3.38	0.07

*significant at p<0.05 level

8.2 Appendix Two

Sediment and soil colour, texture and total carbon and nitrogen content coupled with sediment flux estimation at embedded spatial scales to understand landscape soil erosion dynamics.

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Abstract

Landscapes experiencing periodic events of high intensity rainfall are the sites for significant soil erosion resulting in transport and delivery of sediments from river catchments. The ways in which soil material is detached by water erosion, transported and eventually exported from river catchments is a key issue in environmental sciences. Although the different soil erosion processes have been thoroughly investigated, soil erosion dynamics, specifically sediment source locality and continuity of erosion processes are yet to be quantified. The main aim of this study was to evaluate the changes in sediment characteristics and fluxes during downslope and downstream transport and to interpret these in term of catchment scale soil water erosion. The study was conducted in a 10 km² (e.g., 1000×10^4 m²) catchment of the Drakensberg foothills (South Africa). Soil texture, soil colour, and soil organic carbon and nitrogen content in sediments exported from nested scales (1, 10, 23×10^4, 100×10^4 and 1000×10^4 m²) were compared to in-situ surface and sub-surface soil horizons in the catchment, river bank soils, and hillslope and fluvial sediments. Sediment fluxes at the scales were monitored during the 2009-2011 rainy seasons using totalizers at 1 m^2 (1×1m) and 10 m^2 (2×5m) plots and weirs with automatic samplers from the micro-catchment to the catchment. There was a sharp increase of sediment fluxes with increasing slope length (846±201 $gm^{-1}y^{-1}$ for SL=1m *vs* 6820±1714 $gm^{-1}y^{-1}$ for SL=5m) revealing a limited contribution of splash compared to the other sheet erosion mechanisms (RIFT, RD-FT, Kinnel, 2001) in the downslope transfer of sediments. Compared to the bulk soil and the plot sediments, 1 m^2 plot sediments were enriched in clay and nutrients suggesting sediment sorting by splash desagregation. Thereafter, sediment fluxes decreased to 500±100 $gm^{-1}y^{-1}$ at the 23×10^4 m² micro-catchment, 100±10 $gm^{-1}y^{-1}$ at 100×10^4 m² to 1±0.1 $gm^{-1}y^{-1}$ at the $1000^4\times10$m² pointing out the predominance of sedimentation during the downslope and downstream transport of sediments. Sediments exported from the micro-catchment and the catchment were significantly much sandier than the topsoil and subsoil while sediments exported from the basin were more clayey than their potential sources, thus putting into question the assumption of absence of enrichment, dilution or depletion of tracers used by mixing models for sediment sourcing evaluation. From a PCA generated from sediment characteristics we learn that the micro-catchment sediments exhibited a signature intermediary between sediments generated by sheet erosion (*coarse sands and nutrient enriched*) and river sediments (*coarse sands and nutrient depleted*), the average contribution of the later, estimated from the Euclidian PCA distances, being 63%. During their downstream transport, sediments were discriminated by the second PCA axis which correlated with the clay and fine silt content, 100×10^4 m² sediments showing negative coordinates to this axis while 1000×10^4 m² sediment collected at the outlet of two dams having positive coordinates. This new knowledge is expected to improve management strategies to mitigate soil water erosion at landscape level as well as to improve understanding and assessing of sediment sourcing and catchment functioning.

Key words: catchment, particle size distribution, sediment source, soil colour, soil nutrients.

Introduction

Soil water erosion is a very dynamic process with direct and indirect consequences on ecosystem functioning. These include reduced efficiency of the land to grow food products and other biomass, depressed biodiversity and mitigation of rising environmental threats such as water scarcity and climate change through the decreased storing capacity by soils of elements such as water and atmospheric carbon respectively. Soil water erosion can be in some situations beneficial to ecosystems. This usually happens when the eroded soil material is concentrated to some limited areas of the landscape, generally the lowlands.

Soil erosion by water is a complex and dynamic process which involves an array of mechanisms responsible for the detachment, the transport, the sedimentation and the ultimate export of soil material from river basins.

Detachment is the initial step of soil erosion. It can occur by splash only or through a combination of splash and flow (named rain-impacted flow), the soil material being detached by splash and transported by raindrop impact lifting the loose particles or aggregates up into the flow. The flow can detach and transport particles alone when the energy of the flow is sufficiently large to detach soil material from the bulk soil and to entrain it. The detached sediments can be transported either on short distance by splash or on longer distances by the running water. Sediment deposition is by opposition the process of soil material settling when gravity and friction forces prevail. As a result, sediment delivered from a catchment may have been subjected to several detachment, transport and sedimentation mechanisms. Exported sediments might as well come from different sources, e.g., ranging from surface soil horizons to river bed sediments through deep soil horizons at gully or river banks. In some cases, the detached soil material, especially this from upslope positions, may never reach the river system because of its permanent sedimentation in the landscape.

Because detachment, transport and sedimentation mechanisms are spatially and temporally variable, understanding catchment functioning in respect of soil erosion requires not only sediment sources to be identified but the continuity between detachment and river exports to be accessed (e.g., Walling, 1983). This type of information is of prime importance for understanding the different soil erosion mechanisms, evaluating both their on-site and off-site impacts on terrestrial and aquatic ecosystems as well as finding the best remediation practices to soil erosion.

Typical methods employed in soil erosion research to assess soil erosion dynamics within landscape include the use of runoff-plots of different sizes both under natural or artificial rain, the monitoring of catchment soil loss using flumes or weirs, natural or artificial tracers, among others (Wishmeir and Smith, 1978; Poesen *et al*., 2003; Walling *et al*., 2006).

Numerous studies have used microplots (generally of 1×1m) (Le Bissonnais et al., 1998; Fox and Bryan, 1999; Stomph et al., 2002; Chaplot and Le Bissonais, 2003; Dlamini et al. 2010; Podwojewski et al., 2011) to evaluate the contribution of local erosion mechanisms (mainly splash and rain-impacted flow) on soil displacement from its initial place. Several mechanism-based studies have been performed to link soil water erosion to environmental factors of control. Podwojewski et al. (2011) under relatively similar conditions in South Africa, assessed the vegetation cover thresholds for decreased soil infiltration and increased soil erosion. Other microplot studies have considered other erosion controlling factors such as slope gradient (e.g., Fox and Bryan, 1999) or specific soil constituents such as organic carbon (e.g., Boix-Fayos et al., 2009). Microplots have been extensively used as well for assessing the spatial variations of soil erosion. Under sloping lands and clayey soil conditions, Dlamini et al (2010) in a 350 m long rangeland hillslope of the Drakensberg foothills of South Africa found soil losses to vary between 3 and 13 ton ha^{-1} y^{-1}, the highest rate being found on bare and crusted soils. Although microplots have allowed some interrill erosion processes and factors of control to be better understood and quantified, they do not allow a complete assessment of soil erosion dynamics at the landscape level. While they allow point scale interrill mechanisms such as splash and to some extent rain-impacted flow (Kinnel, 2004) to be evaluated, other sheet or linear erosion and sedimentation processes that require a greater surface area to be operative are not accessed. Longer plots (e.g. Wischmeier and Smith, 1978) aid in avoiding some of these limitations by including more erosion mechanisms such as flow detachment and flow transport, however, they do not account for the entire range of catchment-scale erosion processes.

H-flumes or weirs allow impact of the different detachment, transport, and sedimentation mechanisms on catchment exports to be assessed (e.g., Verbist *et al*., 2010). The different studies available reveal that the sediment yields from catchments represent a minute portion only of those estimated from microplots or plots (Roehl, 1962; Walling, 1983; Le Bissonnais *et al*., 1998; Verstraeten and Poesen 2001; Cammeraat, 2004; Beven *et al*., 2005; de Vente *et al*., 2006; Parsons *et al*., 2006; Walling *et al*., 2006). Expressed as a percentage of total soil displacement, catchment yields of sediments were shown to range between 1% in 166 to 234 km^2 catchments in southern England (Walling et al., 2006), 2% for a 60 ha catchment in the sloping lands of South east Asia (Chaplot et al., 2005). Although these studies inform on the amount of catchment exports of sediments relative to the displaced soil material, our understanding of both the transport continuity of the eroded soil material from hillslope to catchment outlet and the several interactions between the different erosion mechanisms remain incomplete.

In an attempt to gain an improved understanding of soil erosion dynamics at the catchment level, few studies considered embedded scales while others benefitted from the use of tracers. Le Bissonnais et al. (1998) using a series of scales from the microplot to the catchment level (1, 10, 500 m^2 and 70 ha) pointed out that the continuity of sediment transport is largely dependent upon the soil surface characteristics of the considered area, crusted soils allowing sediment transport on longer distances. From the study of Puigdefabregas et al. (1999) in southeast Spain we learn that most detached sediments do not reach the lower parts of hillslopes nor the catchment outlet because of the presence of few vegetated portions in hillslopes acting as runoff and sediment sinks. Mingguo et al. (2007) in the Loess Plateau in North China, similarly showed that vegetation is able to significantly reduce sediment losses at the hillslope level. These authors additionally indicated a decreased impact of the vegetal cover at catchment level where gully erosion seemed dominant. Comparable studies by Chaplot et al. (2005) and Wang et al. (2010) inform on sediment and soil organic fluxes at different scales in an attempt to investigate the different erosion mechanisms interacting at catchment level. Vandaele and Poesen (1995) using catchment flux estimation together with linear erosion evaluation showed that between 37 and 63% of the total erosion measured at the outlets of two adjacent Belgium catchments can be attributed to ephemeral gully erosion, thus improving understanding of sediment sources. These studies have allowed making progress on the impact of the different erosion mechanisms and sediment sourcing. However, there still remain large uncertainties on sediment sources and continuity of sediment transport.

Environmental tracers such as ^{210}Pb and ^{137}Cs have been largely applied for sediment sourcing as their use constitutes effective alternative techniques (e.g., Walling, 2005). Because cesium-137 fallouts accumulate in surface soil horizons (mainly to a depth of 0.2m under cropped fields), if little or no ^{137}Cs is detectable in sediments exiting a catchment, it can be deduced that these sediment have a subsoil origin. For instance, in New South Wales (Australia) Krause et al. (2003) using ^{137}Cs, ^{210}Pb Cu, Pb, Zn, Fe, Mn and K identified riverbank sediments as the predominant catchment sediment source (98%). A similar results was found by Poulenard et al. (2009) in the French Alps but by using infrared spectroscopy, a much cheaper technique. Li et al. (2003) in the Yangjuangou reservoir catchment of the Chinese Loess Plateau (northwest China) with different land use suggested that cultivated soils (both surface and sub-surface horizons) were the main contribution to the reservoir sedimentation, with an average ^{137}Cs concentration in sediments of 3.45 Bq kg^{-1} compared to 4.2 and 2.6 Bq kg^{-1} for the 0-5 cm and 0.5-0.20 cm soil layers, respectively. However, the existence of other potential sediment sources such as surface and sub-surface forested or grassland soils with an average ^{137}Cs concentration of 8.24 Bq kg^{-1} can be seen as a major limit for interpreting the results.
On the one hand, tracers allow sediment sources to be identified with relatively high accuracy but the techniques are expensive, difficult to implement for numerous sediment sources, and mostly fail in the identification of the erosion mechanisms thus limiting the assessment of the areas of sediment generation, sedimentation and further remediation of erosion. Moreover, the contemporary use of tracers such as ^{137}Cs and ^{210}Pb emitted during the 1960s is being compromised by a half-life of less than 30 years, low concentrations or inhomogeneous spreading, especially in the southern hemisphere, and new deposition episodes associated with the Chernobyl and the more recent Fukushima disasters, thus putting an end point to the use of the technique in many areas. On the other hand, nested scales have been successful in evaluating the different erosion mechanisms interacting at catchment level but they show limitations in the quantification of sediment sources and in assessing the continuity of sediment transport. Because for the most part, multi-scale studies and tracers have been used independently, further understanding of soil erosion dynamics at catchment level would highly benefit from a more holistic approach involving both sediment fluxes estimation at embedded spatial scales and sediment sourcing methods that would be cost effective and easy to implement.
It is commonly believed that the ideal tracers for the study of soil erosion and sediment sources should (i) be strongly bound to soil particles or easily incorporated into aggregates; (ii) be easy and inexpensive to measure; (iii) not be easily taken up by plants; and (iv) be environmentally friendly. Here we hypothesise that changes in sediment characteristics (texture, colour, and nutrients) during the downslope and downstream transport together with sediment flux estimation will improve understanding of landscape soil water erosion.

Methodology

Study site description

The study area is located in Potshini, an agricultural area situated approximately 10 km from Bergville in KwaZulu-Natal, South Africa (S: 29.36°, E: 28.82°). Potshini is localised in the north sloping lands of the upper Thukela basin (30 000 km^2). The climate is humid, sub-tropical with a summer rainfall pattern (October-March) (Schulze, 1997). According to a 30 year rainfall record the mean annual precipitation of Bergville is 684 mm per annum with a potential evaporation of 1600 mm per annum and a mean annual temperature of 13 ℃ (Schul ze, 1997). The study area consists of a 1000 ha catchment with 2 embedded catchments of 23, 100 ha corresponding to three different land uses, namely; unmodified grazing land (23 ha) homesteads and subsistence (100 ha) and commercial scale agriculture (1000 ha). The steep slopes of the Potshini catchment are concentrated within the 23 ha head water catchment were the mean slope is 15.3% while the mean slope gradient of about 9% for the 100ha level. The stream network which flows through the 1000 ha catchment begins in the 23 ha headwater catchment where a large gully is gradually widening and retreating as a result of fluvial processes.. The stream channel feeds into a dam located on a commercial farm in the 1000 ha catchment. The dam is vulnerable to sedimentation as a result of soil erosion occurring upstream. The stream water is used by the community members for household purposes. Additional sources of water for domestic use are located at two borehole pumps within the 100 and 1000 ha catchments

The experiment design

An assessment of soil water erosion rates at different spatial scales was made with the core hypothesis that variations in these would be in response to dominant processes taking place within the landscape. Observations have shown that soil erosion processes vary considerably spatially and temporally, there is however a general consensus that the main detachment and transport process at the cm^2 scale is splash erosion and that a circumstantial threshold surface area is required for the dominant operation of overland flow detachment (herein termed runoff detachment) (lateral erosion) or stream channel erosion (linear erosion).

In this soil water erosion study, local erosion processes consisting mainly of splash and slight rain impacted flow (Kinnell, 2004) were evaluated using conventional 1 m^2 (1×1m) erosion plots. The evaluation of sheet or linear erosion herein referred to as rain impacted flow tranport (RIF) erosion (Kinnell, 2004) was done using 10 m^2 (2×5m^2) erosion plots. The reason for the use of 5 m long plots was that field observations have shown that eroded soil aggregates deposited in local depressions whose distance was between 3 and 5 m. Also, this plot length aided in minimising detachment transport and deposition cycles which facilitated the avoidance of the underestimation of RIF erosion processes. Wischmeier and Smith (1978) would have been inappropriate for this study as their use may have facilitated the development of rills while the purpose of the plots were to evaluate lateral erosion processes. 1 m^2 and 10 m^2 plots were installed at five topographic positions (from the footslope to the shoulder) of a typical hillslope showing the presence of deep Acrisols at footslopes and hillslope plateau and shallow Acrisols middle-slope. The mean slope gradient at the shoulder, terrace, middle-slope and foot-slope were 18, 22, 29, 24 degrees respectively. Three 1 m^2 plot and two 10 m^2 plot replicates were installed at each slope position. The 0.1 and 0.3 m high metal borders surrounding the 1 m^2 and 10 m^2 plots respectively were inserted in the soil to a depth of 0.1 m. It was assumed that the 1 m^2 and 10 m^2 plots described the diversity of the entire hillslope because they were installed hillslope positions exhibiting different soil types, basal covers and slope gradients. Erosion processes operating at the 23 and 100 ha catchment scales were evaluated using delivery observations for water, sediment and SOC.

The quantification methods

Soil and sediment sampling

Field measurements of water erosion were carried out from 18th October 2010 to 15th May 2011 (the last rainfall event of the season). It was assumed that measurements were made under steady-state soil loss conditions for the reason that no significant soil cracking or features of rill erosion were observed within the 1 m^2 and 10 m^2 plots. On 1 m^2 and 10 m^2 plots runoff (R) depths in the reservoirs were measured after each rainfall event using a measuring tape. A volumetric determination of R was made using a calibrated equation. Aliquot samples of 500 ml were taken after the determination of R depth. The samples were oven dried at 50 ^oC and weighed to determine average sediment concentration (SC). Soil loss (SL) was determined by the product of R and SC. During this study, a total of 450 samples were collected from 17 erosive rainfall events. Rainfall event characteristics such as rainfall amount, maximum and average rainfall intensity were estimated using an automatic rain gauge with a 6-min step counter located at the study site. Conventional H flumes coupled to ISCO 6712 and 3700 series automatic samplers are situated at the outlets of the 23 and 100 ha catchment respectively. The automatic water samplers were used to quantify catchment runoff and soil losses during base flow periods and on the rising and falling limb of a hydrograph during rainstorm events.
Soil samples from the different 1 m^2 and 10 m^2 plots (n=5) were collected in the field. They constituted of 1kg bulk sample. Surface 0-0.005m and subsurface 0.5-0.9m horizons were considered in this study.
At the microcatchment and catchment levels sediment samples were collected using automatic samplers during rainfall events and manual sampling in between events. Due to the quantity of soil material required for particle size analysis for the pipette method (20 g) and analysis of total soil fertility (±350 g), sediment samples were collected after eight consecutive rainfall events at a time from the erosion 1 m^2 and 10 m^2 plots. A total of 52 sediment samples were collected.

Laboratory analysis.

Chemical characteristics of soils and sediments

The soils and sediments for carbon and nitrogen analysis were air-dried. The fraction of soil material < 2 mm was obtained by sieving through a nylon mesh. The soil material underwent analysis for total carbon (C) and nitrogen (N) by complete combustion using a Leco TruSpec Carbon Nitrogen analyser. After analysis of the nutrient content of the fertility it was decided that C and N were appropriate indicators of soil nutrients as C content is an indication of soil organic matter content and soils with high soil organic matter are generally fertile.

Physical Characteristics of soils and sediments

An adaptation of the pipette method (Gee and Bauder, 1986) was used to determine the particle size distribution of the soils and sediments. Air dried soil material with a mass of 20 g was sieved (< 2 mm fraction) and dispersed by the addition of 10 ml of Calgon (sodium hexametaphosphate and sodium chloride) and 15 ml of distilled water. Samples were subsequently treated ultrasonically for 3 minutes. The dispersed sample was carefully passed through a 0.053 mm sieve into a 1 litre sedimentation cylinder, distilled water was added to increase the volume to 1000 ml. The sand fraction (> 0.053 mm) was oven dried at the 105 ^oC for 24 hours. The sand fraction was then subdivided by means of a sieve stack into very fine (< 0.106 mm), fine (0.106 – 0.250 mm), medium (0.250 – 0.500 mm) and course sand (> 0.500 mm). The < 0.053 mm fraction in the sedimentation cylinders was then brought into suspension by agitation using a handheld a plunger. The quantities of coarse silt

(0.02 - 0.053 mm) fine silt (0.002 - 0.02 mm) and clay (< 0.002 mm) were determined according to Stoke's law by sedimentation and pipette sampling, after appropriate settling times for each size fraction. The fine silt and clay were also dried at 105 ^{o}C. The average percentages of soil and sediment sand, silt and clay at the different scales were fitted to a texture triangle after the texture triangle compiled by the USDA in an attempt to assess soil erosion trends selectivity of erosion mechanisms at the different scales.

Air dry sediment colour was determined using a Munsell colour chart. The hue component of the colour description for soils was transformed to a numerical value called the colour development equivalent as proposed by Buntley and Westin (1965) The CDE combines the redness of hue with its purity (chroma). This combined aspect of soil color appears to be closely related to color development, which, in turn, may be related to soil development. Using this method of numerical transformation, a hue of 10YR was assigned a numerical notation of 1.0, 7.5YR a notation of 2.0, 5YR a notation of 3.0, and 2.5YR a notation of 4.0, thus indicating an increasing level of redness.

It was expected that sediments eroded from the 1 m^2 plots would be enriched in clay in comparison to the *in-situ* soil due to predominant low energy transported limited erosion mechanisms. Erosion mechanisms at the 10 m^2 and catchment scales were presumed to get progressively less selective with an increase in particle transport efficiency. Because clay particles are the most chemically reactive fraction of a soil and soil organic matter is light in comparison to the particle fraction of the soil it was assumed that sediments eroded at the 1 m^2 and 10 m^2 plot level would be enriched in nutrients in comparison to the *in-situ* soil. Sediments eroded at the 23 and 100 ha scales were presumed to similar in content to the *in-situ* soil due to the predominant subsoil origin of the eroded sediments. Sediments deposited at the 1000 ha scale were assumed to be enriched in sediments in comparison to the 23 and 100 ha scales due to preferential deposition of clays and nutrients in the dam.

Runoff (R) was expressed in litre of water per m^2, sediment concentration (SC) in gram per litre and soil losses (SL, the product of SC by R) in gram per square metre. Additionally we estimated SLw, the soil losses flux, expressed in gram per metre width of plot.

Statistical analysis

Multivariate analysis was applied to the data. A first Principal Component Analysis (PCA) generated using soil erosion variables at the different scales as dependent variables versus environmental characteristics as supplementary variables was generated. A second PCA was applied to the data to find relationships between redness (hue), value, chroma, clay, fine silt course silt, very fine sand, fine sand, medium sand, course sand, C and N. A PCA was used as it has been previously shown to be well adapted to large sets of variables and to identify the structure or dependence in data sets (Webster, 2001). The ADE4 software (Chessel et al., 2004) was used for this study.

Results

Evaluation of the rainfall characteristics

The 2010-2011 rainfall season was a considerably wet season. The total rainfall at Potshini, 1055.4 mm which is considerably higher than the 2009-2010 amount of 675mm and the MAP of 684 mm. The characteristics of the considered rainfall events which occurred during the 2010-2011 rainfall season are summarised in Table 1. General statistics of the rainfall characteristics such as mean and maximum rainfall amount (RA) and rainfall intensity (I) and maximum half hour intensity (I_{30}) values indicate that rainfall characteristics were highly variable and of high magnitudes during the rainfall season. The highest and most erosive event had an I_{30} of 52.8 mm h^{-1} with a standard error of 4.2 mm h^{-1}. This is less that the 2 year return period 90% occurrence value of 61 mm h^{-1} and surprisingly less than the 2009-2010 maximum of 64.8±3.9 mm h^{-1}. The mean and maximum rainfall event duration changed from 2.1±0.4 and 6.4±0.4 hours to 1.0±1.3 and 16.8±1.3 hours for the 2009-2010 and 2010-2011 rainy seasons respectively. The median, first and third quartile RA and I_{30} values indicate that the majority of the rainfall events which occurred during the rainfall season relatively high depths and intensities.

Evaluation of soil erosion at the different spatial scales

The general statistics of series of soil erosion event characteristics occurring between 18th October 2010 and 15th March 2011 are summarised in Table 2. Maximum R decreased from the 1 m^2 and 10 m^2 plots, and 23 ha catchment (89.0±5.3, 49.5±4.1 and 31.4±2.9 L m^{-2}) and increased sharply at the 100 ha catchment (169.3±6.6 L m^{-2}). The maximum SL values at all scales were considerably high apart from those observed at the 100 ha scale. As expected, SL was highest at the 10 m^2 plot scale (558.5±12.9 g m^{-2}). Maximum SL decreased at the 1 m^2 plot level (127.8±6.0 g m^{-2}) and increased slightly at the 23 ha level (234.1±9.0 g m^{-2}). The 100 ha catchment yielded a maximum SL of 8.9±1.6 g m^{-2}. Maximum values of SC at the 23 and 100 ha catchment scales were also comparatively low. The median values of R indicate that the 1 m^2 and 10 m^2 plots experienced similar overland flow behaviour, however the 100 ha catchment yielded the largest runoff amount.

An assessment of the temporal evolution of the cumulative R at the different spatial scales indicates that the 1 m^2 and 10 m^2 plots experienced similar overland flow responses during the series of rainfall events (Figure 2). R values indicate that the 1 m^2 and10 m^2 plots were considerably responsive to the due timely generation of runoff upon the occurrence of rainfall events. The cumulative R values at the 1 m^2 and 10 m^2 plot scales were 234.3 and 270.2 L m^{-2}. The 100 ha catchment became responsive as the rainfall season proceeded. The interestingly greatest response occurred in February 2011 after several large rainfall events. The 100 ha yielded a cumulative R of 530.2 L m^{-2}. The 23 ha catchment was comparatively not as responsive as the other scales and yielded a cumulative R of 86.17 L m^{-2}.

A further evaluation of the temporal evolution of SL at the mentioned scales shows soil losses were greatest at the 10 m^2 plot scale by comparison (Figure 2). The cumulative soil loss value at the 10 m^2 plot scale was approximately 1399.8 g m^{-2} in comparison to 406.2 g m^{-2} at the 1 m^2 plot scale. Despite having a considerably low cumulative R by comparison the 23 ha catchment yielded a SL considerably higher (807.1 g m^{-2}) than the 1 m^2 plot and 100 ha scales (406.3and 33.9 g m^{-2} respectively). Results show that cumulative soil losses decreased by approximately 4129 %.

A measure of the SC trends at the spatial scales with temporal evolution is shown in Figure 3. The SC results indicate that sediment concentrations at the three smaller scales (1 m^2, 10 m^2 and 23 ha) corresponded to changes in rainfall characteristics during the rainy season. Sediment concentrations at 1 m^2 and 10 m^2 plot scales were relatively high at the onset of the rainfall season and gradually decreased in January 2011. Interestingly at approximately the same time SC values at the 23 ha level increased rapidly in response to rainfall events of high intensity and particularly high depths (i.e. 26.6 g L^{-1} in response to 139.8 mm of rainfall with a maximum intensity of 64 mm h^{-1}). The 1 m^2 and 10 m^2 plots and 100 ha catchments yielded SC values 1.92, 14.3 and 0.1 g L^{-1} for the same event.

Factors controlling erosion fluxes

An evaluation of the correlation of selected environmental factors and the soil erosion variable to assess their impact on soil erosion processes and soil losses at the different scales (Table 3). Of the selected environmental factors rainfall amount (RA), maximum rainfall event intensity (Imax), maximum half hour rainfall event intensity (I_{30}max), rainfall event duration (RDur), antecedent rainfall three and ten days prior to sample collection (AR_3 and AR_{10}) had the most significant impact on soil erosion variables particularly at the 1 m^2 and 10 m^2 plot scales. The correlation and therefore the influence of the factors tended to decrease with increasing spatial scale at the 23 and 100 ha catchments. Increasing landscape heterogeneity may have caused selected environmental factors to become less significant.

The principal component analysis (PCA) accounting for 53 % of the data variability and which compared soil erosion (dependent) variables at the different spatial scales against selected environmental (supplementary) variables (Figure 4) showed that R and SL at the 1 m^2 and 10 m^2 plot scales were significantly correlated to the antecedent rainfall conditions as an indication of antecedent moisture content (AMC) and strongly correlated to rainfall event characteristics such as amount and intensity. Figure 4 also indicates that fewer environmental characteristics were significantly correlated to the soil erosion variables at the 23 ha level. Correlation values and proximity of variables on the PCA show that rainfall amount and duration and significant effects on sediment concentrations while AR_{10} had significant effects on soil losses. At the 100 ha level poor correlations existed between all the selected environmental variables as indicated by the length and direction of the lines representing R,SC and SL in relation to the positions of the environmental variables (Figure 4). Minor yet noteworthy correlations existed between the antecedent rainfall amount three and ten days and maximum I_{30}. Correlations were stronger between these variables were stronger at the 100 ha level compared to the 23 ha level.

Quality of sediments from the different scales

General characteristics of sediments and soils

Selected sediment and soil physical characteristics were analysed as a preliminary exercise to understand soil erosion dynamics at the given scales (Table 4). Additional sources to the mentioned scales are introduced and are listed in Table 4. The considered surface soil horizons were located on the hillslope were the 1 m^2 and 10 m^2 plots were located and thus was a source of material for hillslope eroded sediment. It was assumed that 23 ha riverbed sediments and 23 ha sediments would have a mixture of origins from surface and deep soil horizons. Sediments showed an initial enrichment of fine soil particles (clay and fine silt) at the 10 m^2 plot scale. A decrease in the percentage of fine particles in correspondence to an increase of sand percentage was observed with increasing spatial scale. A similar trend was followed when comparing the average in-situ soil particle size distribution to that of the eroded sediments at the different spatial scales.

Regarding the Munsell colour characteristics, a slight decrease in redness of soil material was observed from the 1 m^2 and 10 m^2 plot scales to the catchment scales. Subtle to no differences were observed between the value of the first three considered scales (4 for the 1 m^2 and 10 m^2 plot scales and 23ha to 4.4 for the 23ha catchment riverbed), however, Value of the 100 ha sediments increased to 6, followed by a decrease decrease in value to 4.5 at the 1000 ha dam. A distinct difference was observed between the Chroma at the 1 m^2 and 10 m^2 plot scales (4.4) compared to the 23 ha riverbed, 23 ha catchment and 100 ha catchment (6). Soil material chroma decreased to 2.8 at the 1000 ha scale.

Eroded sediments at the 1 m^2 and 10 m^2 plot and 23 ha scales were generally enriched in total carbon % (C) and total nitrogen % (N) compared to the in-situ surface soil material. Riverbed sediment was however depleted in C and N compared to the sediments at the other scales and enriched compared to the deep soil horizons. At the 100 ha catchment, sediments were noticeably in C and N, however the 1000 ha dam sediments were more enriched.

Physical and chemical characteristics of eroded sediments

Results of soil particle distribution of soil and sediments were superimposed onto a United States Department of Agriculture (USDA) texture triangle (Figure 5A). Sediments eroded at the 1 m^2 were enriched in clay in comparison to the surface soil material (0-0.05 m) while 10m^2 sediments were slightly depleted in clay. Sediments located at the 23 ha catchment riverbed and the 23 and 100 ha catchment outlets were also depleted in clays compared to deep soil horizons (0.4-0.5m). Sediments located at the 1000 ha level were enriched in clay compared to the other scales. According to the USDA texture classification, sediments eroded at the 1 m^2 level were classified as clay/clay loam; sediments eroded at the 10 m^2 and 23 ha levels were classified as clay loam however their high sand and contents placed them close to sandy loam textured sediments; sediments eroded at the 100 ha level were classified as sandy clay loam and 1000 ha sediments were classified as clay textured.

Two PCs were generated (Figure 6A and B), the first was to compare physical and chemical properties of sediments and soils from the different locations within the 23 ha research catchment while the second compared the grouped properties of the soils and sediments. The correlation between the soil physical and chemical properties indicated that strong correlations existed between clay and fine silt (Fi-Si); total carbon (C) and total nitrogen (N), course sand (Co-Sa) and medium sand (Me-Sa); chroma, value and fine sand (Fi-Sa) (Figure 6A). Figure 6B shows that the 1 and 10 m^2 plot sediments were similar in properties and were therefore located within close proximities to each other. Erosion processes created dissimilarities between *in-situ* surface soil and *ex-situ* 1 and 10 m^2 plot sediments in response to selectivity of erosion processes. Stronger similarities were found between river sediments and deep soil horizons as a result of the low selectivity of erosion processes and the similarity of the properties of the soil and sediments. A measure of the Euclidean distance of the 23 ha sediment to the river and 1 and 10 m^2 plot sediments reveals that lateral processes erosion at the hillslope level contributed to 37% of the total catchment soil loss whereas a 63% contribution was made by linear erosion processes within the stream network.

Discussion

Evaluation of soil erosion fluxes at the different spatial scales

Soil loss results at the different scales indicate that soil erosion processes vary considerably within the landscape. The differences in soil losses at the 1 m^2 and 10 m^2 plot levels are explained by the predominant scale dependent erosion mechanisms in operation. Previous studies have indicated that soil erosion processes are dependent upon spatial scale and that soil erosion is transport limited at short slope lengths (> 1 m). At local scales the basic erosion mechanisms of splash erosion are dominant as surface runoff which is essential for sheet erosion has little opportunity to gain gravitational acceleration to entrain and transport soil material a considerable distance (Le Bissonnais *et al*., 1998; Bryan 2000; Chaplot and Le Bissonnais, 2000; Kinnell, 2004; Ghahramani *et al*., 2011; Mayor *et al*., 2011). Sheet erosion was more operative at the 10 m^2 plot level. On account of greater slope lengths facilitating the acquisition of greater runoff velocity allowing for the transport of more sediment per m^2 at the 10 m^2 level than at the 1 m^2 level (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000; Ghahramani *et al*., 2011).

The significant decrease in soil losses between the 10 m^2 plot and 23 ha catchment level is due to numerous detachment, transport and deposition cycles causing erosion discontinuity from the hillslope to the catchment outlet. Investigations have shown that the opportunity for runoff infiltration increases with increasing spatial scale thus aiding sedimentation and that catchment scale soil loss measurements are often an underestimation of the total soil erosion processes occurring in a given catchment (Cammeraat, 2004; Mingguo *et al*., 2007; Mayor *et al*., 2011). Further decreases in soil losses at the 100 ha catchment outlet are attributed to greater increases in landscape heterogeneity, threshold requirements related to rainfall characteristics and catchment morphology such as greater catchment length and reduced slope gradient and (Cammeraat, 2004). Cumulative runoff increased sharply in late January 2011 to values well above the other considered scales. This increase is attributed to groundwater exfiltration supplementing 100 ha stream flows. The increase in runoff at the 100 ha level was not accompanied by an increase in soil losses possibly due to the presence of sedimentation areas within the 100 ha catchment. The consistent decrease in soil losses with increasing spatial scale is supported by the notion of increased landscape heterogeneity and complexity of erosion processes both contributing to more sediment retention with increased spatial scale (Le Bissonnais *et al*., 1998; Chaplot and Le Bissonnais, 2000; Cammeraat, 2004; Ghahramani *et al*., 2011; Mayor *et al*., 2011).

Sediment concentration patterns at the different scales indicate that more sediment per unit runoff was eroded in the first half of the rainy season. The accumulation of loose material at the 1 m^2 and 10 m^2 plot levels by factors such as biological activity may explain the initial high sediment concentrations in 2010 in comparison to 2011. The sharp increase in sediment concentration during December 2010 may be explained by large amount of runoff in the stream channel entraining and transporting sediment deposited close to the 23 ha outlet. Additionally the deposition of soil material into the fluvial system from the scouring of stream banks also provided loose soil material for runoff transport.

Factors controlling soil erosion fluxes

The correlation matrix (Table 3) and PCA (Figure 4) indicates that antecedent rainfall conditions as an indication of increasing antecedent soil moisture (AR_3 and AR_{10}) and rainfall depth (RA), duration (RDur) and intensity (Imax, and I_{30}max) had significant positive correlations (P<0.05) with runoff rates and soil losses. The positive correlations at the 1 m^2 and 10 m^2 plots are explained as follows: Increased AMC (AR_3 and AR_{10}) reduces soil sorptivity and soil hydraulic conductivity of the soil profile allowing for increased potential for R generation during rainfall events (Bryan, 2000; Cammeraat, 2004; Imax and I_{30}max supply raindrops with high kinetic energy, these are able to detach soil material providing loose material for transport by adequate amounts of R with sufficient surface flow velocity (Vandaele and Poesen, 1995; Bryan, 2000; Cao *et al*., 2009). Moreover, the rapid supply of rainwater for overland flow ensures rapid R generation and connectivity with high erosive energy (Parsons and Stone, 2006); RDur and RA further facilitated the occurrence of R connectivity which provided opportunity for greater sediment transport distances during rainfall events thus increasing SL from larger spatial areas (Stomph *et al*., 2002). Surprisingly Imax and I30max were marginally correlated with sediment concentrations at the 1 and 10 m^2 levels. This may have been a result of general moderate to high basal cover at the 1 m^2 and 10 m^2 plot locations (Mayor *et al*., 2011).

Correlations between the environmental and soil erosion variables decreased with increasing spatial scale (23 ha and 100 ha). The possible reason for this is a shift in scale dependency of erosion inducing factors (Cammeraat, 2004; Mingguo *et al*., 2007). Positive correlations between SC and RA and RDur are explained by high magnitude long duration rainfall events increasing runoff transport efficiency of sediment. No significant correlations were found between the environmental and soil erosion variables at the 100 ha level. Previous studies indicate that the likely cause is related to increased landscape heterogeneity contributing to an increased mosaic of factors governing soil erosion trends and decreased connectivity and continuity of erosion processes (Cammeraat, 2002; Cammeraat, 2004; Mingguo *et al*., 2007).

Physical and chemical sediment characteristics as an indication of soil erosion dynamics

Particle size distribution trends of the eroded sediments at the different indicate is explained particle selectivity of erosion mechanisms decreasing with increasing erosion efficiency. The selectivity of erosion processes between the 1 m^2 and 10 m^2 plot levels is illustrated further in Figure 5B where selected individual hillslope positions are shown. Erosion was predominantly transport limited at the 1 m^2 level due to the prevention of the adequate generation of erosive runoff flow velocities (Kinnell, 2004). Predominant splash erosion processes at the 1 m^2 scale were only able to erode fine material during rainfall events resulting in sediments being enriched in clay in comparison to the surface soil horizon (Wang *et al*., 2010). The decreased clay percentage of the 10 m^2 sediments is indicative of reduced selectivity of erosion processes due to increased contribution of rain impacted flow erosion at the 10 m^2 level (Teixeira and Misra, 1997, Kinnell, 2004). Differences in the particle size distribution between the 10 m^2 level and the surface soil horizon were negligible due to the less selective erosion mechanisms. Mechanisms of lateral and linear erosion (streambank erosion) contribute to catchment soil loss at the 23 and 100 ha levels which explain the continued enrichment of courser soil material at these scales. Sediments at the outlet of the 1000 ha catchment were enriched in clay in comparison to the other scales due to the deposition of the suspended load.

Nutrient (C and N) enrichment of sediments at the 1 and 10 m^2 levels compared to surface soil horizons is a result of the preferential removal of light organic soil material during erosion events (Table 4) (Rumpel *et al.,* 2009; Wang *et al*., 2010). Within the 23 ha river network bed load sediments were depleted in C and N compared to deep soil horizons. This is possibly due to the preferential erosion of exposed subsurface horizons by river bank and gully erosion processes followed by the favoured removal and transport of fine and light soil material by fluvial processes (Rumpel *et al.,* 2009; Wang *et al*., 2010). The C and N enrichment of sediments at the 23 ha level compared to surface and deep soil horizons and the 10 m^2 sediments is most likely a result of the deposition of fine material and nutrients transported from the upper areas of the 23 ha river network and the hillslope (Wang *et al*., 2010). Field observations show that the flume where deposition occurs is adjacent to an area of significant deposition of soil material which has resulted in the proliferation of a grassed section of the fluvial system.

Physical and chemical sediment characteristics as sediment source tracers

Previous studies have indicated that the use of particle size distribution alone may have limitations unless the potential sources had distinctly different particle size distributions (Kurashige and Fusejima, 1997). In this study, sediments eroded at the 10m^2 and 23 ha outlet had similar particle size distributions which may be a function of efficiency of erosion. The identification of sources within the 23 ha catchment was thus supplemented using colour and total C and N of the 23 ha soils and sediments as additional parameters. Sediments lost from the 23 ha were slightly enriched in total C and N and similar in redness value and chroma to the sediments of the stream channel. Thus, a greater contribution to catchment soil loss was made by processes of linear erosion within the 23 ha stream channel.. This notion was supported by erosion discontinuity from the hillslope to the 23 ha catchment outlet indicated by the total soil loss results at the considered scales (Le Bissonnais *et al*., 1998). Krause *et al*. (2003) who adopted a multi-parameter approach to sediment fingerprinting made similar findings in a 1.2 km^2 catchment in New South Wales where gully erosion had a greater contribution to catchment soil loss than erosion occurring on grazed pastures. Li *et al*. (2003) reported that gully erosion was the main contributor to reservoir sedimentation in the Yangjuangou reservoir catchment in China. Collins *et al*. (2001) found that in cultivated catchments soil losses from gullies and channel banks can be substantially lower than those measured from cultivated fields. With regard to this study, vegetated areas of the hillslope retained a large amount of sediment eroded by sheet erosion processes. Descroix *et al*. (2008) also obtained a greater sheet erosion contribution to catchment soil loss compared to gully erosion in the Western Sierra Madre. It was noted, however, that few gullies were present in their research catchment.

The 37 % contribution of lateral erosion processes to total catchment soil loss from the 23 ha catchment was also facilitated by the small size of the considered catchment. Literature has shown that hillslopes may contribute to significant soil loss from small catchments due to their low thresholds for runoff generation and enhanced potential for runoff continuity (Cammeraat, 2004). Furthermore, the close proximity of the potential sources increased the likelihood of the contribution of more potential sources to total catchment soil loss.

Conclusion

In this study in the 1000 ha catchment of Potshini our main objective was to evaluate sediment fluxes and selected physical and chemical characteristics of sediments eroded at the different scales (1 m^2, 10 m^2, 23 ha, 100 ha and 1000 ha scales) in an attempt to better understand soil erosion dynamics at the landscape level. From this study two main conclusions can be drawn:

Different processes of soil erosion exist and these are highly dependent on spatial and temporal scales. We found that the local processes of splash erosion are dominant at the 1 m^2 level due to erosion processes being transport limited. Relatively low soil losses were observed that this scale. Furthermore, erosion processes occurring at the 1 m^2 level are selective for the reason that clay particles and organic matter are preferentially removed. With an increase in spatial scale to the 10 m^2 level soil losses increase in correspondence to the operation of more erosive forms of lateral erosion such as rain impacted flow. At the 10 m^2 scale runoff is able to accumulate and accelerate obtaining more energy for entraining and transporting soil particles over a greater distance from their initial location. Erosion processes are less selective at the 10 m^2 level due to the transport of a greater percentage of courser silt and sand particles. Total seasonal soil losses decreased at the 23 ha level despite the operation of more erosion mechanisms such as sheet erosion at the hillslope level and gully and stream bank erosion within the stream network. This is due to an increase in heterogeneity and variability of landscape characteristics such as slope and basal cover and complexity of erosion processes such as increased detachment, transport and deposition cycles. Our results indicate that sedimentation seems to become dominant at this scale. The same trend was observed at the 100 ha level where the lowest soil losses were observed despite the operation of lateral and linear erosion processes. *Sedimentation increased even more*.

Properties of eroded sediments such as particle size distribution and total C and N content give an indication of soil erosion processes at the different scales. Our results indicate that light and fine soil material (clays and particulate organic matter) were preferentially eroded at the 1 m2 level and sediments eroded at this scale were enriched in clays and total C and N in comparison to the surface soil horizon. Selectivity of erosion processes decreased at the 10 m^2, 23 ha and 100 ha levels in response to increased efficiency of erosion processes such as rain impacted flow, streambank and gully erosion.

Properties of eroded sediments may also give an indication of the dominant form of erosion and the locality of important sediment producing areas. Our results indicate that the dominant form of erosion contributing to catchment soil loss were the processes of stream bank and gully erosion processes. Approximately 63% of the sediments at the 23 ha level were delivered by gully erosion during erosive rainfall events. This is detrimental for the quality of the 23 ha catchment for the reason that gully widening is rather than upward retreat occurring.
Recommendation to secure the gully banks.

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Table1. Rainfall characteristics of the study events (n=17).

	I	Imax	I_{30}	I_{30}max	RA	Rdur	ARD	AR	AR_3	AR_{10}
Mean	4.1	28.1	4.1	22.3	55.4	1.0	107.0	685.8	29.4	89.0
StDev	2.6	21.0	2.3	17.3	52.2	1.6	51.8	353.4	28.2	97.6
SE	1.6	4.6	1.5	4.2	7.2	1.3	7.2	18.8	5.3	9.9
CV	63.3	74.5	56.2	77.7	94.2	161.6	48.4	51.5	96.1	109.6
Variance	6.8	439.1	5.4	300.0	2723.4	2.6	2678.7	124912.0	797.1	9521.7
Min	1.3	4.0	1.0	3.6	0.2	0.3	10.0	31.4	0.2	6.8
Max	12.8	64.0	10.6	52.8	177.6	16.8	187.0	1055.4	103.4	436.8
Mode	n/a	11.2	n/a	10.8	n/a	0.3	n/a	n/a	n/a	n/a
Quartile 1	2.7	11.6	2.6	10.0	25.0	0.3	76.0	425.3	9.7	34.0
Median	3.4	16.8	3.5	12.8	31.6	0.3	120.0	859.0	23.0	53.0
Quartile 3	4.6	53.2	5.0	42.0	75.4	1.0	145.0	954.7	42.7	109.5
Skewness	2.2	0.7	1.3	0.8	1.1	4.7	-0.5	-0.9	1.4	2.8
Kurtosis	6.5	-1.4	1.7	-1.2	0.3	32.6	-0.6	-0.8	1.5	9.2

Table 2. General statistics of the soil erosion characteristics (R: runoff; SC: sediment conce,ntration; SL: soil losses; SLw: soil flux per meter width) as function of plot scale for the 2010-2011 rainfall season.

	R $L\ m^{-2}$				SC $g\ L^{-1}$				SL $g\ m^{-2}$				SLw $g\ m^{-1}$	
	$1m^2$	$10m^2$	23ha	100ha	$1m^2$	$10m^2$	23ha	100ha	$1m^2$	$10m^2$	23ha	100ha	$1m^2$	$10m^2$
Mean	15.5	23.4	5.1	31.2	1.3	2.9	7.7	2.0	23.9	82.3	47.5	2.0	23.9	41.2
StDev	17.0	28.2	8.4	43.2	1.0	3.4	9.0	2.7	35.7	167.6	80.4	2.7	35.7	83.8
SE	4.1	5.3	2.9	6.6	1.0	1.8	3.0	1.6	6.0	12.9	9.0	1.6	6.0	6.5
CV	109.4	120.9	165.7	138.7	78.3	117.2	117.0	133.3	149.4	203.5	169.4	133.3	149.4	101.8
Variance	289.5	798.0	70.6	1869.6	1.0	11.4	80.6	7.1	1275.1	28083.3	6467.9	7.1	1275.1	14041.7
Min	0.8	0.7	0.0	0.0	0.3	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2	0.0
Max	49.5	89.0	31.4	169.3	4.0	10.6	27.4	8.9	127.8	558.5	234.1	8.9	127.8	279.3
Mode	n/a	n/a	n/a	0.0	n/a	n/a	n/a	0.0	n/a	n/a	n/a	0.0	n/a	n/a
Quartile 1	3.3	3.2	0.5	1.5	0.6	0.8	1.7	0.5	2.4	4.6	0.3	0.5	2.4	2.3
Median	7.9	7.4	1.0	20.4	0.9	1.0	3.3	1.2	5.3	7.6	4.8	1.2	5.3	3.8
Quartile 3	28.5	44.2	8.4	43.2	1.8	4.0	11.1	2.6	35.7	82.3	80.4	2.6	35.7	41.2
Skewness	1.0	1.3	2.4	2.3	1.2	1.4	1.3	2.1	2.0	2.5	1.6	2.1	2.0	1.2
Kurtosis	-0.4	0.5	5.8	6.2	1.4	0.8	0.7	3.7	3.6	5.1	1.1	3.7	3.6	2.5

Table 3. Correlation matrix between soil erosion variables and environmental factors (RA: event rainfall amount; I: average rainfall intensity; Imax: maximum rainfall intensity; I_{30}: average thirty minute rainfall intensity; I_{30}max: maximum thirty minute rainfall intensity;; RDur: rainfall event duration; ARD: cumulative antecedent rain days; AR: antecedent rainfall since onset of rainy season, 3 or 10 days prior to the event)

	RA	I	Imax	I_{30}	I_{30}max	RDur	AR	ARD	AR_3	AR_{10}
R_1m^2	0.83*	-0.16	0.65*	-0.17	0.68*	0.81*	-0.1	-0.14	0.54*	0.61*
SC_1m^2	0.38	-0.20	0.25	-0.27	0.28	0.24	-0.39	-0.41	0.11	0.22
SL_1m^2	0.87*	-0.09	0.71*	-0.10	0.74*	0.80*	-0.19	-0.19	0.51*	0.50*
R_10m^2	0.88*	-0.12	0.70*	-0.13	0.73*	0.62*	-0.32	-0.31	0.67*	0.42
SC_10m^2	0.06	0.10	0.11	0.00	0.17	0.01	-0.52*	-0.46	-0.12	-0.17
SL_10m^2	0.51*	-0.09	0.58*	-0.01	0.60*	0.38	-0.45	-0.37	0.32	0.09
R_23ha	0.11	-0.16	0.08	-0.17	0.09	0.11	0.17	0.16	0.04	0.28
SC_23ha	0.50*	-0.35	0.42	-0.37	0.35	0.58*	-0.17	-0.19	0.12	0.47
SL_23ha	0.43	-0.22	0.42	-0.24	0.33	0.36	0.03	0.00	0.28	0.62*
R_100ha	-0.11	0.03	0.28	0.01	0.42	0.19	-0.29	-0.22	0.13	-0.03
SC_100ha	0.12	0.03	0.28	0.01	0.42	0.19	-0.29	-0.22	0.13	-0.03
SL_100ha	0.09	-0.2	0.12	-0.18	0.05	-0.12	0.17	0.16	0.02	0.10

* and bold correlations are significant at $p<0.05$

Table 4. Characteristics (Clay: clay content ; FiSi: fine silt content; CoSi: coarse silt content; CoSa: coarse sand content; MeSa: medium sand content; FiSa: fine sand content; VFiSa: very fine sand content; Redness: Munsell redness; Value: Munsell value; Chroma: Munsell chroma; C: total carbon content; N: total nitrogen content) of sediments and soils collected within the study area.

	Clay	FiSi	CoSi	CoSa	MeSa	FiSa	VFiSa	Redness	Value	Chroma	C	N
1m^2	40.3	15.8	8.6	6.2	15.7	7.6	5.9	3.2	4	4.4	5.8	0.6
10m^2	36.1	14.8	5.5	11.7	19.5	9.7	2.6	3.2	4	4.4	3.9	0.4
23 ha riverbed	31.8	11.4	5.7	1.8	6	35.5	7.9	3	4.4	6	1.9	0.2
23ha	29.7	16.7	8.1	3.2	10.1	25.7	6.4	3	4	6	4.3	0.2
100ha	28	10	6.8	0.5	22.9	29.7	2.4	2	6	6	0.1	0.1
1000 ha	49.3	27.3	4.4	1.2	3.7	7.5	6.8	2	4.5	2.8	1.2	0.2
Average	*32.8*	*15.0*	*5.5*	*4.1*	*17.2*	*20.1*	*5.3*	*2.7*	*4.5*	*4.9*	*3.2*	*0.3*
Surf soil hor.	35.9	17.6	6.2	0.5	4.2	25.3	10.3	3.8	3.2	3.4	2.2	0.2
Deep soil hor.	39.7	15.5	9.1	0.8	4.2	21.5	9.2	3.4	4.3	4.6	0.6	0
Average	*37.4*	*16.5*	*7.65*	*0.65*	*4.2*	*23.4*	*9.75*	*3.6*	*3.75*	*4*	*1.4*	*0.1*

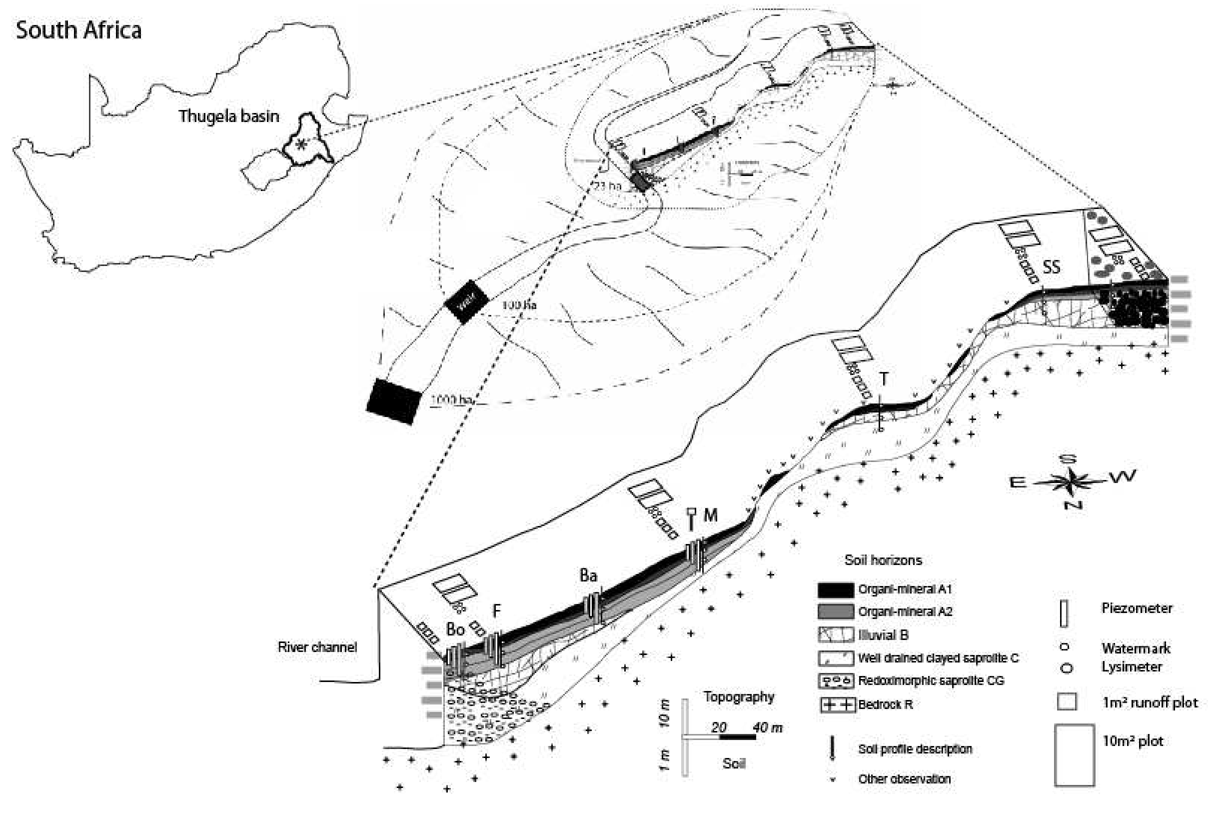

Figure 1. Location of the study area and experimental design for water and sediment flux estimation.

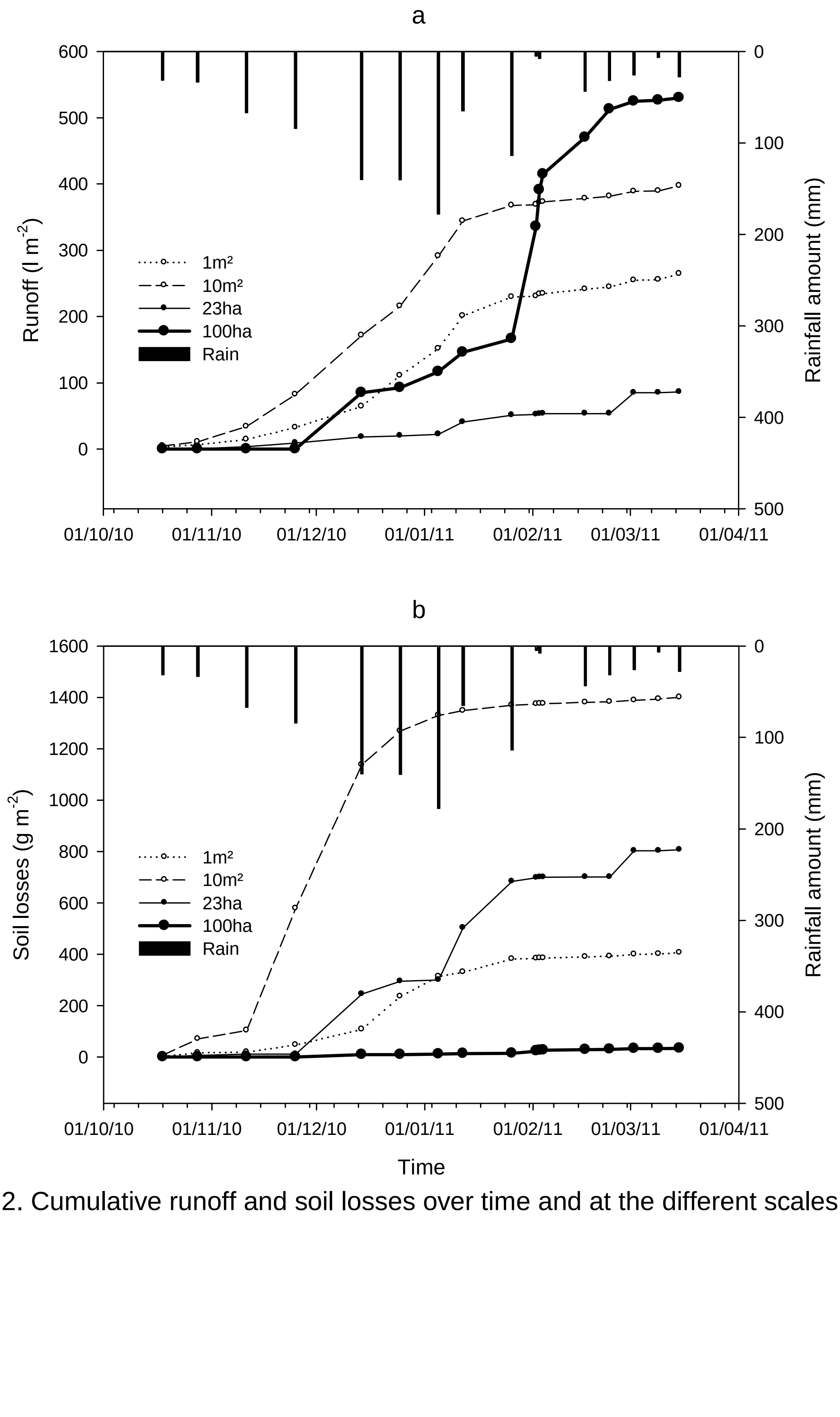

Figure 2. Cumulative runoff and soil losses over time and at the different scales.

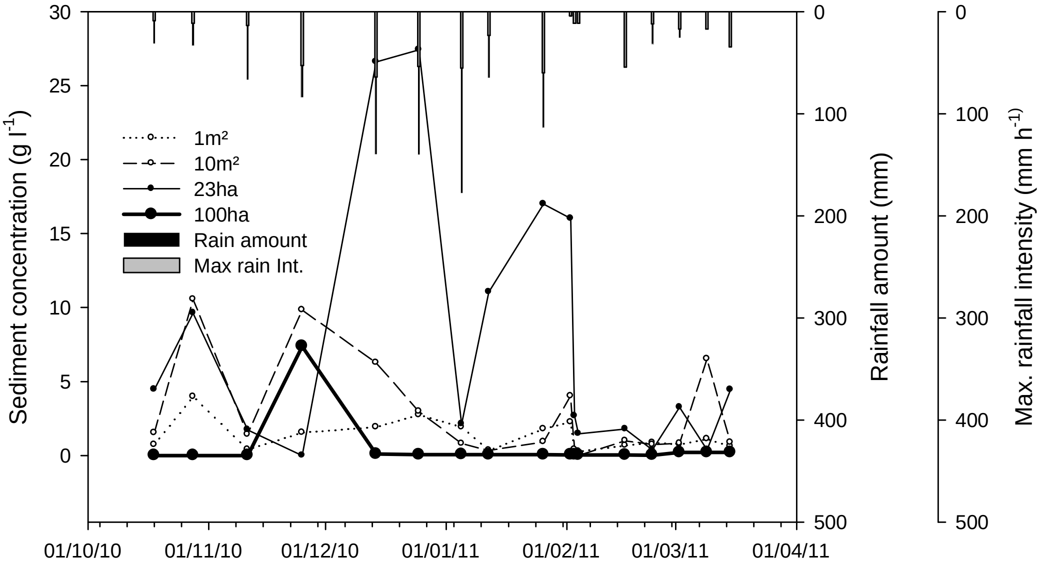

Figure 3. Sediment concentration and its variations over time and at the different scales.

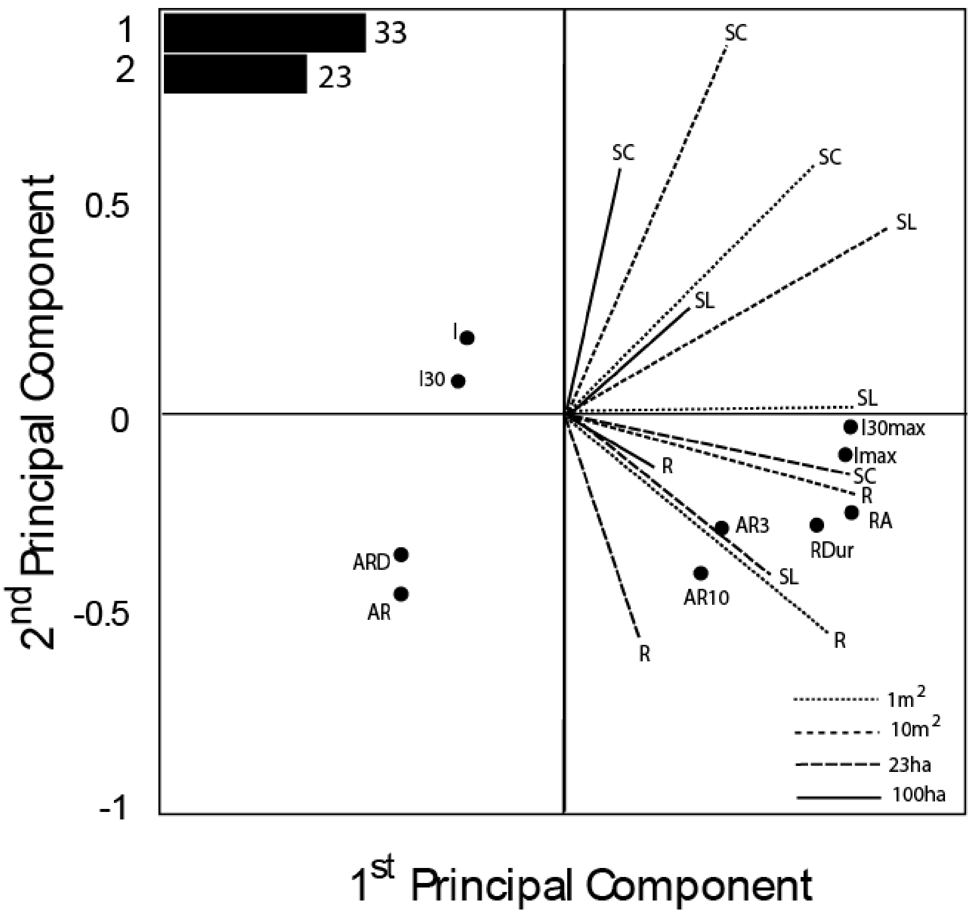

Figure 4. Principal Component Analysis generated using soil erosion variables at the different scales as dependent variables versus environmental characteristics as supplementary variables.

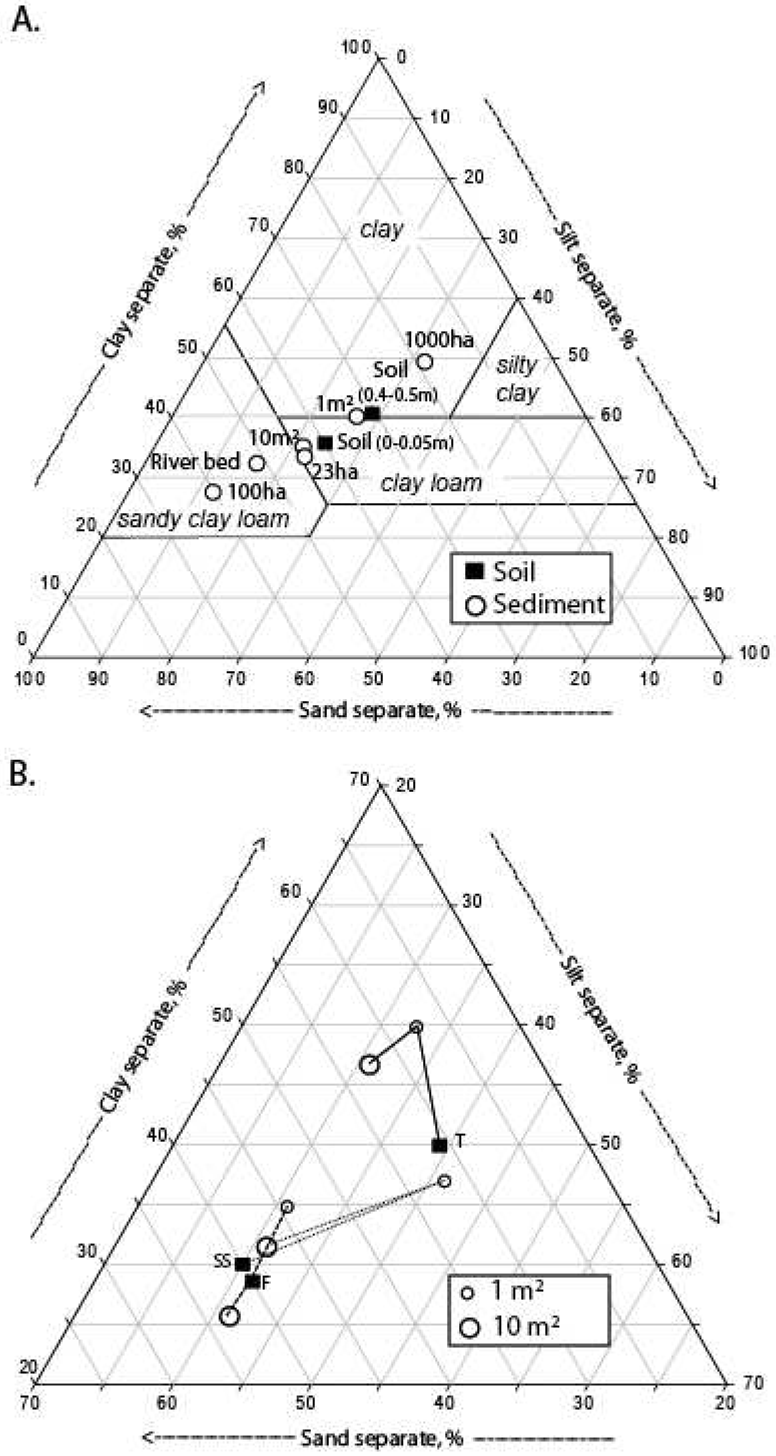

Figure 5. Average texture distribution for soils and sediments (A) and for plots and 1 m^2 plot sediments versus surface soil horizons at three landscape positions (F: footslope; T: terrace; SS: shoulder schist) (B).

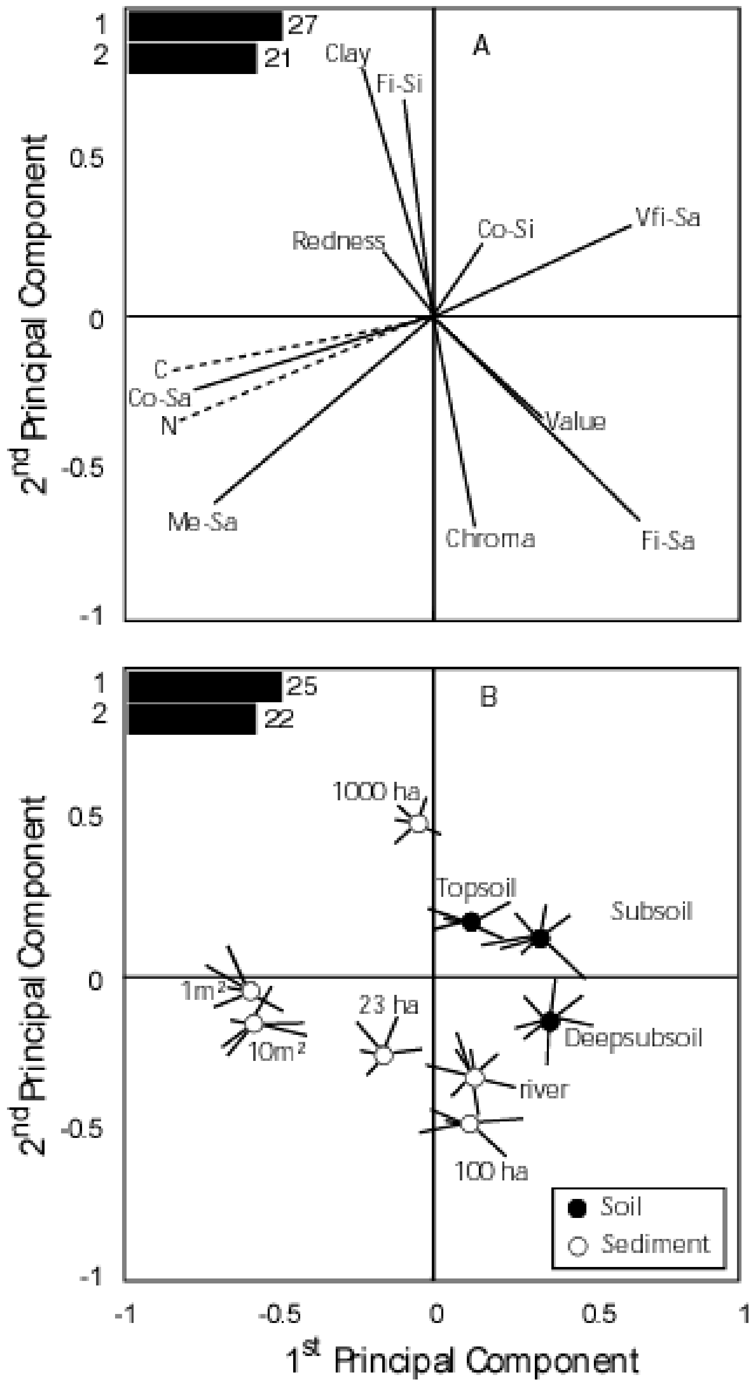

Figure 6. Principal Component Analysis generated using environmental characteristics as dependent variables and position of soils and sediments with average value and replicate as supplementary variables.